Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Lateral and Longitudinal Control

U.S. Department of Transportation
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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research and Development

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16. Abstract
This report analyzes the requirements, issues, and risks associated with lateral and longitudinal control of vehicles operating on the AHS. This report presents a possible evolutionary path for the automation of lateral and longitudinal control. This evolutionary path is characterized by five evolutionary representative system configurations (ERSCs). This analysis looks at the development of longitudinal, lateral and finally combined lateral and longitudinal systems in terms of the performance and reliability requirements and deployment scenarios. The performance requirement analysis covers driver comfort and acceptance issues during automatic control and transitions between automatic and manual control in addition to investigating the sensor, actuator and controller requirements for the control systems. Roadway traffic controllers may improve traffic flow through traffic networks in terms of travel time reduction and congestion avoidance. The reliability requirements analysis uses NHTSA’s accident rates data to quantify the reliability requirements in various levels of vehicle automation. This report derives the reliability functional requirements for the automatic systems used in lateral and longitudinal control. The reliability functional requirements allows us to assess the required redundancy and structural complexity in implementing these automatic systems. This information can be used to estimate the cost and difficulty to build the automated highway systems.

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vehicle lateral and longitudinal control, evolutionary representative system configurations, reliability requirements, redundancy, performance requirements, human factors, capacity benefits, autonomous vehicles

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-lock Braking System
AHS	Automated Highway System
AICC	Autonomous Intelligent Cruise Control
ALK	Automatic Lane Keeping
ALLC	Automatic Lateral and Longitudinal Control
ATIS	Advanced Traffic Information Systems
ATMS	Advanced Traffic Management Systems
AVI	Advanced Vehicle Identification
BSW	Blind Spot Warning
CDMA	Code Division Multiple Access
ERSC	Evolutionary Representative System Configuration
FDMA	Frequency Division Multiple Access
FHWA	Federal Highway Administration
FMEA	Failure Mode and Effects Analysis
GPS	Global Positioning System
ICC	Intelligent Cruise Control
ID	Identification
LCD	Liquid Crystal Display
LCW	Lateral Collision Warning
LED	Light Emitting Diode
LDW	Lane Departure Warning
MTTF	Mean Time to Failure
NHTSA	National Highway Traffic Safety Administration
PATH	Program on Advanced Technology for the Highway
PSA	Precursor Systems Analysis
RECA	Rear-End Collision Avoidance
RECW	Rear-End Collision Warning
SA	Steering Assist
SHM	Speed and Headway Maintenance
SHMS	Speed and Headway Maintenance System
tbd	to be determined

List of Acronyms
(continued)

TCAS	Traffic Alert and Collision Avoidance System
TDMA	Time Division Multiple Access
TLC	Time to Line Crossing
TTC	Time to Collision
USC	University of Southern California
VRC	Vehicle-Roadway Communications

EXECUTIVE SUMMARY

The report analyzes the requirements, issues, and risks associated with lateral and longitudinal control of vehicles operating on AHS. This report is part of the Precursor Systems Analysis (PSA) study sponsored by the Federal Highway Administration (FHWA).

The contractor team for this project consisted of the University of Southern California (USC), Ford and Daimler-Benz. The USC group led the effort with P. Ioannou as the principal investigator. Other investigators include faculty from the Department of Human Factors at USC. Ford Motor Company assisted the USC group by providing experimental data, technical guidance and information related to vehicle dynamics, hardware, lateral and longitudinal control functions.

This report presents a possible evolutionary path for the automation of vehicle lateral and longitudinal control systems. This path is characterized by five evolutionary representative system configurations (ERSCs). Each ERSC builds upon the earlier ones in terms of performance and vehicle complexity. If a failure occurs then the system falls back to the previous ERSC. ERSC 1 has a dedicated lane for vehicles with speed and headway maintenance systems. In ERSC 2 the vehicles have steering assist, more vehicle to vehicle communications, lane departure warnings, and rear-end collision avoidance. ERSC 3 has "hands-off" steering in a single lane, lateral collision warnings, and maneuver coordination near entry and exit points. In ERSC 4 vehicles can change lanes automatically. These vehicles also have collision avoidance capability in both the lateral and longitudinal directions. ERSC 5 corresponds to a fully automated system where the infrastructure can guide and route the vehicles. For each ERSC, we analyze the performance and reliability requirements for automatic lateral and longitudinal control.

The performance requirement analysis covers safety, driver comfort and acceptance issues during automatic control and transitions between automatic and manual control. The analysis also investigates the sensor, actuator and controller requirements for the automatic control systems. The reliability requirement analysis uses NHTSA's accident rates data to estimate the required reliability at various levels of automation. This report also derives reliability functional requirements for automatic lateral and longitudinal control systems. The reliability functional requirements provide a way to assess the required redundancy and complexity in designing these automatic systems. The driver task analysis highlights the causes and effects of human driver interactions with the automated systems. Finally the report discusses the benefits in terms of capacity, traffic congestion, and safety of each level of automation.

The summary of key findings and issues of this research are:

1. Communication systems and sensors such as radar will be used on vehicles in all stages of AHS deployment. When multiple radar operate in a small area at similar frequencies, the radar on different vehicles may interfere with one another. This interference could lead to shorter sensor ranges and poor performance. Such interference is a safety issue since the sensors or communications systems may not work as expected. This issue may also affect how the highways are built and what separation is required between lanes.

2. Vehicle-to-vehicle communication can reduce the number of false alarms in rear-end collision warning systems without reducing the detection rates. Each vehicle sends its braking data to the vehicle behind it. These communications can serve as a sort of electronic brake light for the vehicle behind. This lets the following vehicle anticipate the braking of the vehicle ahead. This warning can decrease the number of false alarms in the rear-end collision warning system. However, the government will need to set communication frequencies and protocols so that a common communication system can be used on all highways.

3. A roadway traffic controller can decrease traffic congestion even in cases of low levels of automation. This controller eases roadway congestion by regulating vehicle speed and traffic density along sections of the roadway. This can smooth traffic flow and decrease backups due to incidents on the roadway. Studies at USC show considerable improvements in congestion reduction and stability of traffic flow by using appropriate roadway traffic controllers.

4. Multiple types of driver warnings for lateral/longitudinal collisions will be installed on vehicles in the early stages of AHS deployment. Some examples are rear-end collision and lateral collision warnings. The driver may experience warning overload and warning confusion problems while interacting with other vehicle and roadway functions. More research needs to be done on the interaction and prioritization of these warnings for the driver.

5. Collision avoidance systems use braking and steering to avoid crashing into other vehicles or stationary obstacles in the lane. Under the current system, the vehicle manufacturer may be liable for collisions caused by vehicle failures. This may have an impact on the automobile manufacturer’s willingness to produce automated vehicles. It may also affect the design and operation of the automated systems. The legal system may need to limit manufacturer’s liability.

6. Collision avoidance requires combined lateral and longitudinal control. Our work proposes an evolutionary system for the development of AHS. In one partial automation scenario the driver can override the automatic lane keeping system but not the longitudinal control for the throttle. The driver may not be able to perform lateral collision avoidance maneuvers using steering control only. This issue needs more human factors studies.

7. Our original evolutionary design split the development of full lateral control into two parts. The first part was automated lane keeping. The second part was lane changing and lateral collision avoidance. These control modes should not be separated since the driver becomes a passenger once the vehicle takes over lane keeping. Human factors studies show that humans do not perform monitoring tasks well.

8. A roadway controller that sends speed commands to vehicles can smooth vehicle speeds and improve traffic flow when incidents occur. The vehicle can respond to the roadway controller commands automatically as proposed in the Prometheus project or the driver can change the vehicle’s cruising speed. If the vehicle automatically responds to the speed commands from the roadway, the driver’s reliability in detecting rear-end collision danger may be degraded. The driver may be put into a situation that he/she can not handle and may blame the roadway for any rear-end collision. The roadway may be liable for accident caused by incorrect speed commands. However, if the vehicle does not respond directly to roadway speed

commands, the effectiveness of the roadway traffic flow control will be reduced since the driver may not follow the roadway commands.

9. At each stage of the AHS evolution, drivers are required to have a basic understanding about the system operation so they can interface with AHS safely and efficiently. Drivers may need to be trained to handle the necessary tasks and workload.

10. Vehicles require a distance and closing rate sensor for speed and headway maintenance or intelligent cruise control. This system can also warn the driver of potential rear-end collisions. The rear-end collision warning system computes the Time-to-Collision and warns the driver of a potential collision in time to avoid the collision (about 1.5 s before the collision). The sensors for this type of system only need to be accurate to within 3-5 km/hr.

11. As the AHS evolves to higher ERSCs, the driver's functions are gradually replaced by the automatic control systems of vehicle and roadway. These systems needs to be more reliable than human drivers so that the AHS can be accepted by the public. They also need to be fail-safe to guarantee the safety of drivers. These reliability requirements may substantially increase the component redundancy and design complexity.

12. The reliability requirements for automatic systems in each ERSC can be used to assess the required component redundancy and design complexity. This gives us a way to estimate the gaps between ERSCs in terms of technical difficulties, cost and risks.

13. Safety and efficiency benefits in higher ERSCs can only be realized by heavily instrumented vehicles, using roadway lane reference aids and a roadway navigation system. It will take joint efforts of the public, the automobile manufacturers and the government to settle the potential legal and liability problems arising from AHS operation.

14. The communication requirements for AHS increase rapidly with the level of automation. When the vehicles have only longitudinal control, each vehicle needs to communicate only with the vehicle behind and in front. In a fully automated system the vehicles must communicate with the roadway and the surrounding vehicles to coordinate maneuvers. This change requires increases in bandwidth and reliability and more sophisticated communication protocols.

15. The human factors issues are very complex in the ERSCs that mix automated and manual control systems. Humans do not perform well as supervisors of automated systems. Systems that rely on a human driver who is not actively involved in lateral or longitudinal control to respond to infrequent warnings for collision avoidance or other emergencies may not work well. Once the vehicle can perform hands-off, feet-off driving in the dedicated lane, the human factors issues may be less critical to system design.

Along the proposed AHS evolutionary path, the key findings and issues and risks of each of the five ERSCs are:

ERSC 1 Key Findings

1. There are significant safety and performance benefits even with low levels of automation. Simple systems like the roadway velocity controller can give large increases in capacity and traffic flow volumes. Furthermore, the driver can serve as a back up to the automated systems at this level. The speed and headway maintenance function does not have to be very accurate in this ERSC (5-10%) since it is limited by human perception and reaction times. This suggests that speed and headway maintenance systems at this level may be derived from the intelligent cruise control systems planned by several companies.[74,26]

2. There are significant human factors issues associated with warnings and driver interface that must be researched for even low levels of automation. The warning systems will require multiple levels of warnings. Vehicle to vehicle communication systems can reduce the number of false alarms in collision warning systems without reducing the detection rates.

ERSC 1 Issues and Risks

1. Driver Interface
Research needs to be done on the driver interface with the speed and headway maintenance, rear end collision warning, and blind spot warning functions. In particular, we need to investigate if the driver's reliability as a back-up to the SHM system will be degraded when he/she is interfacing with the on board SHM system and the roadway speed commands. It may be too much of a burden on the driver to expect him/her to change lanes and enable the automated systems immediately. The driver may need to preset the target speed, minimum headway, and warning thresholds when he/she starts the vehicle.

2. Dedicated Lane
The biggest social issue for AHS is how to get a separate lane for automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

3. Legal/Liability
In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short.[102]

4. Communication Protocols
The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

ERSC 2 Key Findings

1. The driver can not act as a back-up for an automated rear-end collision avoidance system that uses short time headways. In this case there is not enough time for the driver to react to dangerous situations. The reliability requirement for the rear-end collision avoidance system is: “Under no circumstances should a single component/point failure let the vehicle crash into any moving or stationary object in the lane, and there should be no common failure modes.” One

possible design leads to multiple control paths and sensors to ensure system reliability. This increases the cost and complexity of automated rear-end collision avoidance systems.

2. Driver warnings from the lane departure warning system and the blind spot warning system must be prioritized to avoid driver confusion if multiple warnings occur. Great care must be taken in ERSCs that combine automated systems with manual driving to make sure that the driver interface is simple to understand and operate.

ERSC 2 Issues and Risks

1. Legal/Liability
Rear end collision avoidance gives rise to new liability issues. If a vehicle collides with the vehicle in front, then who is at fault? The driver may set the time headway too small or the collision avoidance system may have not worked properly.

2. Driver Override of Braking
The driver may need to override the automated braking system if he/she sees an object that the collision avoidance sensors do not. However, this could lead to dangerous situations and a loss of vehicular control. This issue needs further study.

3. Fully automated longitudinal control with manual lateral control
When only the longitudinal control is automated, the speed/headway maintenance and rear-end collision avoidance system may have difficulties in avoiding crashing into stationary obstacles that suddenly appear in the lane. This can happen when, for example, the preceding vehicle abruptly changes lanes to avoid hitting a stationary object in the lane. In this case, the vehicle may not have enough distance to stop the vehicle without a collision. The probability of such collisions can be reduced if we increase the headway used in vehicle following control. However, the capacity of the AHS will be affected by increasing the headway.

4. Warning Overload and Confusion
The driver may experience warning overload and warning confusion problems while interfacing with BSW, LDW and other vehicle and roadway functions.

ERSC 3 Key Findings

1. Automatic lane keeping (ALK) will reduce the collisions caused by vehicle lane departures. The most destructive lane departure accidents take place when the driver is fatigued during a long drive. The ALK system can help reduce this type of accidents. It will require redundant active control channels for fail-safe design since the driver can not back up the automatic lane keeping system if it fails. The reliability functional requirement of the automatic lane keeping system is: “Under no circumstances, should a single point/component failure let the vehicle depart from the lane, and there should be no common failure modes”.

2. It may be impractical to have the driver perform lateral collision avoidance while giving him/her only steering override authority.

3. The operation of lane keeping control requires preview information about the roadway. The on-board automatic lane keeping (ALK) system obtains this data with the help of roadway lane reference aids. The sensing technologies used by the automatic lane keeping system determine the types of lane reference aids. Possible lane reference aids include vision based systems, magnetic nails, radar, and GPS with dead-reckoning. Some types of lane reference aids may not reliably provide preview information under certain environmental conditions such as rain or snow. Reliability studies show that two independent control paths may be necessary for reliable fail-safe lane keeping. Each control path needs to have an independent sensor type.

ERSC 3 Issues and Risks

1. Cost

A potential automatic lane keeping system design to fulfill the reliability functional requirement will need two redundant, independent steering control channels. This substantially increases the cost of automated vehicles in ERSC 3 due to the design complexity and required redundant components.

2. Reliability of Lane Reference Aids

The operation of lane keeping control requires preview information. The on-board automatic lane keeping (ALK) system obtains it with the help of roadway lane reference aids. The sensing technologies used by the automatic lane keeping system determine the types of lane reference aids. It might not be easy for some types of lane reference aids, such as vision based, to reliably provide preview information under certain environmental conditions.

3. Driver’s Lateral Collision Avoidance

Lateral collision avoidance may require combined lateral and longitudinal control. In ERSC 3, the driver can override the automatic lane keeping system but not the longitudinal control. The effectiveness of the driver’s lateral collision avoidance, using steering control only, has not yet been verified and requires further research.

4. Legal/Liability

Since the roadway is involved in the dedicated lane entry and exit coordination, the roadway may be liable for accidents if it fails to send out proper speed/headway commands to coordinate the entry/exit maneuvers. The driver may still blame the roadway for an entry/exit accident even it is caused by the his/her improper merging/demerging maneuvers. In addition, the roadway may be liable for accidents caused by failures of the lane reference aids. The vehicle manufacturers may also be responsible for the failure of the ALK system.

ERSC 4 Key Findings

1. The driver will not be able to back up the automatic lateral and longitudinal control (ALLC) system if it fails. The reliability functional requirement of the ALLC system is: “Under no circumstances should a single component/point failure result in a lateral or longitudinal collision, and there should be no common failure modes.

2. A potential ALLC system design to achieve the reliability functional requirement will need two active redundant control channels with substantial doubling of components.

3. The fully automated vehicles perform maneuver coordination to further reduce accident rates and improve traffic flow rates. This will require complicated vehicle-to-vehicle communication and maneuver protocols.

ERSC 4 Issues and Risks

1. Cost
The required reliability of the ALLC system enormously increases the system cost and design complexity. The required instrumentation on the vehicle will be very costly. In addition, there are multiple dedicated lanes in ERSC 4. Since each lane needs to be equipped with redundant independent lane reference aids, the cost of the roadway infrastructure will be increased considerably.

2. Legal/Liability
The roadway may be liable for traffic accidents due to its involvement in the vehicle lateral and longitudinal control, such as sending speed/headway commands, assisting maneuver coordination, and providing lane reference aids, etc. The vehicle manufacturers may also be responsible for the ALLC system failures during operation.

3. Reliability of Lane Reference Aids
If a dedicated lane has lane reference aids failure in some roadway sections, the AHS may have to prohibit vehicles from entering those sections. This will reduce the highway flow rate and cause traffic control problems.

ERSC 5 Key Findings

1. Network controllers may improve traffic flow through traffic networks in terms of travel time reduction and congestion avoidance or limitation. The roadway to vehicle communication system must be highly reliable since incorrect speed or lane change messages could cause congestion or unsafe situations.

2. The roadway controller proposed in earlier ERSCs for vehicle velocity control was local in nature. That controller aimed to improve local traffic conditions on a single stretch of road without coordination with other related systems such as ramp metering. The roadway controller is also isolated from other traffic control systems for route selection and navigation. Freeway network control uses real-time and predicted information to smooth traffic flow throughout the traffic network. ERSC 5 proposes an integrated controller that makes route and course recommendations and ramp metering decisions to achieve a common goal. The goal of freeway network control can be either user optimality or network optimality.[71] User optimality can be in terms of trip time or fuel expended. Network optimality can be in terms of overall travel time at the cost of some vehicles taking longer paths to meet their goals.

3. Simulation studies by Messmer and Papageorgiou indicate that there is good potential for improving traffic flow in freeway networks in terms of travel time reduction and congestion avoidance or limitation.[71,7] More detailed controllers will select lanes and speeds for each vehicle on the highway.

ERSC 5 Issues and Risks

1. Network Traffic Control Effectiveness
Network freeway control needs extensive study and simulation before appropriate controllers can be selected. The system must also offer demonstrable improvements from the driver's existing ERSC 4 route selection system. Otherwise drivers will not use the network controller and will rely directly on their own vehicle to choose their route.

2. Driver's Navigation
Driver overrides would allow individual drivers and vehicles to disregard commands from the roadway and use their own navigation systems. While this may benefit one driver, it may hurt overall traffic flow and cause safety problems if one vehicle makes many lane changes in an attempt to go at a certain speed. The effect of having network guided vehicles and independent vehicles on the same traffic network needs to be studied.

3. Communication
Some researchers [111] have proposed network controllers that send control signals directly to each individual vehicle. This puts stringent performance and reliability constraints on the communications system since the messages are frequent and time-sensitive. System reliability considerations dictate that the communications system must be fail-safe with no single point failures for autonomous vehicles. This could lead to multiple independent communications systems.

This report also identifies some key areas for further research that are described below.

- The evolution of the AHS will be governed by the safe and efficient interaction between the human and the automated systems in the vehicle and the roadway. The (potential) automation technologies that can lead to the fully automated highway system are avaliable. However, it is an engineering challenge to incorporate these useful technologies to build automated systems that can be accepted by the users. Thus, human interaction with automatic control systems and driver assist devices need to be studied further. It is unknown how much attention the driver will devote to the driving task. Research also needs to be done on when and how the driver can safely override automated systems for collision avoidance, lateral or longitudinal control. The experience in the airplane cockpit design for controller–human interface analysis will be helpful.

- Sensor and actuator capabilities need to be improved. Sensors are needed that can see everything that a human driver can see. This allows the automatic control system to take the place of the human driver and prevents unsafe overrides of the automatic control system. The state of the art in vision-based sensors falls woefully short of this goal. The detection systems must have low false alarm rates and high probabilities of detection to work well.

- Extensive communications between vehicles and between vehicles and the roadway will be needed to coordinate maneuvers. Further research needs to be done to characterize the data volume, speed, and reliability requirements of this system.

LATERAL AND LONGITUDINAL CONTROL ANALYSIS

Section 1: Introduction

The first phase of the automated highway system (AHS) development program is an analysis that lays the groundwork for prototype system development. The goal of this analysis is to provide a better understanding of the issues and risks associated with the design, deployment, and operation of AHS facilities. Ford Motor Company and Raytheon Company have formed a consortium that addresses 15 AHS activity areas in order to provide a comprehensive, integrated study. The consortium consists of Ford Motor Company, Raytheon Company, the University of Southern California (USC), the Georgia Institute of Technology, Tufts University, Daimler-Benz, and the University of Tennessee.

The design of AHS where fully automated vehicles will be driven by computer control systems and guided to their destinations without any or much intervention by the driver is considered by many experts to be the ultimate and most efficient form of transportation. It is going to revolutionize highway driving and introduce considerable benefits in terms of safety, capacity, driving comfort, and automobile pollution reduction. The development of such a complex system will depend on driver acceptance, vehicle manufacturer’s willingness to produce automated vehicles and the ability of the local, state and federal government to develop and maintain the roadway infrastructure and resolve the associated legal, liability and institutional issues. The success of AHS will be based on the its ability to improve traffic flow and highway safety.

The complexity of these issues suggests that the development of AHS is going to follow an evolutionary path, along which issues associated with technology, human factors, policy, etc. will be resolved gradually over time. Initial market introductions will be based on small, incremental increases in the level of automatic control added onto existing vehicle dynamic systems. If these products are successful then this will lead to a complete implementation of an automated highway system. Therefore, we examined each of the essential elements of automation separately. Once the issues and limits of each component was understood, a deployment road map was developed that combined the elements of automatic control to provide a complete AHS.

Our analysis uses two types of representative system configurations from a generic automated roadway configuration. These two configurations are a dedicated automated roadway and a mixed roadway, where “mixed” means dedicated automated and manual lanes on the same roadway. Manual lanes contain instrumented (for automation, but not automatically operating) vehicles and non-instrumented vehicles. Designated lanes contain only instrumented vehicles.

In this report we present five representative system configurations that follow an evolutionary path. We refer to them as evolutionary representative system configurations (ERSCs). These ERSCs allow us to study the issues and risks associated with AHS in an incremental fashion

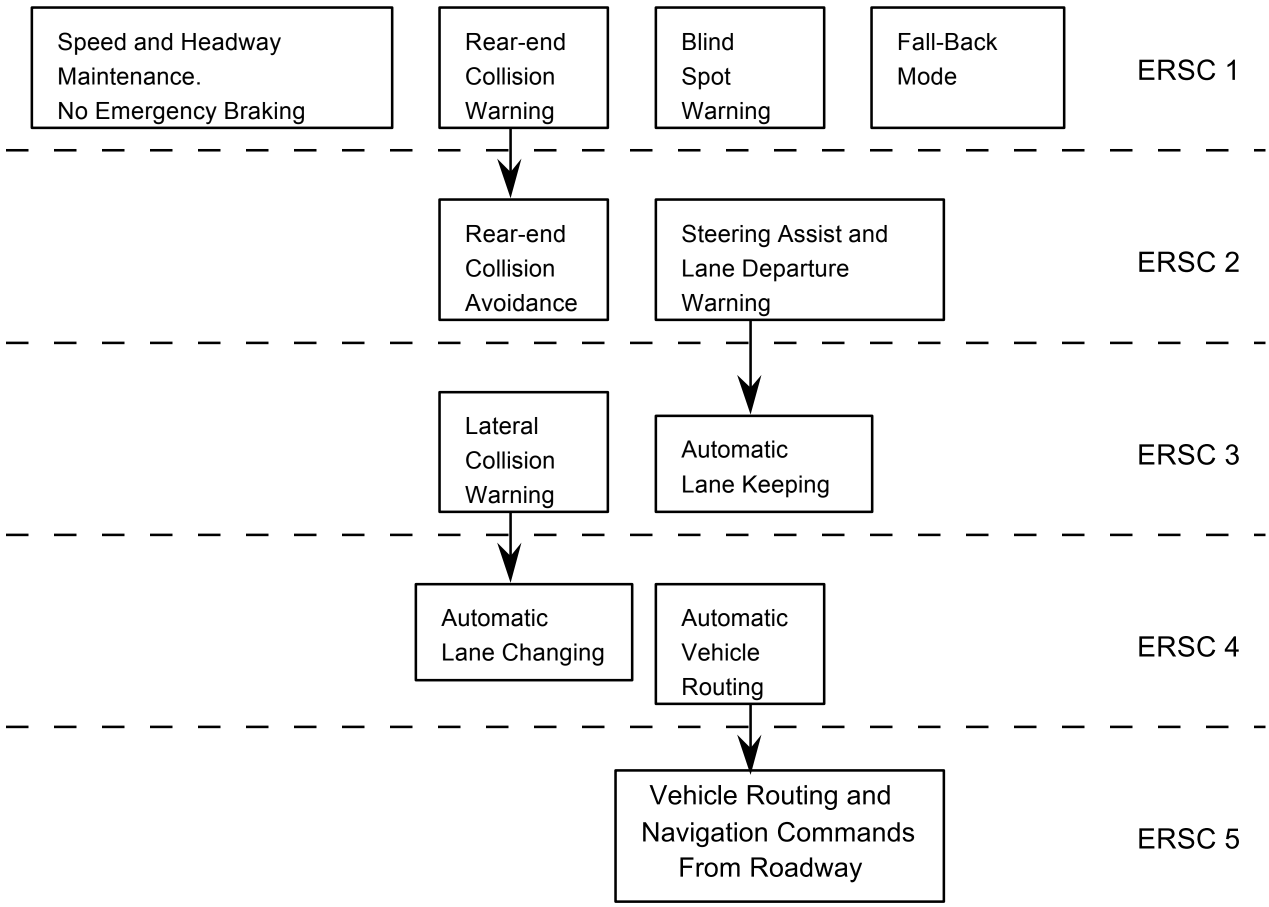


Figure 1. Main automatic vehicle functions for each ERSC. The arrow indicates the introduction of a new fully automated vehicle function.

starting from partial automation, close to today's driving, and building towards a fully automated vehicle/roadway system. The ERSCs could also represent stages of implementation of AHS. As a result, each ERSC is chosen based on the complexity of issues involved, feasibility of technology, and benefits in terms of capacity and safety. Our emphasis in the area of lateral and longitudinal control and vehicle operational analysis is the evolution of vehicle automation for AHS. As we go from one ERSC to the next, we automate additional driving functions until we arrive at a fully automated vehicle whose motion is largely dictated by the roadway. Figure 1 shows the main automatic functions of the vehicle for each ERSC.

In the following sections we present a detailed description of each ERSC and the roadway, vehicle and driver functions that we analyzed under the areas of lateral/longitudinal control and vehicle operational analysis. This research addresses the desired performance requirements of longitudinal, lateral, and fully automatic control. The desired performance requirements include inputs from the USC and Ford human factors groups. These requirements include driver comfort and acceptance. A major part of this study focuses on understanding the human factors issues involved in automatic control and transitions between manual and automatic control. Then we investigate the reliability and fault tolerance requirements for fail-safe system design at each ERSC. This task establishes a basis for quantifying the reliability of automated systems.

This basis will be used for assessing the reliability requirements for vehicles under different types of automated and manual vehicle control. Successful implementations of automatic controllers will involve multiple independent control channels to avoid single-point failures in longitudinal and lateral controllers. This requirement will pose a heavy burden on automobile manufacturers. The results from the reliability and performance requirements studies allow us to look at the gaps between today's vehicles and future automated vehicles.

The first two ERSC's concentrate on longitudinal control. In an AHS longitudinal control may be used for functions such as speed and headway maintenance, rear-end collision avoidance, and lane changing. Headway refers to a measure of inter-vehicle spacing either in distance (constant space headway) or in time (constant time headway). Space headway is the product of time headway and vehicle speed. Potential gains in traffic throughput have prompted several researchers in the field to suggest constant spacing headways of around 1 meter. This gap leads to small relative collision velocities that may lead to minor or no damages to colliding vehicles. However this analysis does not take into account lateral collision forces that may lead to extensive vehicle damage. One meter gaps between vehicles would increase the capacity of the freeway. It has also been argued that by organizing the vehicles into platoons of 10 to 30 vehicles with large gaps between them, minor intervehicle collisions can be contained within the platoon. This gap raises many important issues related to safely, human factors, and the capabilities of sensor and computer technologies. Therefore this analysis takes a collision-free approach in which each vehicle can come to a complete stop without hitting the vehicle in front of it.

The second two ERSC's concentrate on lateral control. Lateral control may be used for functions such as keeping the vehicle in the lane, lane changing, entry/exit maneuvers, and lateral collision avoidance. Lateral collision avoidance maneuvers and lane changing require a combination of lateral and longitudinal control.

Section 2 of this report describes the five ERSCs that we analyzed in this report. Section 3 covers the mathematical models used to determine safe stopping distance and freeway traffic densities. Section 4 gives background and definition of terms used in reliability analysis. Sections 5 through 9 cover each of the five ERSCs for performance requirements, reliability requirements, benefits, and risks. Section 10 summarizes these issues and risks for the ERSCs.

Section 2. Evolutionary Representative System Configurations

The evolution of todays' vehicles to fully automated ones will be gradual. It will be dictated by market forces and liability obstacles. This evolution has already started. Automatic features such as cruise control, anti-lock braking systems (ABS) and, more recently, headway maintenance systems and other warning devices will be standard items on most vehicles in the very near future. There is also considerable research on steering assist devices, blind-spot detector devices, collision warning systems, etc. A continuing trend in the development of vehicles is the use of more electronics and computers. Products such as steer-by-wire, drive-by-wire and brake-by-wire have been experimentally tested and will gradually appear in vehicles. From the roadway and infrastructure point of view, developments such as automatic toll collection, automated traffic light control and emerging technologies for Advanced Traffic Management Systems (ATMS) and Advanced Traffic Information Systems (ATIS) are already implemented, or they are going to be implemented in the very near future.[(55)]

Based on the evolution of these technologies the following deployment scenarios or evolutionary representative system configurations (ERSC) for AHS may become feasible. Each ERSC builds upon the one before it in terms of safety and reliability. If a failure occurs then the system drops down to the previous ERSC. ERSC 1 has a dedicated lane for vehicles with speed and headway maintenance systems. In ERSC 2 the vehicles have steering assist, more vehicle-vehicle communications, lane departure warnings, and rear-end collision avoidance. ERSC 3 has "hands-off" steering in a single lane, lateral collision warnings, and communications between vehicles in separate lanes. In ERSC 4 vehicles can change lanes automatically. These vehicles also have a collision avoidance ability in both the lateral and longitudinal direction. ERSC 5 is the fully automated highway that can guide and route the vehicles. Table 1 summarizes these ERSCs. We define each ERSC with the roadway, the driver, and the vehicle. Each ERSC raises new issues and risks as the amount of automation increases.

Table 1. Summary of the functions of the roadway, vehicle and driver in each ERSC.

ERSC	ROADWAY	VEHICLE	DRIVER
1	• Provides dedicated lane • Sends target speeds to vehicles • Sends minimum headway to vehicles • Sends traffic status information to vehicles • Receives vehicle speed, headway and operational status information and identification from vehicles (option)	• Speed & headway maintenance • Rear-end collision warning • Blind spot warning • Receives speed, headway commands and traffic status information • Sends speed, headway, operational status and i.d. to the roadway (option) • Driver/roadway interface • Fall-back mode	• Lane keeping & lane changing • Responds to blind spot and rear-end collision warnings • Collision avoidance (lateral/longitudinal) • Route Planning • Vehicle interface
2	• Provides dedicated lane • Sends target speeds to vehicles • Sends minimum headway to vehicles • Sends traffic status information to vehicles • Receives speed, headway, operational status information, and i.d. from vehicles • Provides lane reference aids for lane departure warning	• Speed & headway maintenance • Rear-end collision avoidance • Blind spot warning • Receives target speed, headway commands and traffic information from roadway • Sends speed, headway, operational status and i.d. to the roadway • Lane departure warning • Steering assist • Driver/roadway interface • Fall-back mode	• Lane keeping & lane changing • Responds to blind spot and lane departure warnings • Lateral collision avoidance • Route Planning • Vehicle interface
3	• Provides dedicated lane • Sends target speeds to vehicles • Sends minimum headway to vehicles • Sends traffic information to vehicles • Provides lane reference aids for lane keeping • Receives vehicle status speed, headway data • May assist in vehicle maneuver coordination	• Speed & headway maintenance • Rear-end collision avoidance • Lateral collision warning • Receives speed, headway and traffic information from roadway • Transmits vehicle status and speed to roadway • Lane keeping • Maneuver coordination with communication (lane change/merge in AHS entry/exits) • Driver interface • Fall back mode	• Lane changing • Responds to lateral collision warning • Route Planning • Lateral collision avoidance • Vehicle interface

4	• Provides multiple dedicated lanes • Sends target speeds to vehicles • Sends minimum headway to vehicles • Sends traffic information to vehicles • Provides lane reference aids for lane keeping and lane changing • Receives vehicle status data • Assists in vehicle maneuver coordination	• Speed & headway maintenance • Rear-end collision avoidance • Lateral collision avoidance • Receives speed, headway and traffic information from roadway • Transmit vehicle status and speed to roadway • Lane keeping • Lane changing • Maneuver coordination • Route Planning • Driver/roadway interface • Fall-back mode	• Vehicle interface
5	• Provides multiple dedicated lanes • Sends lateral/longitudinal control commands • Receives vehicle status, i.d., position, speed, acceleration, headway, and destination • Provides lane reference aids • Coordinates vehicle maneuvers • Vehicle route planning	• Speed & headway maintenance • Rear-end collision avoidance • Lane keeping • Lane changing • Lateral collision avoidance • Receives control commands from roadway • Sends its operational status, identification. position, speed, acceleration, headway, and destination to roadway • Maneuver coordination • Driver/roadway interface • Fall-back mode	• Vehicle interface

ERSC 1

In ERSC 1 the automated vehicles use a dedicated lane provided by the roadway. The lane could be isolated and accessed by a dedicated ramp or it could be next to a manual lane and accessed at designated points or at any point along the manual/dedicated lane boundary. The roadway is responsible for maintaining the dedicated lane and providing emergency vehicle response. It could also assist in keeping non-fit vehicles off the dedicated lane. The roadway senses traffic flow (average speed, density) and environmental conditions on the dedicated lane and provides target speed commands, minimum time headway recommendations and traffic status information to the vehicles. The roadway also performs ramp metering and incident management if needed.

The automated vehicle can maintain a selected headway and speed relative to the preceding vehicle by using a computer control system to control the throttle and the brake. Automatic braking is limited to soft braking applied when the engine torque is not sufficient to maintain the selected headway. It does not include hard braking for emergency stops or other situations. The vehicle provides blind spot and rear-end collision warnings to the driver. It receives target speed commands, minimum time headway recommendations and traffic status information from the roadway. It responds to the speed commands automatically in a smooth way as long as the resulting headway is not smaller than the one selected by the driver. If the target speed is larger than the one the driver feels comfortable with, the driver may be required to exit the lane. The vehicle responds to the recommended minimum time headway provided it is larger than the selected one. The vehicle provides the driver with the traffic status information received from the roadway. It responds to driver commands for changing the headway, and setting the cruising speed. It also enables or disables the speed headway maintenance system (SHMS) upon driver command. The vehicle may send its speed, headway and operational status and identification to the roadway to be used for traffic flow control purposes. If the SHMS fails the vehicle fall-back mode allows the driver to take over this function and continue the trip until the next exit.

The driver is responsible for driving the vehicle into the dedicated lane with the aid of the blind spot warning system. Once in the lane the driver switches the SHMS on and sets the desired headway for vehicle following or the cruising speed. The driver supervises the SHMS and overrides it when hard braking is required for emergency stops and other situations. The driver is aided by the rear-end collision warning in avoiding rear-end collisions. The driver is responsible for lane keeping, lane changing and lateral collision avoidance. The driver is also responsible for choosing the route of the vehicle and conforming to traffic regulations. In case of malfunction of the SHMS or at the end of the trip the driver drives the vehicle out of the dedicated lane by using the next available exit with the aid of the blind spot warning system.

The motivation behind ERSC 1 is:

- to improve safety through the use of warnings and roadway headway recommendations

- to smooth traffic flow through the use of roadway target speed commands

- to increase capacity through the use of roadway commands for smooth traffic flow control and possibly smaller headways selected by the drivers

- to reduce the number of possible liability issues by making the driver responsible for vehicle emergencies

- the feasibility of deployment based on current and near-term availability of technologies

ERSC 2

In ERSC 2, the roadway provides a dedicated lane with the same vehicle accessibility as in ERSC 1.

The roadway maintains the dedicated lane and provides emergency vehicle response. It assists in keeping non-fit vehicles off the dedicated lane. The roadway receives vehicle status data such as speed, headway, operational status and vehicle identification. It uses the vehicle speed and headway information for calculating the average speed and density of the traffic flow in the lane and computes the desired target speed at each section of the lane for smoother traffic flow. It sends information to the vehicles regarding minimum time headway based on environmental conditions. The operational status and identification of the vehicle are used for check-in purposes and for roadway emergency response in case of disabled vehicles. The roadway also assists drivers in route planning by providing them with traffic status information. The roadway may also assist vehicles merging into the automated lane by recommending larger headways at the entry points or sections or the dedicated lane. The roadway provides lane reference aids that support the vehicles' lane departure warning and steering assist function.

The vehicle has all the capabilities as in ERSC 1, with the rear-end collision warning being upgraded to rear-end collision avoidance. The SHMS and rear-end collision avoidance allow the driver complete "feet-off" driving, while in the dedicated lane. The vehicle provides steering assist to smooth the driver's steering by compensating for roadway disturbances, wind gusts and small driver steering errors. The vehicle also has lane departure warning to warn the driver during large deviations from the center of the lane. The vehicle sends its speed and headway, operational status and identification to the roadway. It sends its braking capabilities and acceleration and deceleration intentions to the vehicle behind. It receives the braking capabilities and acceleration and deceleration intentions of the vehicle in front. The vehicle also receives and responds to target speed commands, headway recommendations, and traffic status information sent by the roadway in the same way as in ERSC 1.

The braking capabilities and acceleration/deceleration intentions of the vehicle in front as well as the headway recommendations sent by the roadway are used by the vehicle to calculate the minimum time headway for collision free vehicle following. The SHMS chooses a headway that is larger than the calculated one based on some tolerance for additional safety. Since the driver is not considered to be a back up in a rear-end collision avoidance situation the calculated headway does not take into account the driver reaction time and is therefore smaller than the one used for collision warning in ERSC 1. The vehicle responds to driver commands for changing the headway and setting the cruising speed. It also enables and disables the SHMS and rear-end collision avoidance functions upon driver commands. The driver disengagement of the rear-end collision avoidance function initiates a smooth transition sequence that does not put the driver in a situation of a short time headway relative to his reaction time. The vehicle provides a blind spot warning for aiding the driver during lane changing and a lane departure warning for aiding the driver during lane following. A steering assist vehicle function used in series with the driver improves the accuracy of steering in the presence of disturbances such as wind gust and road surface varying conditions. As in ERSC 1 the vehicle has on-board diagnostics that are used to detect malfunctions. The vehicle provides a fall-back mode to ERSC 1 in case the rear-end collision function or steering assist and lane departure warnings fail. In such a case the vehicle increases the headway and warns the driver to assume control of the failed function.

The driver drives the vehicle to the entrance of the dedicated lane, provided the vehicle is fit to operate in the lane, and looks for a safe gap in the lane for positioning his/her vehicle. The entrance could be a long lane boundary next to a transition lane that allows speed synchronization. Since the vehicle is equipped with vehicle-to-vehicle and vehicle-to-roadway communications its intentions to enter the lane could be communicated to the roadway and surrounding traffic and used to negotiate request or safe gaps.

Once in the lane the driver switches on the SHMS, the rear-end collision avoidance, the lane keeping warning and steering assist functions. The vehicle chooses a safe headway that does not take into account the driver's reaction time. As a result, the driver function in the longitudinal direction is feet-off. The driver may be given the option to increase the headway if he/she does not feel comfortable with the one chosen by the system. The driver however will not be able to reduce the headway chosen by the system. The driver is fully responsible for lane keeping, route planning, lane changing, and for lateral collision avoidance. For these functions he is assisted by the lane departure, blind spot warnings and steering assist. In case of malfunction or at the end of the trip the driver is responsible for driving the vehicle out of the lane and for obeying all traffic regulations. When the vehicle falls back to ERSC 1 due to malfunctions of the collision avoidance or steering assist and lane departure warning functions the driver is responsible for taking over the failed functions.

The motivation behind ERSC 2 is:

- to increase capacity by using smaller headways made possible by the rear-end collision avoidance function, vehicle-to-vehicle and roadway-to-vehicle communications

- to improve safety and driver comfort by introducing lane keeping warning and steering assist

- to smooth traffic flow through the use of roadway traffic flow control achieved by conforming to roadway specified vehicle target speeds, and headways.

- the feasibility of deployment based on current and near-term availability of technologies

ERSC 2 allows us to focus on the analysis of the fully automated vehicle longitudinal control function.

ERSC 3

In ERSC 3 the roadway provides and maintains a dedicated lane with a similar accessibility to vehicles as in ERSC 1, 2. The roadway also provides lane reference aids that support the lane keeping function of the vehicle as well as preview lane information for smooth and accurate lane following.

The vehicle has all the capabilities as in ERSC 2, with the exception of the lane departure warning and steering assist that evolve into automatic lane keeping. The automatic lane keeping function keeps the vehicle in the center of the lane at highway speeds and curvatures. The blind spot warning evolves into a lateral collision warning. The vehicle is fully responsible for vehicle-following in the longitudinal direction, for rear-end collision avoidance and for keeping the vehicle in the center of the dedicated lane without any support from the driver. It sends its speed, headway and operational status to the roadway. It responds to target speed and headway commands and traffic information received from the roadway in a similar manner as in ERSC 1, 2. The vehicle notifies the driver in case of malfunctions and responds to commands for switching from the manual to automated mode and vice versa. The vehicle also responds to and coordinates its maneuvers with other vehicles during merging and exiting the dedicated lane.

The vehicle alerts the driver when is the time to assume manual control and transfers control to the driver in a smooth way that is compatible with driver's skills and reaction times. The vehicle uses its on-board diagnostics to notify the driver of the fitness of the vehicle to operate on the dedicated lane. In case of malfunctions or failures of some of the automated vehicle functions the vehicle has a fall-back mode that allows the vehicle to operate as in ERSC 2 or ERSC 1 or the manual mode for a designated time. In such case it warns and aids the driver in assuming control of the failed functions.

The driver is responsible for merging the vehicle into the dedicated lane with the aid of lateral collision warning and vehicle-to-vehicle communication for maneuver coordination and for switching on and off the automated mode. The driver is also responsible for operating the vehicle in a fall-back mode and for driving the vehicle out of the dedicated lane in case of malfunctions of the automated functions and at the end of the trip. Since driving is hands-off and feet-off, the driver has no responsibility during vehicle operation in the dedicated lane apart from deciding the route of the vehicle and the end of the trip. The point at which the driver releases manual control could be in the dedicated ramp or in the dedicated lane depending on the entry configuration. Similarly the point at which the driver assumes manual control from the automated mode depends on the exit configuration.

The motivation behind ERSC 3 is:

- to smooth traffic flow and increase capacity by using the roadway commands and smaller headways

- to improve safety by introducing a lateral collision warning

- the feasibility of deployment by evolving from ERSC 2 to ERSC 3.

ERSC 3 allows us to focus on the analysis of both the fully automated longitudinal control and lane keeping functions, i.e., feet-off and hands-off operation without the complexity of automatic lane changing.

ERSC 4

In ERSC 4 the vehicle is fully automated. The vehicles of ERSC 3 add automatic lane changing and lateral collision avoidance capabilities. The roadway provides and maintains the dedicated lanes and provides emergency vehicle response. It also provides lane reference aids for lane keeping and lane reference aids for lane changing. The dedicated lanes could be segregated and accessed from dedicated ramps or could be next to manual lanes and accessed through transition lanes depending on the particular entry/exit configuration. As in ERSC 2 and 3 the roadway receives vehicle status information, assists in the check-in and merging process and sends target speed, headway commands and traffic information to the vehicles.

The additional capabilities of automatic lane-changing and lateral collision avoidance allow the vehicle to take over the entire driving task when the vehicle is in the dedicated lanes. All vehicle maneuvers, such as lane changes and merges, are coordinated with the surrounding automated vehicles. The vehicles use cooperative communications and their own sensor measurements for this coordination. Each vehicle broadcasts its position and heading to the vehicles around it. These communications may be routed through the roadway so that the roadway can monitor the highway status and coordinate communication traffic and protocols. The vehicle plans its route according to the trip destination entered or changed by the driver and the traffic information received from the roadway. The vehicle may display the planned route and the estimated travel time to the driver. The vehicle alerts the driver and assists him in resuming manual control. It has a contingency plan if the driver cannot resume manual control at the end of the trip or during certain emergencies. The vehicle plans and performs all collision avoidance maneuvers. The vehicle is designed to be fail safe and completely reliable during automated driving. The vehicle uses its on-board diagnostics to check the fitness of the vehicle for operating in the automated mode and notify the driver accordingly.

The vehicle has a fall-back mode that allows the vehicle to operate as in lower ERSCs in case of malfunctions.

The driver enters the destination and manually drives the vehicle to the entry point. The vehicle passes a check-in test. The driver switches on the automatic mode and the vehicle assumes control. Once the automated mode is on the driver becomes a passenger until he/she initiates a request to switch back to a lower ERSC or to manual mode. In the case of switching back to the manual mode the vehicle initiates a check-out procedure and the driver gradually regains full manual control in a transition lane or at the exit ramp. When malfunctions occur and the fall-back mode of the vehicle becomes active the driver is responsible for operating the vehicle as in lower ERSCs. At the end of the trip, the driver gradually resumes control from the vehicle. Driver control resumption includes tests for alertness, coordination, etc.

The motivation behind ERSC 4 is:

- to analyze the benefits in terms of driver comfort, safety and capacity that could be achieved by full vehicle automation

- to study the evolution of technology from ERSC 3 to ERSC 4

ERSC 4 allows us to focus on the analysis of the vehicle fully automated functions as they interact with each other to perform driving and emergency tasks without relying too much on the roadway infrastructure.

ERSC 5

In ERSC 5, the roadway provides multiple dedicated lanes as described in ERSC 4. The roadway is responsible for maintaining these dedicated lanes and the communications infrastructure.

The roadway receives position, speed, destination, and capabilities data from the vehicles. The roadway senses traffic flow and environmental conditions on the dedicated lanes. The roadway uses this data to provide detailed course commands to the vehicles. These commands tell the vehicle what lane to travel in, when to change lanes and what speed and headway to use. The roadway coordinates these maneuvers to avoid collisions and smooth traffic flow. Based on the indicated trip destination the roadway plans the vehicle's route.

The vehicle has all the capabilities for full lateral and longitudinal control described in ERSC 4. Additionally the vehicle receives detailed course commands from the roadway. The vehicle responds to these commands automatically as long as it judges the maneuver to be safe. The vehicle sends its position, speed, maneuver status, and capabilities to the roadway. The vehicle coordinates each roadway-commanded maneuver with the vehicles around it. The vehicle provides the driver with traffic information and trip status data. It responds to driver commands for changes in destination. In case of malfunctions the vehicle may fall-back to a lower ERSC and notify the roadway and driver appropriately.

The driver manually drives the vehicle to the dedicated lane check-in point. The driver initiates the check-in procedure and releases control to the vehicle and roadway. The driver inputs a trip destination that is used by the vehicle and roadway for route planning. The driver, as in ERSC 4, can request a check-out procedure and resume manual control at the next chosen exit ramp or transition lane depending on the exit configuration used.

The motivation behind ERSC 5 is:

- to maximize highway system throughout by permitting full roadway control of all vehicle activities.

- to improve driver comfort and reduce trip time.

- to efficiently detour traffic around traffic incidents and roadwork.

ERSC 5 allows us to focus on the analysis of a highly coordinated AHS where the roadway plays an active role in the lateral and longitudinal control of the automated vehicles by planning their path and coordinating their maneuvers.

Section 3: Headway Selection And Capacity

The inter-vehicle spacing or headway in vehicle following affects both safety and highway capacity. For collision-free vehicle following, the headway should be large enough so that under a worst case stopping scenario no collision can take place. For a high capacity highway system, the headway setting should be as small as possible. Since safety cannot be easily traded-off, the choice of the minimum safety headway for a collision-free environment is important both from safety and capacity points of view.

Traffic accidents involve various types of vehicle crashes, such as rear-end collisions, backing collisions, single vehicle road departure accidents, etc.(60) During vehicle following operations, rear-end collision is the most common type of accident. In 1990, 23 percent of all police-reported crashes were rear-end collisions that caused 4.7 percent of all fatalities.(60) Current statistics portray these rear-end crashes as resulting largely from driver delayed recognition and relatively long reaction time when driving under high speed and close inter-vehicle separation.(60)

In principle, the possibility of a rear-end collision can be reduced by reducing vehicle speed and increasing inter-vehicle spacing. Since roadway capacity is proportional to vehicle speed and inversely proportional to inter-vehicle spacing, a large reduction in speed or a large increase in spacing leads to a low capacity highway system. This is the so called safety/capacity trade-off that is well known in the area of transportation.

The choice of the operating vehicle speed (V) and inter-vehicle spacing (S) for maximum capacity under the constraint of collision-free vehicle following environment is a big challenge in the design of roadway/vehicle systems. The design of vehicles imposes an upper bound on the maximum velocity a vehicle can attain. State and federal regulations also impose upper bounds on the maximum allowable velocity. The spacing S can be reduced under the imposed safety constraints. One way to characterize these safety constraints is to consider a worst case stopping scenario in a vehicle following operation. Such a scenario may be used to calculate the minimum value of S for collision-free vehicle following.

Stopping Scenario for Vehicle Following

We consider the following worst case stopping scenario in a single lane vehicle following situation.

Leading vehicle : At time instant $t = 0$, the leading vehicle brakes with maximum jerk (J_{lmax}) until it reaches its maximum deceleration ($-a_{lm}$), and then keeps this deceleration until a full stop is achieved. The acceleration profile of the leading vehicle is shown in figure 2. Table 2 describes the parameters used in figure 2.

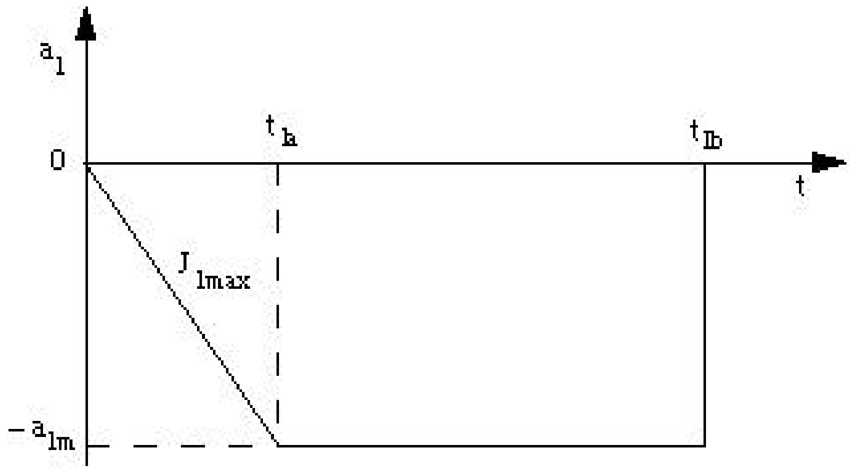


Figure 2. Acceleration profile for the leading vehicle in the worst case.

Table 2. Parameter definitions from figure 2.

Parameter Name	Description
a_{lm}	the maximum deceleration of the leading vehicle
J_{lmax}	the maximum jerk of the leading vehicle
t_{la}	the time required for the leading vehicle to reach $-a_{lm}$
t_{lb}	the time for the leading vehicle to come to a full stop

The jerk value J_{lmax} is constrained by the mechanical limits of the vehicle braking system. The maximum deceleration a_{lm} is determined by the condition and properties of the vehicle braking system as well as the condition of the road. The impact of the road geometry and condition on the braking ability of the leading vehicle is illustrated in figure 3.

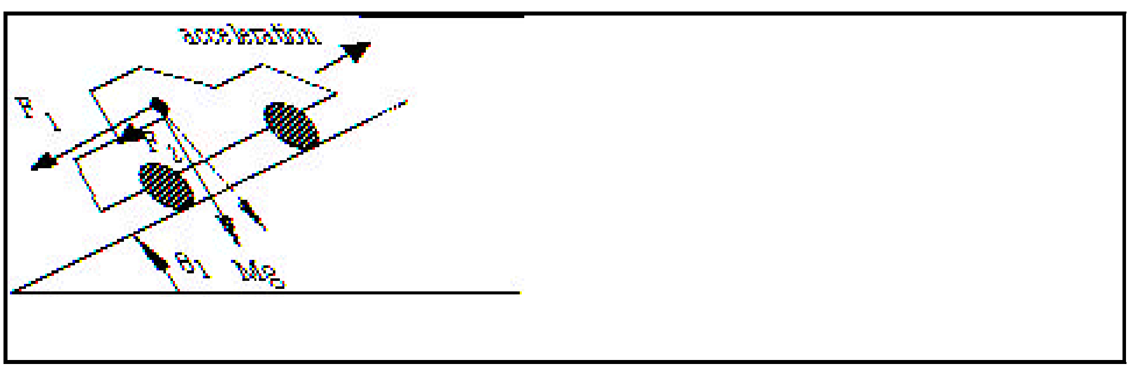


Figure 3. Longitudinal forces on the leading vehicle.

In figure 3, M is the mass of the leading vehicle; θ_l denotes the road slope angle; F_1 denotes the maximum braking force; F_2 is the force due to the gravity along the road slope. These two forces can be further described as:

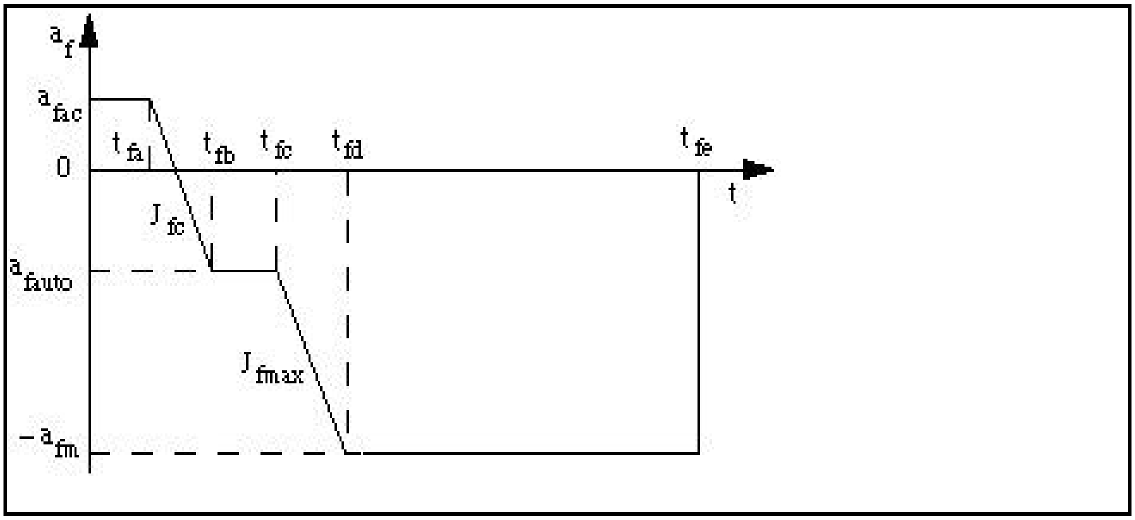


Figure 4. Acceleration profile of the trailing vehicle.

$$F_1 = {}_{l\max} M A_{lm} \cos {}_l$$
$$F_2 = Mg \sin {}_l \qquad (1)$$

where μ_{lmax} denotes the maximum road-tire friction coefficient. A_{lm} denotes the maximum deceleration under normal dry road with zero slope angle.

Using Newton's Second Law, the maximum deceleration of the leading vehicle can be written as

$$a_{lm} = g \sin \theta_l + \mu_{l\max} A_{lm} \cos \theta_l \qquad (2)$$

The time values t_{la} and t_{lb} in table 2 can be calculated from other parameters shown in figure 2.

$$t_{la} = \frac{a_{lm}}{J_{l\max}} \qquad (3)$$

$$V_l(0) + \int_0^{t_{lb}} a_l(t)dt = 0 \Rightarrow t_{lb} = \frac{-V_l(0) + \frac{1}{2} J_{l\max} t_{la}^2}{a_{lm}} + t_{la} \qquad (4)$$

Trailing vehicle :
At time t = 0, the trailing vehicle is accelerating with a constant acceleration (a_{fac}). After a certain time delay (T_1), the driver or the trailing vehicle detects the braking maneuver of the leading vehicle. Then after some reaction delay (τ_B), the trailing vehicle starts to brake with certain jerk (J_{fc}) and deceleration rate (a_{fauto}) at t = t_{fa}. Since the trailing vehicle may not know that the leading vehicle is executing an emergency stop, its initial braking is done to control the speed and its spacing relative to that of the leading vehicle. After the trailing vehicle or the driver detects that the leading vehicle is in the emergency stopping mode, it brakes with its maximum jerk (J_{fmax}) to achieve the maximum deceleration ($-a_{fm}$) at $t = t_{fc}$ until it reaches a full stop. The acceleration profile of the trailing vehicle is shown in figure 4. The parameters in figure 4 are explained in table 3.

In table 3, the parameter J_{fc} and a_{fauto} indicate a soft braking stage in the stopping maneuver of the trailing vehicle. This braking stage may due to the response of a driver to the brake lights of the leading vehicle, or due to an automatic "soft" braking mode of an Intelligent Cruise Control (ICC) system .[50] The maximum deceleration a_{fm} can be obtained from a similar equation as (2).

The time parameters t_{fa}, t_{fb}, t_{fd} and t_{fe} in figure 4 can be expressed as follows:

$$t_{fa} = T_1 + \tau B \tag{5}$$

$$t_{fb} = \frac{a_{fac} - a_{fauto}}{J_c} + t_{fa} \tag{6}$$

Table 3. Parameters for trailing vehicle.

Parameter Name	Description
a_{fac}	the acceleration value at time t = 0
a_{fauto}	the acceleration value for soft braking
a_{fm}	the maximum deceleration of the trailing vehicle
J_{fc}	the jerk value for soft braking
t_{fmax}	the maximum jerk of the trailing vehicle
t_{fa}	the time that the trailing vehicle initiates a braking maneuver
t_{fb}	the time that the trailing vehicle reaches a_{fauto}
t_{fc}	the time that the trailing vehicle starts to brake as hard as possible
t_{fd}	the time that the trailing vehicle reaches $-a_{fm}$
t_{fe}	the time that the trailing vehicle comes to a full stop without collision

$$t_{fd} = \frac{a_{fauto} + a_{fm}}{J_{f\max}} + t_{fc} \tag{7}$$

$$t_{fe} = t_{fd} + \frac{1}{a_{fm}}[V_f(0) + a_{fac}t_{fa} - \frac{1}{2}J_{fc}(t_{fa} - t_{fb})^2 + a_{fauto}(t_{fc} - t_{fb}) - \frac{1}{2}J_{f\max}(t_{fd} - t_{fe})^2] \tag{8}$$

where T_1 denotes the detection delay of the driver (or the automated vehicle control system). The actuation delay of soft braking is denoted by τ_B. t_{fc} denotes the time when the driver (or the automated vehicle control system) initiates a maximum deceleration maneuver. If the trailing vehicle is driven manually, the value of t_{fc} indicates how fast the driver perceives and reacts to an emergency stopping maneuver of the leading vehicle. For automated vehicle driving, this t_{fc} includes the detection, data processing and actuation delays of the automated vehicle control system.

The above stopping scenario includes many cases that have been considered in the past as well as new cases that are relevant to the operation of automated vehicles. For example, by taking $J_{lmax} = \infty$, $a_{lm} = \infty$, and $t_{lb} = 0$, we have the so called "brick-wall" scenario. In automated vehicle following operations, advanced hardware and software systems may be implemented to reduce the reaction time of the trailing vehicle. If the automated system of the trailing vehicle can perceive and react to the emergency situation before the soft braking stage (a_{fauto}) is achieved, then we can have a scenario that $t_{fc} < t_{fb}$. If vehicle to vehicle communication is available then the leading vehicle can communicate its actions to the trailing vehicle. This gives a deceleration function of the trailing vehicle in which $a_{fauto} = a_{fac}$, $t_{fa} = t_{fb} = t_{fc}$ and t_{fa} is a small time value.

Minimum Headway For Collision-Free Vehicle Following

In this subsection we calculate the minimum headway between the leading and trailing vehicles that will guarantee no rear-end collision under the worst case stopping scenario described above. If we let S_0 to be the constant space headway at $t = 0^-$ (just before the stopping scenario is initiated), then the inter-vehicle distance $S_r(t)$ is given by

$$S_r(t) = S_0 + [V_l(0) - V_f(0)]t + \int_0^t \int_0 [a_l(s) - a_f(s)]dsd \tag{9}$$

If S_0 is large enough, we could have $S_r(t) > 0$, $\forall\ t \in [0,T]$, where $[0,T]$ is the time interval of vehicle following under consideration. This situation means that no collision takes place. We are looking for the minimum value of S_0 that will guarantee that a collision does not occur. This minimum value of S_0 is *the minimum space headway for collision-free vehicle following* and is denoted by S_{min}. It can be calculated by solving for the marginal collision case as follows:

Consider the following minimization problem

$$\min_{t \in [0,T]} \{S_r(t)\} = \min_{t \in [0,T]} \{S_0 + [V_l(0) - V_f(0)]t + \int_0^t \int_0 [a_l(s) - a_f(s)]dsd \ \} \tag{10}$$

and let $S_{rmin} \triangleq \min_{t \in [0,T]} \{S_r(t)\}$. We have marginal collision situation when $S_{rmin} = 0$, which indicates that the minimum space headway (S_{min}) for avoiding collision is

$$S_{\min} = \max_{t \in [0,T]} \{[V_f(0) - V_l(0)]t + \int_0^t \int_0 [a_l(s) - a_f(s)]dsd \ , 0\} \tag{11}$$

Equation (11) indicates that S_{min} is a function of the initial vehicle speeds ($V_l(0)$, $V_f(0)$) and accelerations ($a_l(t)$, $a_f(t)$). The vehicle accelerations are functions of many variables, including time indices, jerks and acceleration limits as shown in figure 2 and 4. The values of these variables can be easily calculated from Equation (2) through (8).

From the value of S_{min} we can calculate the minimum time headway h_{min} in seconds, i.e.,

$$h_{\min} = \frac{S_{\min}}{V_f(0)} \tag{12}$$

Similarly, the minimum k-factor headway k_{min} is given by

$$k_{\min} = \frac{S_{\min}}{V_f^2(0)} \tag{13}$$

Figures 5 through 8 show how the minimum headway (h_{min}) changes. The simulation analyses in this subsection are done using the parameter values shown in table 4. Figure 5 shows that h_{min} is linear with respect to the reaction delay of the trailing vehicle. If advanced technologies (e.g., vehicle-to-vehicle communication) are implemented to reduce t_{fc}, h_{min} can be reduced accordingly.

Table 4. Parameter values for simulation study.

$V_l(0)$	60*mph*	A_{fm}	0.80*g*
$V_f(0)$	60*mph*	T_1	0.1*second*
J_{lmax}	72 *meter/sec*^{3}	t_{fc}	0.35*second*
A_{lm}	0.85*g*	τ	0.1*second*
a_{fac}	0.05*g*	μ_{lmax}	1
J_{fc}	20 *meter/sec*^{3}	θ_l	0
a_{fauto}	-0.20*g*	μ_{fmax}	1
J_{fmax}	72 *meter/sec*^{3}	θ_f	0

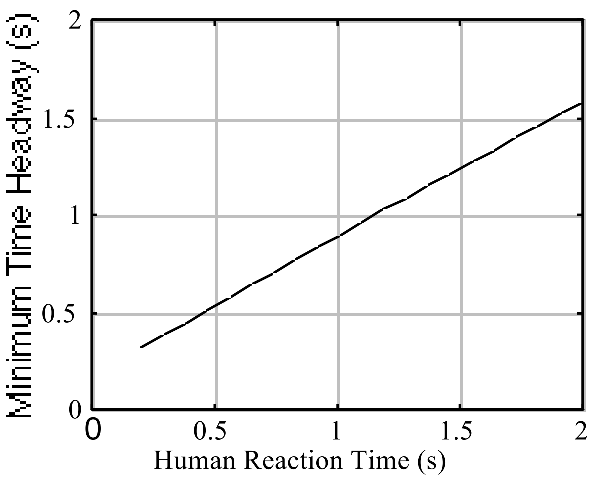


Figure 5. The effect of trailing vehicle reaction time.

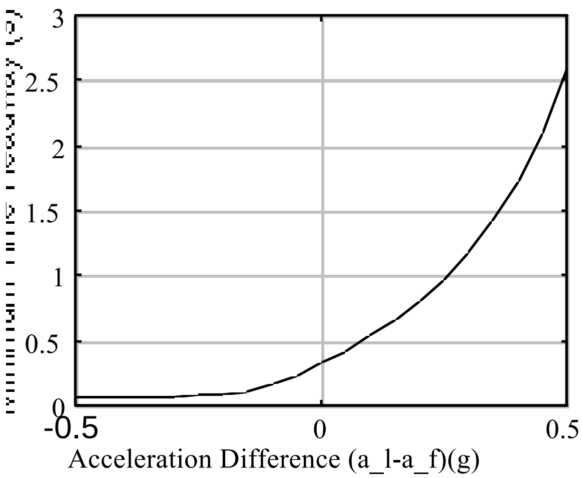


Figure 6. The effect of deceleration difference between the leading and trailing vehicles.

Figure 6 shows a non-linear relationship between h_{min} and the deceleration difference between vehicles ΔA_m. If the leading vehicle can brake faster than the trailing vehicle ($\Delta A_m > 0$), then the headway setting should be increased compared to the case that both vehicles have the same maximum deceleration value ($\Delta A_m = 0$) or the trailing vehicle can decelerate faster than the leading vehicle ($\Delta A_m < 0$).

If we ignore the impact of road slope angle and other factors (e.g., loading effect, wind), Equation (2) shows that the maximum deceleration value is proportional to the maximum road-tire friction coefficient. In case that $\mu_{max} \triangleq \mu_{lmax} = \mu_{fmax}$, $A_{fm} = 0.8g$, the effect of road-tire friction coefficients can be illustrated by a plot of h_{min} versus μ_{max} (figure 7). h_{min} has non-linear relationship with the maximum road-tire coefficient. If the leading vehicle can brake faster than the trailing vehicle, and ΔA_m is a constant, then h_{min} increases as the road surface becomes slippery.

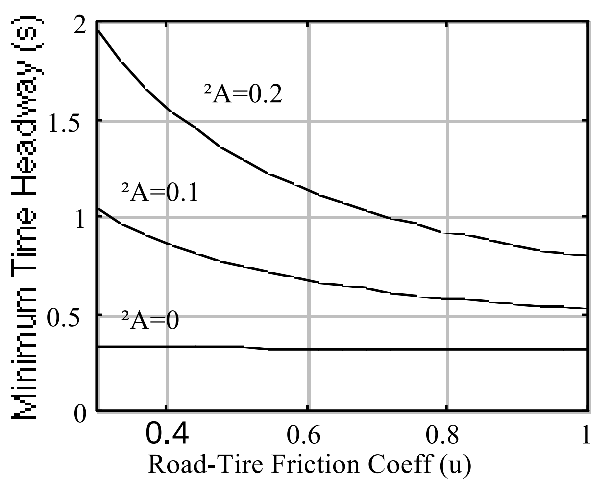


Figure 7. The effect of road-tire friction coefficient under constant ΔA_m

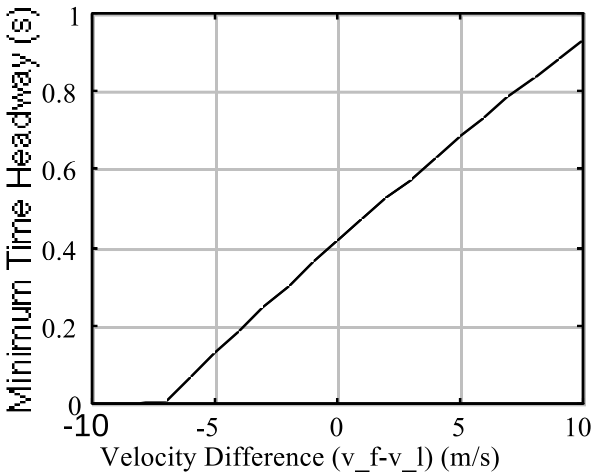


Figure 8. The effect of initial velocity difference

Figure 8 shows that when a vehicle changes from a high speed lane to a low speed lane, a large headway is needed to avoid collision with its leading vehicle. Also, when a vehicle changes to a lane that has lower speed, a large separation between this vehicle and its trailing vehicle is needed to avoid possible collisions.

Accident Severity And Headway Selection

The values of vehicle speed (V) and spacing (S) in the case of rear-end collision have a significant effect on the severity of the collision or the level of vehicle damage. Their effect manifests itself in the amount of kinetic energy dissipated at impact. Several studies have been performed to quantify and understand the severity of rear-end collisions. Rahimi *et al.* [(88)] defined a *safety index* as a function of vehicle operating characteristics that are related to the kinetic energy dissipated during the rear-end collision. Calson [(13)], Lenard [(63)] and Glimm and Fenton [(35)] defined another measure of the dissipated kinetic energy called *accident severity index*. They formulated this accident severity index in different ways. Various functions of collision speeds are used to calculate the accident severity index.

In Equation (10), $S_{rmin} < 0$ indicates a rear-end collision occurs during the vehicle following operation. If the leading and trailing vehicles have constant jerk and deceleration values during the entire stopping maneuver, then the negative value of S_{rmin} could be taken as an approximate measure of the kinetic energy of the trailing vehicle at impact. Rahimi *et al.* defined the quantity S_{rmin} as a safety index .[(88)]

Calson [(13)] defined the accident severity index by a function of both the relative speeds of the colliding vehicles and their absolute speeds. Lenard [(63)] described the severity of an accident as a function of the square of the collision velocity. Glimm and Fenton simplified Lenard's definition [(35)] They expressed the accident severity index (S^2) for a platoon of (n+1) colliding vehicles as

$$S^2 = \sum_{i=1}^{n} \Delta V_{i+1,i}^2 (T_{coli}) \tag{14}$$

where $\Delta V_{i+1,i}(T_{coli})$ denotes the relative speed at impact between vehicle i and i+1. Here, we only consider two-vehicle collisions. By using Glimm and Fenton's definition, the accident severity index can be simplified as [35]

$$\begin{aligned} S^2 &= \Delta V^2(t_c) \\ &= [V_f(t_c) - V_l(t_c)]^2 \end{aligned} \tag{15}$$

where t_c is the time when a rear-end collision is initiated. If the headway is less than the minimum safety headway, then a rear-end collision would take place in the worst case stopping scenario (figure 2 and 4).

The accident severity index depends on the headway setting. The accident severity depends on parameters such as maximum deceleration values (A_{lm}, A_{fm}), trailing vehicle reaction time (T_1, t_{fc}). If not explicitly stated, the simulation analyses in this subsection are done with parameter values shown in table 5.

Table 5. Parameter values for simulation study

$V_l(0)$	60mph	A_{fm}	0.70g
$V_f(0)$	60mph	T_1	0.1$second$
J_{lmax}	72 $meter/sec^3$	t_{fc}	0.85$second$
A_{lm}	0.80g	τ_B	0.1$second$
a_{fac}	0	μ_{lmax}	1
J_{fc}	0	θ_l	0
a_{fauto}	0g	μ_{fmax}	1
J_{fmax}	72 $meter/sec^3$	θ_f	0

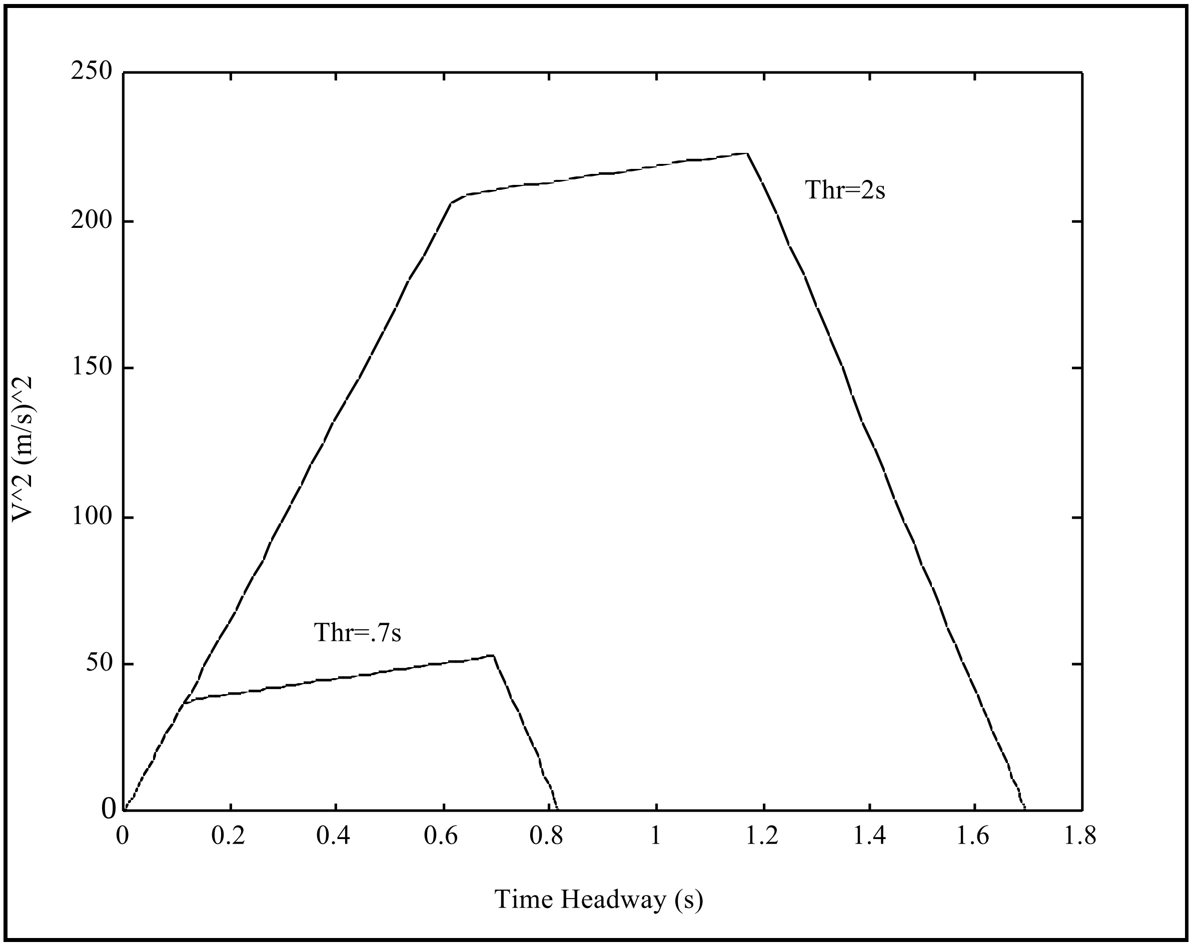


Figure 9. (h, ΔV^2) curves for different values *of* t_{hr}.

Figure 9 shows the effect of the trailing vehicle reaction time (t_{fc}). Figure 9 shows that when the headway setting is very small or large enough, the value of the accident severity index is small. There is a critical headway value (h_c) between 0 and the minimum safety headway that yields the maximum collision damage. As the reaction delay of the trailing vehicle increases, the potential collision damage increases.

Figure 10 shows the effect of deceleration difference between the leading and trailing vehicles ($\Delta A_m \triangleq A_{lm} - A_{fm}$).

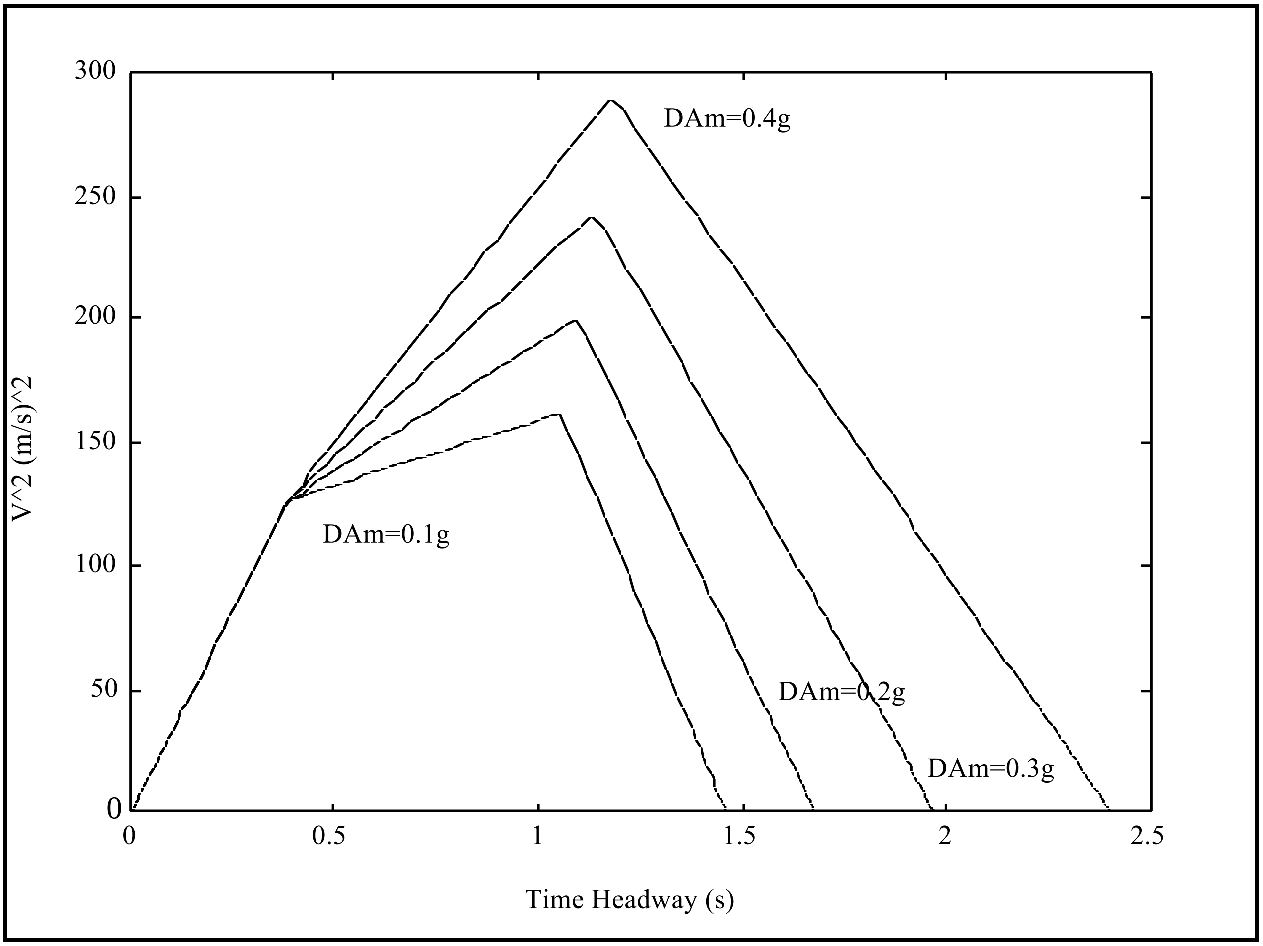


Figure 10. (h, ΔV^2) curves for $A_{lm} = 0.8g$, A_{fm} varies from 0.4 to 0.7g. As A_{fm} decreases the collision damage increases.

As the value of ΔA_m increases, the collision damage increases. When the leading and trailing vehicle have almost the same deceleration capability, the value of accident severity index is bounded by a small value.

The simulation results show that the maximum collision damage increases when the deceleration capability is reduced. If vehicles have and use the same high value of maximum deceleration value, then the probability and severity of rear-end collisions may be reduced.

Using figures 9 and 10 we can come up with the following possible approaches for choosing the minimum safe headway:

(i) Conservative Approach.
We take into account all reasonable extreme conditions, such as maximum possible acceleration difference minimum possible friction coefficient, reaction times, velocities etc. and use a worse case stopping scenario to come up with a value for the minimum headway. This value will be relatively large when compared with the one an average driver uses in manual driving and will reduce highway capacity. For example, the California Department of Motor Vehicles Driver's Handbook suggests three seconds time headway at lower speeds and greater than three seconds

at higher speeds. The majority of today's drivers drive with headways much less than three seconds.

(ii) Vehicle Based Approach.
A vehicle can approximate its braking capabilities with the proper on-board sensors or from the driver's experience. It also knows or can assume a worse possible response for a leading vehicle, i.e., if vehicles can brake with deceleration ranging from 0.3g to 1g the vehicle can assume 1g deceleration for any leading vehicle. Using this knowledge the driver or the computer control system on board of the vehicle could select the appropriate headway for a collision free vehicle following environment. Many drivers follow this approach during manual driving. The more confident a driver feels about the braking capabilities and performance of his vehicle the smaller the headway he may try to maintain during vehicle following.

(iii) An Approach Based on Vehicle to Vehicle Communication.
In partial or fully automated vehicles the braking capabilities of each vehicle can be evaluated with proper sensors and communicated to other vehicles. By knowing its own braking capabilities and those of the leading vehicle the computer control system on board the vehicle could choose an appropriate headway. This approach allows vehicles with different capabilities, such as passenger vehicles, trucks and buses to drive on the same roadway. The value of the headway in this case will be smaller than that of approach (i,ii) when applied to similar situations. Vehicle to vehicle communication could also reduce delays and eliminate human reaction times allowing the minimum headway to be reduced further.

(iv) Uniform Performance.
Vehicles in an automated mode could be made to have similar performance characteristics by proper design of hardware and software tools. This similarity in performance especially with respect to braking capabilities will make the behavior of vehicles more predictable and lead to lower headways.

(v) Aggressive Approach: Short Headway Platooning.
Several researchers argue[111,95] that since the minimum headway depends on many variables that may not be accurately evaluated, one should either choose approach (i) or choose a small intervehicle spacing of about 1 meter or less so that if a rear-end collision takes place the relative velocity at the time of impact is so small (as shown in figure 9) that the collision will be accommodated without any damage to the vehicle or occupants. For additional safety the vehicles could be organized in platoons of 8 to 25 vehicles with interplatoon spacings chosen according to the conservative approach (i). The short headway platooning approach is pursued by most researchers under PATH and is used to study capacity[56;89], safety and different architectures for AHS. [45;46;111]

If a fully automated highway system is to evolve from today's "manual" system then it is unlikely that short headway platooning will be part of any initial deployment. Most likely it will be used towards the final stages of AHS to improve capacity further. The reason is that 1m spacing platooning is a high performance system that requires highly accurate and very reliable technologies that could be very costly to develop initially before the whole idea of vehicle automation is mature and in use. Furthermore the jump from today's driving of relatively large headways to something that appears to the driver or passenger as almost zero headway may pose serious human factors problems and is therefore risky.

We believe that the selection of headway for automatic vehicle following will evolve gradually from that described by approach (i) and (ii) used in today's highways to that described by approach (iii) and (iv), where human time delays will be replaced by the much smaller delays of sensors/actuators and communication devices. Headways based on approach (iii) and (iv) may not provide the capacity improvement that the short headway platooning proponents are advocating but have the potential of improving current capacities by 20% to 200% depending on the architecture of AHS.[50;89]

Steady State Highway Capacity

The velocities of the leading and trailing vehicles are denoted by $V_l\ (t)$ and $V_f\ (t)$ and the accelerations by $a_l\ (t)$, $a_f\ (t)$ respectively. The leading vehicle is assumed to have a total length of L meters. The absolute position of the vehicles measured from a common reference point is denoted by $S_l\ (t)$, $S_f\ (t)$ respectively. The relative distance S_r between the two vehicles measured from the front of the trailing vehicle to the rear of the leading vehicle is given by

$$S_r(t) = S_l(t) - L - S_f(t) \tag{15}$$

The headway between the vehicle can be defined for space or time. The inter-vehicle distance S_r is the space headway. Time headway (h) is the time required for the trailing vehicle to travel through the inter-vehicle distance (S_r), $S_r = hV_f$..

The k-factor headway (k) is proportional to the square of the trailing vehicle velocity. The constant of proportionality k is referred to as k-factor headway, $S_r = kV_f^2$. This is also called *safety factor* headway.

Reduced time headways increase the capacity of the highway. The equation for steady-state traffic flow in vehicles/hour/lane is

$$\text{Flow} = 3600 \frac{V_{avg}}{S_d + L} \tag{16}$$

V_{avg} is the average vehicle speed in meters/second. L is the average length of a car in meters. S_d is the average gap between vehicles in meters. The equation gives an estimate of steady-state traffic flow over long stretches of highway. It does not take entries and exits into account. Most urban highway trips are short so this model gives an upper-bound on capacity. More realistic traffic flow models show model entries and exits into the traffic stream.

Section 4: Reliability

As the AHS evolves, the driver’s functions will be gradually automated by the vehicle and roadway. The automated functions provided by the vehicle and roadway need to be reliable so that safe and efficient AHS operation can be achieved otherwise automated functions will not be accepted by the general public. A major goal of this report is to characterize the reliability requirements of vehicle and roadway automated functions in the AHS evolution.

Reliability Indices

A system's reliability is defined as the probability that the system will perform its intended function for a specified period of time under a given set of conditions. Indices used to characterize a system's reliability property include reliability function, failure rate and mean time to failure (MTTF), etc. The reliability function of a system is

R(t) := The probability that a system operates without failure for a length of time *t*.

The failure rate or hazard function $\lambda(t)$ is defined such that, when the time interval *Æt* is small, $\lambda(t)$ *Æt* is the probability that the system will fail at some time earlier than *t* + *Æt* under the condition that it has not yet failed at time *t*

$$l(t) D\, t = P\{ t < t + D\, t \mid t > t \} \tag{17}$$

The failure rate $\lambda(t)$ can be related to reliability function *R(t)* by the following equation

$$(t) = \frac{f(t)}{R(t)} \tag{18}$$

where *f(t)* is the failure probability density function of time *t*.. Mean time to failure is defined as the expected value of the failure time

$$\mathrm{MTTF} = \int_0^\infty t\ f(t)dt \tag{19}$$

In addition, MTTF can be related to the reliability function *R(t)* by

$$\mathrm{MTTF} = \int_0^\infty R(t)dt \tag{20}$$

A system with a constant failure rate λ gives

$$
\begin{aligned}
f(t) &= \quad e^{-\;\;t} \\
R(t) &= e^{-\;\;t} \\
\text{MTTF} &= \frac{1}{\;}
\end{aligned}
\tag{21}
$$

A system failure stops the system from performing its intended function. In human driving, the potential outcomes of a longitudinal or lateral control failure may be complicated. To use the reliability of today's manual driving to quantify reliability standards for AHS automation in each ERSC, we consider that each failure in manual driving causes a collision.

Longitudinal Reliability of Human Drivers

United States drivers average around one reportable rear-end collision every 50 years.(60,28) Data from Ford Motor Company show that drivers brake about 50,000 times per year on average. The probability of a reportable rear-end collision under the condition that a brake action is needed in manual driving is

$$
\begin{aligned}
P_b &= \frac{1}{50 \times 50{,}000} \\
&= \frac{1}{2{,}500{,}000}
\end{aligned}
$$

This gives a reliability for an average driver R_b of

$$
\begin{aligned}
R_b &= 1 - P_b \\
&= 0.9999996
\end{aligned}
$$

Human drivers are very reliable in longitudinal control.

The probability that a car will have a rear-end collision in its lifetime is $P_{re} = 0.2262$.(60) The average lifetime of a car is assumed to be 13 years.(60) If we assume a constant failure rate, the longitudinal control must have $\lambda < 0.02$ year^{-1}. If we assume a duty cycle c, the failure rate per hour of operation must satisfy

$$
< \quad \frac{0.2}{c} \cdot \frac{1}{365 \times 24} \ \text{hour}^{-1}
$$

If the driver operates the vehicle one hour per day in average, then $c = 1/24$. In this case, the driver's longitudinal control failure rate is

$$
< \quad \frac{0.2}{c} \cdot \frac{1}{365 \times 24} \ \text{hour}^{-1}
$$

Lateral Reliability of Human Drivers

The probability that a car will have a lane departure collision in its lifetime is P_{re} = 0.09 [114] The average lifetime of a car is assumed to be 13 years [59] If we assume a constant failure rate, the reliability of human lane keeping control has $\lambda = 0.00667$ year^{-1} or MTTF = 150 years. If we assume a duty cycle *c*, the human lane keeping failure rate is

$$< \quad \frac{0.09}{c} \cdot \frac{1}{365 \times 24} \text{ hour}^{-1}$$

For *c* = 1/24, the reliability of manual lane keeping control can be approximated by

$$< \quad 1.8265 \times 10^{-5} \text{ hour}^{-1}$$

The probability that a car will have a lane change/merge collision in its lifetime is P_{re} = 0.015.[113] If we assume a constant failure rate, the reliability of human lane changing control has $\lambda = 0.00125$ year^{-1} or MTTF = 800 years. If we assume a duty cycle *c*, the human lane changing failure rate is

$$< \quad \frac{0.015}{c} \cdot \frac{1}{365 \times 24} \text{ hour}^{-1}$$

For *c* = 1/24, the reliability of manual lane keeping control can be approximated by

$$< \quad 3.425 \times 10^{-6} \text{ hour}^{-1}$$

Reliability Requirements of Automated Functions

Automated functions provide no benefits unless they are reliable than today's manual driving. By quantifying the reliability of human drivers, we will be able to estimate the required reliability for automated functions using reliability indices, such as failure rate and mean time to failure. The results of the previous sections provide measures to determine the required reliability when longitudinal and lateral control is automated.

Automation is mainly achieved by automatic control systems from the vehicle and roadway. An automatic control system needs to be design in such a way that it fails in a safe manner. However, from the system design point of view, reliability indices provide little help in obtaining fail-safe system designs. To design a fail-safe system, we will first derive the reliability functional requirement. The reliability functional requirement of an automatic system is concluded by analyzing the interactions between the driver and the system. The requirement guarantees the safety of the driver in case the system fails.

The reliability functional requirement of a system can be used to evaluate the necessity of redundant components and to come up with system design frameworks. This gives us the knowledge of the complexity and difficulty in designing an automatic system. By analyzing reliability requirements for vehicle and roadway functions in each ERSC, we can estimate the technical and cost gaps between ERSCs.

Section 5: ERSC 1 Analysis

Description of ERSC 1

In ERSC 1 the roadway provides a dedicated lane for the use of the automated vehicles. The lane may be isolated and accessed by a dedicated ramp or it could be next to a manual lane and accessed at designated points or at any point along the manual/dedicated lane boundary. The roadway senses traffic flow (average speed, density) and environmental conditions on the dedicated lane and provides target speed commands, minimum time headway recommendations and traffic status information to the vehicles.

The automated vehicle can maintain a selected headway and speed relative to the preceding vehicle by using a computer control system to control the throttle and the brake. Automatic braking is limited to soft braking that is applied when the engine torque is not sufficient to maintain the selected headway. It does not include hard braking for emergency stops or other situations. It receives target speed commands, minimum time headway recommendations and traffic status information from the roadway. It responds to the speed commands automatically in a smooth way as long as the resulting headway is not smaller than the one selected by the driver. If the target speed is larger than the one the driver feels comfortable with, the driver may be required to exit the lane. The vehicle responds to the recommended minimum time headway provided it is larger than the selected one. It responds to driver commands for changing the headway, and setting the cruising speed. It also enables and disables the speed and headway maintenance system (SHMS) upon driver command. The vehicle may send its speed, headway and operational status and identification to the roadway to be used for traffic flow control purposes. If the SHMS fails then the vehicle fall-back mode allows the driver to take over this function and continue the trip until the next exit.

The driver is responsible for driving the vehicle into the dedicated lane with the aid of the blind spot warning system. Once in the lane the driver switches the SHMS on and sets the desired headway for vehicle following or the cruising speed. The driver supervises the SHMS and overrides it when hard braking is required for emergency stops and other situations. The driver is aided by the rear-end collision warning in avoiding rear-end collisions. The driver is responsible for lane keeping, lane changing and lateral collision avoidance. The driver is also responsible for choosing the route of the vehicle and conforming to traffic regulations. In case of malfunction of the SHMS or at the end of the trip the driver drives the vehicle out of the dedicated lane by using the next available exit with the aid of the blind spot warning system.

A list of the roadway, vehicle, and driver functions that are to be studied for ERSC 1 is given in table 6. We will discuss each of these functions in detail in this section.

Table 6. ERSC 1 functions and driver/vehicle/roadway performance requirements.

Function/Section	Requirement	Driver/Vehicle/Roadway Tasks
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead. - Maintain a selected headway for vehicle following. - Smoothly transition between vehicle following and cruising modes	– Respond to driver commands for setting the cruising speed and minimum headway and maintain that cruising speed and chosen headway in a smooth manner – Respond to driver commands for enabling and disabling the SHMS safely – Respond to roadway commands for following target speeds and increasing headway in a smooth manner
Rear-end Collision Warning	Warn the driver of a potential rear-end collision due to moving or stationary obstacles in the lane on time without false alarms	– Detect potential rear-end collisions – Have a high detection rate and a low rate of false or nuisance alarms – Respond to commands from the driver to adjust the sensor threshold – Send driver warnings of rear-end collisions – Communicate braking data from the preceding vehicle to reduce false alarms
Blind spot warning	Warn the driver of moving or stationary obstacles in the vehicle's blind spot	– Detect objects in the blind spot on both sides of vehicle – High detection rate and a low rate of false or nuisance alarms – Warn driver in time to avoid collision – Driver enables blind spot warning – Respond to driver command to adjust warning thresholds
Driver Interface	– Driver should be able to: » override the speed & headway maintenance function » adjust headway and set cruising speed » adjust warning threshold	– Adjust thresholds on warnings – Enable/Disable automatic functions – Adjust headway and cruising speed – Interface should be simple to understand and use
Roadway/Vehicle Speed & Headway Commands	Senses vehicle average speed and density and environmental conditions then sends commands to smooth traffic flow	– Roadway measures the average speed and traffic density, and assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways – Vehicles may display relevant traffic information to driver
Fall-back Mode to Manual Driving	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- sense status of different vehicle control channels - Safely transfer control to the driver if SHM function fails

Performance Requirements

Speed and Headway Maintenance

The speed and headway maintenance (SHM) function should maintain the selected cruising speed when no vehicle is ahead. It should maintain the selected headway during vehicle following. The SHM function operates by measuring the relative speed and spacing, then sending commands to the throttle and brake actuators. Figure 11 shows the structure of the SHM function. This section will discuss the sensor and actuation requirements, control algorithms, selection of a safe headway, and driver/roadway interface for the SHM function.

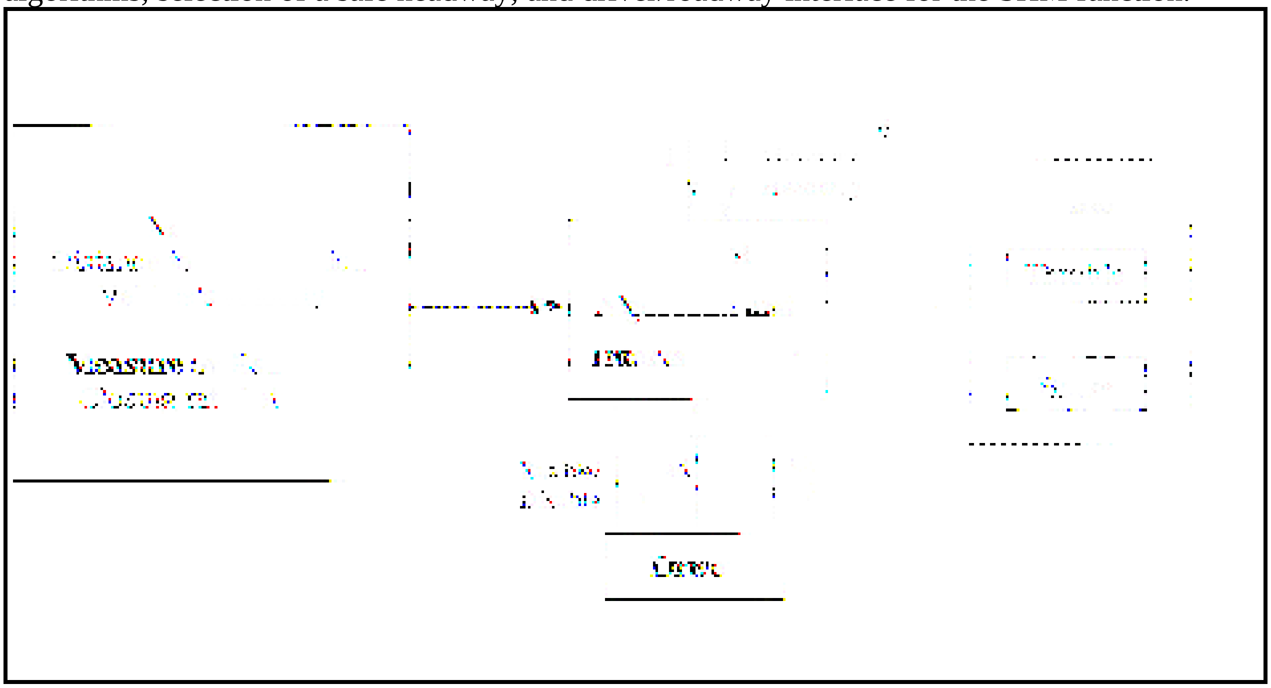


Figure 11. Block diagram of the speed and headway maintenance function. The sensors measure the relative speed and spacing of the vehicles, then the controller sends commands to the brake and throttle actuators so that the vehicle maintains the selected speed and/or headway.

Sensor Requirements

To maintain a target velocity the vehicle must be able to measure its own speed. The sensor measures speeds between 5 and 100 mph. The sensor needs to be accurate within 2-5 mph since humans cannot perceive small changes in velocity.

To maintain a constant time headway the vehicle must be able to measure the distance to the target vehicle ahead. The vehicle must also estimate or measure the closing rate between vehicles. Figure 12 shows the sensor region for headway maintenance. The single beam sensor region is sufficient for vehicle following in the lane and for detecting stationary obstacles. The ideal sensor region shows the sensor requirement for detecting obstacles other than vehicles in the lane such as motorcycles, animals, etc. and vehicles during cut-in situations.

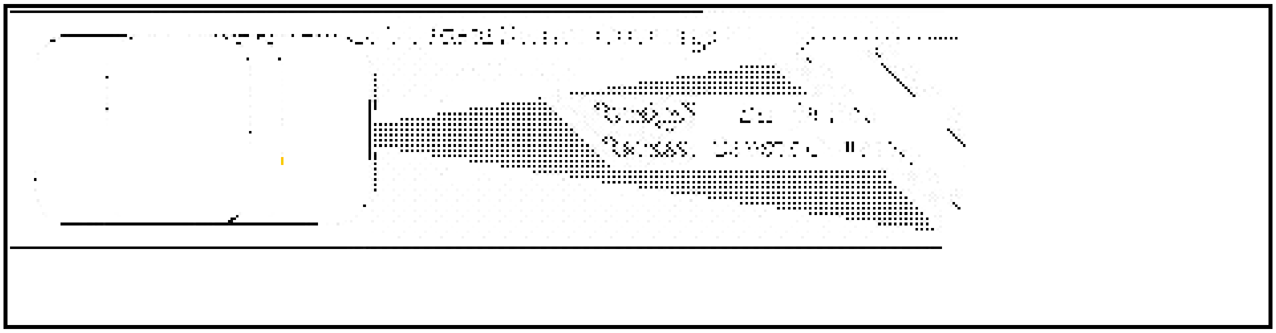


Figure 12 Sensor requirements for range and closing rate detection for the speed and headway maintenance system.

There are several competing requirements that determine the maximum sensor range. The sensor range needs to be the maximum value for these requirements. [29] Since drivers may rely on the SHM function to initiate braking when an obstacle appears in the range of the sensor, the sensor should detect obstacles at a range of at least 3 seconds. The *California Driver's Handbook* states that 3 seconds and higher is a safe time headway for human drivers. If we assume a speed of 60 mph (26 meters/s) this gives a distance of 78 meters. Therefore the vehicle range sensor should work over a distance of at least 80 meters. The second requirement is that the vehicle be able to stop when there is debris or another vehicle stopped in the roadway ahead. This scenario is known as the "brick wall" scenario. Rear-end collisions with a stationary vehicle outnumber rear-end collisions where the lead vehicle is moving by 2:1.[60] Figure 13 shows some range curves for the brick wall scenario for different velocities and a human reaction time T_{hr} of 2 seconds.[1;64] For example, at 60 mph we get a range of 100 m for a vehicle with a maximum braking capability of -0.55 g. Table 8 gives the parameters used in this calculation.

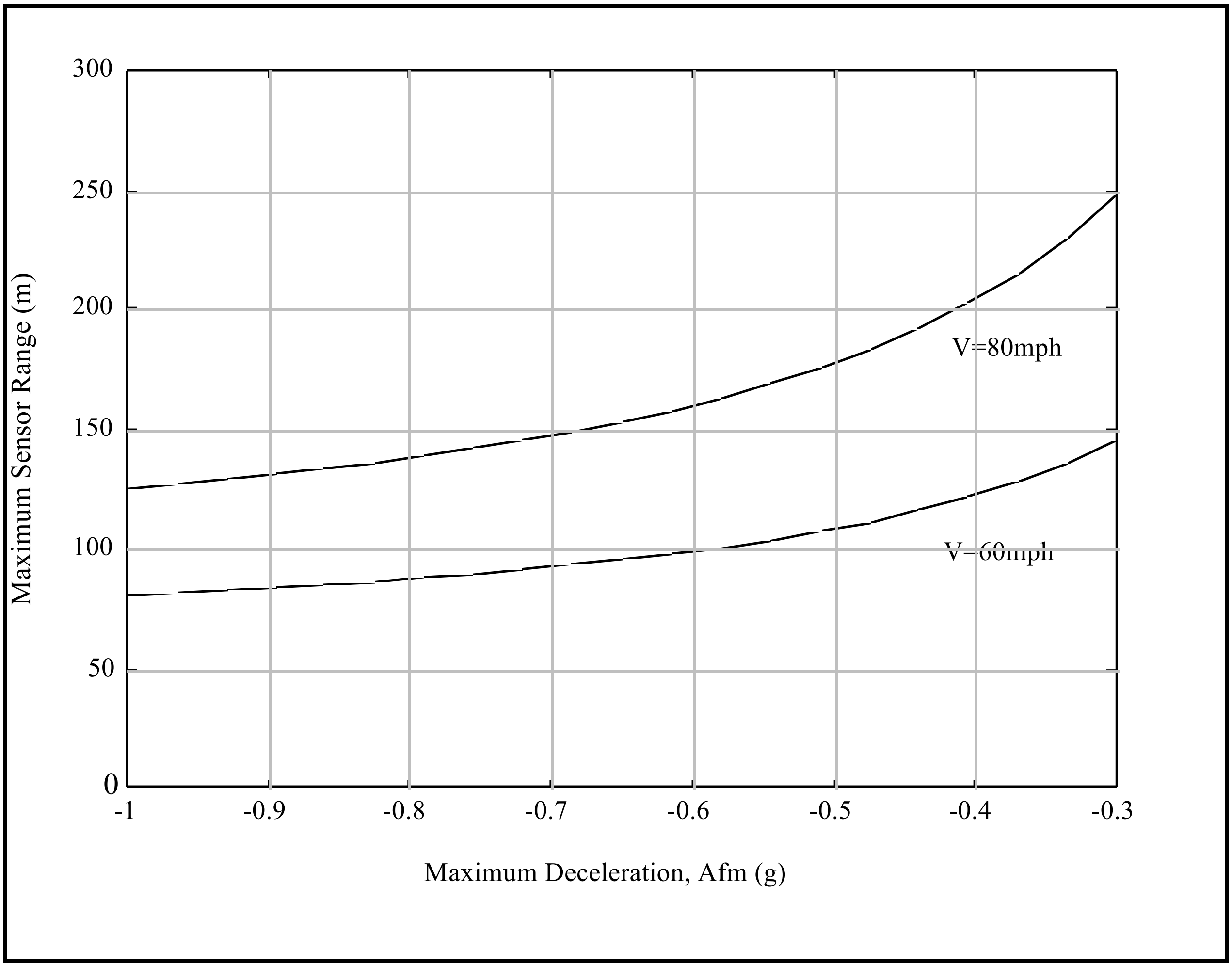


Figure 13. The maximum sensor range with respect to the maximum deceleration of the vehicles for two different velocities. These values come from the "brick wall" scenario when the lead vehicle or debris is stopped on the highway.

The sensor must cover the lane so it does not miss the target vehicle. But it must also minimize interference from adjacent lanes which means that the sensor beam cannot spread out too much or it must use multiple beams. The sensor must be able to track the vehicle around highway curves without losing the target.

The vehicle must also detect or estimate the closing rate between itself and the target vehicle. This may be done directly with a pulse-doppler radar or it may be estimated by taking the derivative of the distance measurement over time. The sensor accuracy needs to be with 5-10% again because drivers cannot tell the difference between small changes in closing rate.

The most common type of distance sensor measures the time-of-flight from the time that a pulse is sent out to the time that the pulse returns. The distance is the (time-of-flight)*(pulse velocity)/2. These types of sensors include radar, ultrasound and laser rangers. These time-of-flight sensors can measure the range, relative speed, and angular position of the target vehicle. Other sensors use triangulation techniques such as stereo to measure the distance to the vehicle ahead. These sensors include vision-based systems and radar.[68,86] The time-of-flight sensors are commercially available for automotive use today,[12,33,76] so they appear to be the best solution for ERSC 1.

Radar systems are time-of-flight systems. Range gates in the receiver look for the return pulse in different time intervals. The receiver can modulate the pulse in frequency to estimate the closing rate of the target. Radars are also long range and accurate. Their performance is not degraded by rain or snow. Since radars have a long range, they also have problems with interference. The beam of a radar spreads out as the pulse propagates as shown in figure 12 and it can hit vehicles or signs in other lanes or along the edge of the roadway. A narrow beam can reduce interference. Reliable performance may require a scanning or multiple beam radar that searches the lane and rejects interference.

Laser radars use high frequency pulses in the *near-infrared* region. They give extremely accurate range measurements. However their narrow beam width can make it difficult to track targets around curves and at large ranges. The performance of laser radars is degraded due to dirt on the transmitter or receiver, heavy rain, thick fog, and car exhaust emissions.[76] Experiments have shown that the maximum detection range of a laser radar can be reduced by 30% in wet weather compared to dry weather.[76]

The vehicle may also use combinations of different sensors to improve performance. This can reduce interference by taking measurements in multiple frequency bands and increase reliability by providing independent measurements of range.

Control Algorithms

The vehicle must respond quickly and smoothly to commands from the driver and roadway. The controller must also limit the jerk and accelerations in normal operation. Humans find longitudinal accelerations above 0.17 g and jerks above 0.2 g/s uncomfortable at low speeds.[15] At high speeds the deceleration should be kept below 0.1g with jerk as low as possible. The maximum deceleration (or soft braking) should be limited to around 0.2 g with low jerk.[15]

The controller must switch smoothly between the vehicle following and cruise modes and avoid sudden accelerations when the preceding vehicle exits the dedicated lanes. Tests on an intelligent cruise control system by Fancher et al showed that abrupt accelerations by the automated vehicle when the sensor lost its target or the vehicle ahead change lanes made drivers feel uncomfortable and unsafe.[26] Thus the controller should not accelerate quickly. The controller must also switch smoothly between the throttle and brake without high frequency oscillations.

Studies on automatic vehicle following go as far back as the mid-70’s where simple point mass vehicle models were used to design throttle and brake controllers, [20,87] Hedrick et al [42] and Sheikholesam and Desoer [93] designed controllers that maintain constant intervehicle gaps. When three or more vehicles begin to follow each other at a constant intervehicle spacing the vehicle dynamics become coupled. Controller and actuator delays can cause instability unless there are vehicle-to-vehicle communications.[87] If the vehicles follow a constant time headway policy instead, the stability of the vehicle dynamics can be achieved without relying on vehicle-to-vehicle communication.[18]

Researchers at the University of Southern California have designed several controllers for the SHM function. Ioannou and Xu designed several throttle and brake controllers for SHM.[51] These controllers showed an accuracy of 5 meters for vehicle following in simulations and real-world tests. The controller limited the acceleration and the braking to keep the ride smooth. The actuators had delays of 0.25-0.5 seconds. A logic switch ensured smooth transitions between the brake and throttle by inserting a neutral zone where neither the throttle nor the brake was active. An alternative controller is a fuzzy rule-based controller.[25] The fuzzy controller also limited acceleration and the change in throttle angle. Simulation results for a similar sensor gave an accuracy of 3 m. Tests on I-15 in California gave an accuracy of 3-5 meters on a hilly stretch of freeway. On a steep downhill the vehicle did not have enough torque to maintain a constant gap and the driver had to override the SHM function.

Actuator Requirements

The brake and throttle actuators must respond quickly to commands from the controller. Faster actuators may give better control. If the delay is too long then vehicle following may be unsafe if there are many vehicles in a row following one another.[50] Tests show that delays less than or equal to 0.3 seconds are sufficient for ERSC 1.[51,25] Table 7 summarizes the requirements for the SHM function.

Table 7. Summary of requirements for speed and headway maintenance system.

Requirement	**Value**	**Background**
Distance Sensor	>100 m	Value comes from a "brick wall" scenario, the warning system gives the driver 2 seconds to react to a warning to brake, see figure 13 for details
Closing Rate Sensor	Measure values between [-160,160] km/hour, with accuracy of 3-5 km/hr	Must be able to measure all velocity differentials between vehicles. System accuracy bounds are limited by human perception
Velocity Sensor	0-160 km/hour	Measure all possible speeds in dedicated lane
Controller distance accuracy	3-5 meters	Humans do not measure distance between vehicles accurately
Acceleration Limit	+/- 0.15 m/s^2	Human factors studies show that drivers find accelerations and decelerations out of this range uncomfortable.[15]
Jerk Limit	+/- 0.2 g/s	Human factors studies show that drivers find jerks out of this range uncomfortable.[15]
Throttle Actuator Delay	<0.3 seconds	Controller studies show that the required SHM system accuracy can be achieved with delays in this range .[51,25]

Safe Headway Selection

The safe headway between vehicles depends on driver reaction time, the braking capabilities of the lead and following vehicles, and environmental conditions. Table 8 gives the variables used in the minimum time headway calculations for ERSC 1. Unless noted these values are used for all the figures. Figure 14 shows the minimum time headway for different maximum deceleration values of the follower car. When the follower vehicle decelerates faster than the lead vehicle the minimum time headway decreases. When the follower vehicle decelerates slower than the lead vehicle the minimum time headway increases. This suggests that proper minimum time headways should be set as if the lead vehicle has a high maximum possible acceleration.

Table 8 Variable values used in the simulations in section 5-1 for ERSC 1.

Variable Name	Description	Value
V_l, V_f	Initial velocity of the lead and following vehicles	100 km/hr
J_{lmax}, J_{fmax}	Maximum jerk of the lead and following vehicles	72 m/s^3
$_{lmax}$, $_{fmax}$	Maximum road-tire friction coefficient of the lead and following vehicles	1,1
A_{lm},A_{fm}	Maximum deceleration of the lead and following vehicles respectively	0.85 g,0.8 g
a_{fac}	Acceleration under vehicle following situation	0.05 g
a_{fauto}	Acceleration value for soft braking	-0.20 g
J_{fc}	Jerk value for soft braking	20 m/s^3
$_b$	Braking actuation delay	0.1 s
$T(1)$	Detection delay of the automated vehicle headway system	0.3s
T_{hr}	Human reaction time from when vehicle warns driver of a potential rear-end collision	1.5 s

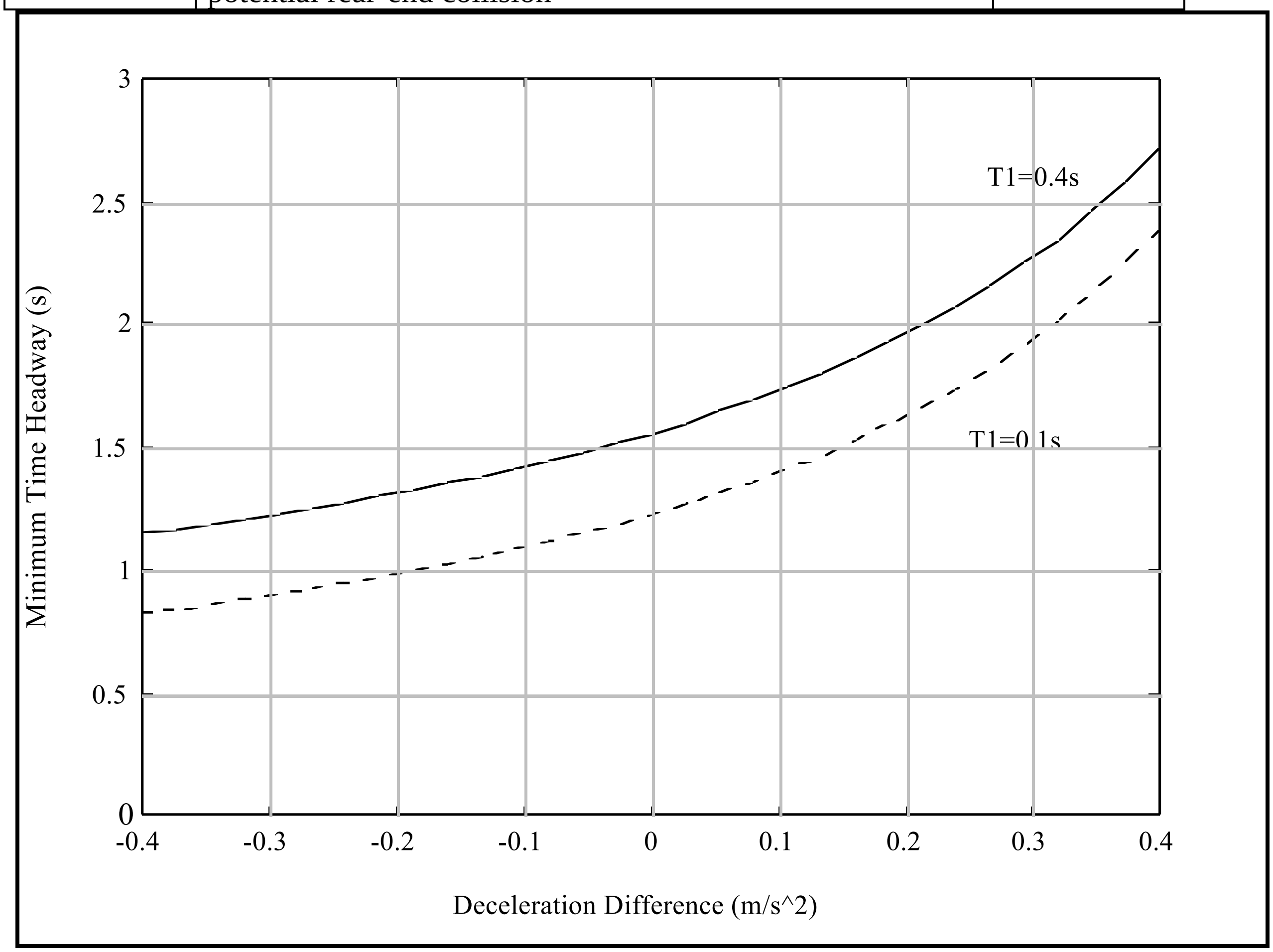


Figure 14. Minimum safe time headway with respect to differences in the maximum deceleration between vehicles ÆA_m= A_{lm}–A_{fm}. A negative acceleration value means that the follower car can brake faster than the lead car. T1 is the time that the following vehicle detects the lead vehicle deceleration and initiates soft braking.

Figure 15 shows the minimum time headway for different human reaction times. Longer reaction times lead to larger minimum time headways. Human factors studies and guidelines suggest that a human reaction time of 1.5 - 2 seconds is sufficient for most people to react to an unexpected braking situation [64,1] The recommended minimum headway for collision-free vehicle following needs to account for human reaction time.

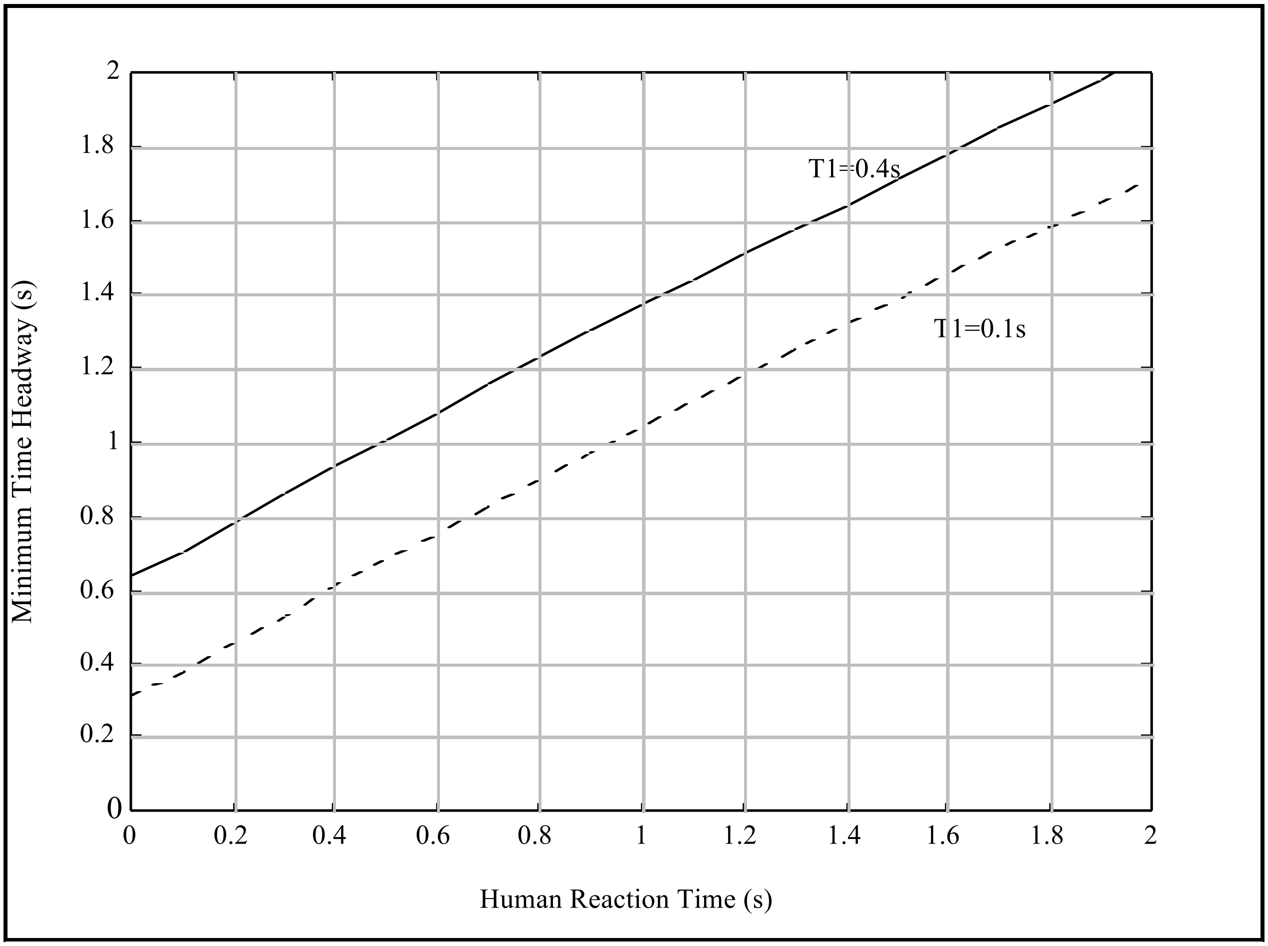


Figure 15. Minimum safe distance between vehicles for different human reaction times. The human reaction time is measured from the time that the vehicle ahead begins braking. The solid line shows the headway for a communications system. The dashed line shows the headway for a sensor-based system.

Driver/Roadway Interface

The vehicle responds to driver commands for switching the SHM function on and off, selecting the minimum headway and the cruising speed, and overriding the SHM function. It also responds to roadway speed commands, headway recommendations, and displays traffic status information received from the roadway to the driver.

The driver turns the SHM function on and off. The SHM function may be turned on before the driver enters the dedicated lane or once the driver has successfully merged into the lane. Tests on a vehicle with one experimental SHM system show that most drivers do not feel safe using this automated system while merging.[26] This switch needs to be standardized and clearly marked so that the vehicles can begin operations quickly and easily. The vehicle must also allow the driver to override the SHM function by braking since the driver is responsible for emergency stops.

The roadway may send target speed commands directly to the vehicle or it may communicate with the driver who then sets the vehicle's speed. The roadway can send the headway and speed to the vehicle with variable message signs or directly to the driver with in-vehicle signing. This system implementation depends on driver cooperation and attention to work well. If the traffic and weather are variable, this implementation could impose a heavy workload on the driver.

Issues and Risks

1 The SHM function does not have to be very accurate in this ERSC (5-10%) since it is limited by human perceptions and reaction times. This suggests that SHM systems at this level may come from the intelligent cruise control systems planned by several companies .[74,26] The next ERSC requires more accurate SHM. The components for a more accurate SHM function need to be designed with AHS requirements in mind instead of taking commercial technology off the shelf.

2 Controller Algorithms

The controller algorithms need to smoothly adjust the brake and throttle to avoid sudden accelerations when the vehicle ahead leaves the lane. Driver tests indicate that drivers feel unsafe when the controller suddenly accelerates.[26] The controller needs to use alternative algorithms that limit accelerations.[51,25]

3 Electromagnetic Interference

Full deployment of ERSC 1 means that most vehicles will have active sensors such as radar. When multiple radar operate in a small area at similar frequencies the radar may interfere with one another. This interference could lead to shorter sensor ranges and poor performance.

4 Driver Interface

Research needs to be done on the driver interface to the SHM function. This device may have separate controls for enable/disable and minimum time headway. It may be too much of a burden on the driver to expect him/her to change lanes and start the SHM immediately. This function may require the driver to preset an initial target speed and minimum headways when he/she starts the vehicle.

Rear-End Collision Warning Function

A rear-end collision warning system needs to be able to accurately predict the likelihood of a collision. If a collision is likely, then the system warns the driver to respond to the threat. Analysis of minimum time headways between vehicles suggests that small reductions in driver reaction times can dramatically decrease the minimum safe headway. Figure 15 shows the effect of driver reaction time on the minimum time headway. Reductions in the reaction time may be achieved by warning the driver. Many accidents are due to failures in human information processing.[59] In many cases the other vehicle was clearly visible. This again suggests that a rear-end collision warning system may increase driver safety.

The rear-end collision warning (RECW) function should warn the driver of a potential rear-end collision due to moving or stationary obstacles in the lane. This function assesses the potential for rear-end collision using vehicle characteristics and driver reaction time, then warns the driver if necessary. Figure 16 below shows the principle blocks of the RECW function and their relationship to one another. This section will discuss the sensor requirements, warning algorithms, vehicle-to-vehicle communications, and driver interface for the RECW function. Table 9 summarizes the requirements for the rear-end collision warning system.

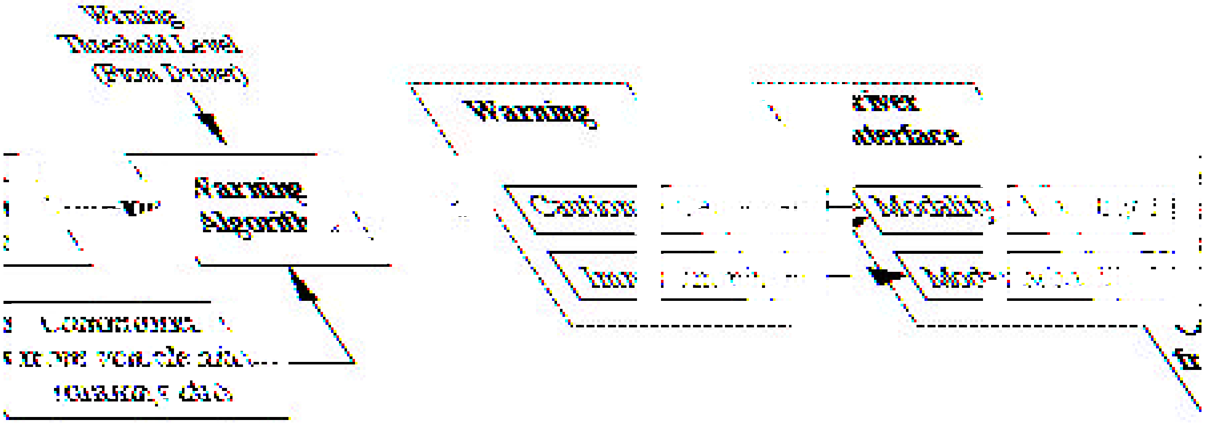


Figure 16. Block diagram for the rear-end collision warning system. The system senses the distance and closing rate of the target vehicle. Then the warning algorithm computes the headway between the vehicles and warns the driver if necessary.

Table 9. Summary of requirements for rear-end collision warning system.

Requirement	Value	Background
Sensor Range	>100 m	Value comes from a "brick wall" scenario, the warning system gives the driver 2 seconds to react to a warning to brake, see figure 13 for details
Obstacles detected	All types of motor vehicles and debris	Sensor must detect obstacles in the lane and warn the driver to brake.
Cautionary Warning	0-15° from line of sight; visual warning	Warning must be non-intrusive; warnings should be near driver's primary line of sight for the task[64]
Imminent Warning	Dual warning modes (Auditory and visual); >1.4 s before collision	Warning needs to give driver enough time to react to possible collision.[64] Studies show that most (95%) drivers react within 1.4 s for braking

<u>Sensor</u>

The rear-end collision warning system can use a velocity sensor, a ranging sensor and a closing rate sensor to recognize potential collisions. These inputs allow the vehicle to estimate the time to collision that is the gap distance over the closing rate, the time headway, and the safe stopping distance. Sensors that estimate the roadway coefficient of friction may also improve the performance of a RECW system.[39]

The vehicle must be able to stop when there is debris or another vehicle stopped in the roadway ahead. This scenario is known as the “brick wall” scenario. Rear-end collisions with a stationary vehicle outnumber rear-end collisions where the lead vehicle is moving by 2:1.[60] Figure 13 shows some range curves for this requirement for different velocities and a human reaction time T_{hr} of 1.5 s. For example, at 60 mph we get a range of 100 m for a vehicle with a maximum braking capability of -0.55 g. Table 7 gives the parameters used in this calculation.

The sensor must also detect "cut-ins" that may change lanes in between vehicles. A single beam sensor does not see the cut-in until it enters the beam shown in figure 11. The speed of detection depends on the beam width $_b$ of the radar, the lateral velocity of the vehicle that is cutting-in, and the distance of the cut-in from the vehicle. A typical lane change takes about 2-6 sec.(66) This gives a bound of less than 0.5 seconds for the detection time between the ideal forward looking sensor and the single beam sensor. In the case of manual braking, the detection time difference for the ideal sensor and a single beam sensor will not reduce the accident severity very much as shown in figure 17. The problem of “cut-ins” may preclude the continuous entry option for check-in.(108)

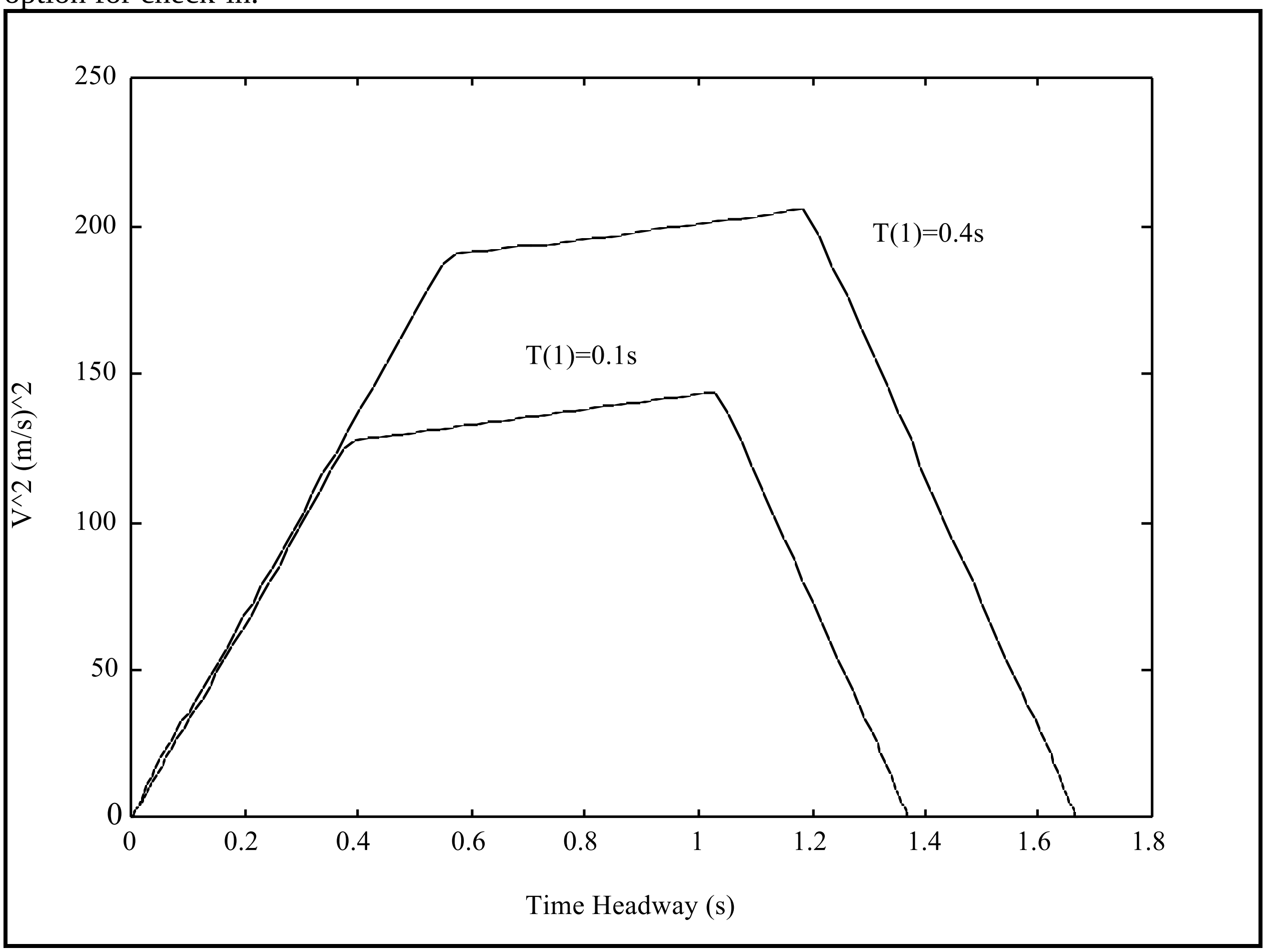


Figure 17. Changes in the detection time for lane change/merge collisions have a small effect on the accident severity. T1=0.1s shows the case for the ideal sensor. T1=0.4s shows the case for the single beam sensor.

Warning

The warning algorithm for rear-end collision warnings is based on the time-to-collision (TTC) or minimum headway between the lead and following vehicles. The response time requirements for the TTC are estimated based on the American Association of State Highway and

Transportation Officials (AASHTO) model for stopping sight distance.[1] The model assumes that the distance required to brake to a stop in reaction to an obstacle ahead is the summation of the distance traveled during the perception-reaction time of the driver and the distance required to decelerate to a complete stop. This gives a 3-5 second TTC criteria based on a 2.0 second driver reaction time.[64]

A warning criterion can also be based on the time headway separation. The minimum headway depends on the driver reaction time, the relative deceleration difference between vehicles and the relative velocity difference. Figure 18 shows the effect of driver reaction time on the collision severity. The reaction time of the driver varies with traffic conditions, past system performance and driver attention. Lerner et al recommend a time headway threshold of 1.0-1.5 seconds.[64] This warning is based on a study of braking responses in reaction to a lead vehicle's brake lights that found that very few drivers reacted by braking if the headway exceeded 1.4 seconds.[106]

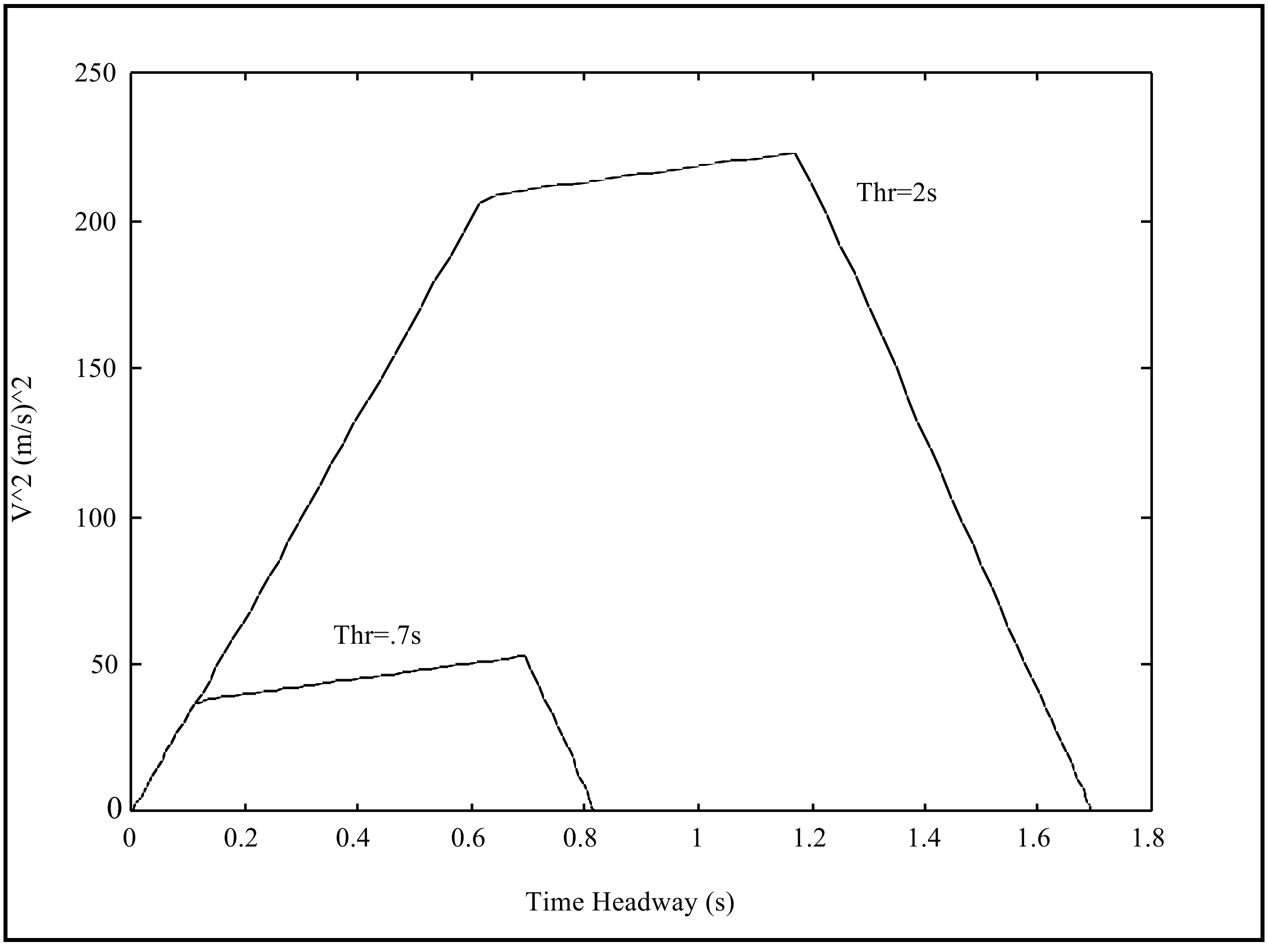


Figure 18. Changes in the human reaction time for lane change/merge collisions affect accident severity. T_{hr}=0.7s shows the best case for human reaction time to an unexpected hazard. T_{hr}=2.0s shows the worst case for human reaction time to an unexpected hazard.

The collision warning system must warn the driver when a collision may occur without false alarms. High rates of false alarms may cause the driver to ignore the warnings or turn off the system. The follower vehicle must detect that the lead vehicle is starting to brake hard. This can be done either with the detection of a change in the relative velocity or acceleration between the vehicles or with the reception of an emergency transmission from the leading vehicle (a sort of electronic brake light) A deployed system may require both measurements for an emergency warning.

Human factors studies show that there should be multiple levels of warning.[98] The severity and intensity of the warning depends on the immediacy of the threat. Lerner et al [64] suggest two levels of warning: cautionary and imminent. The warnings end when the driver takes action to end the threat.

A cautionary crash avoidance situation exists when another vehicle is sensed in front of the vehicle and the time-to-collision is estimated at greater than 3-5 seconds. The cautionary warning gives the driver time to recognize a hazard and correct the problem. The warning needs to give the driver informational feedback on his /her headway maintenance performance.[64]

An imminent crash avoidance situation exists when a vehicle or object is sensed the sensor detection zone with a short time-to-collision or a short time headway. The goal of the warning is to make the driver react immediately. The AASHTO models use a driver reaction time of 2 seconds for this warning. Other studies find that most drivers respond to warnings within 1.4 seconds. We use 1.5 seconds in our analyses.

The collision warning system needs to recognize potential collisions accurately. No warning system will ever be perfectly accurate so it is important to investigate how false alarms affect the driver. The number of false alarms depends on the accuracy of the collision detection system. Communication of braking data between vehicles can help lower the rate of false alarms while maintaining a high detection rate.

<u>Vehicle to Vehicle Communications</u>

The vehicle needs to estimate the TTC or minimum headway as described above. When the car ahead begins to brake with a deceleration, a_{bmax} , the TTC decreases. However the measurements for the distance and closing rate between the vehicle itself and the target vehicle can be quite noisy and inaccurate for quick estimates of the TTC. The RECW function must distinguish between sensor measurement noise and a true braking maneuver. Appendix A gives the derivation of this relationship between detection time, false alarms, and detections.

Figure 19 shows the relationship for P_D and P_{FA} with respect to d. The curves change with . $= \infty$. This corresponds to the case where the receiver always decides no acceleration. $= 0$ corresponds to the case where the receiver always decides that acceleration is present. In this case the cost for a false alarm is about the same as the cost of a correct detection . This gives a around 1. This shows that as the time available to detect a deceleration ahead increases for constant noise and accelerations, the performance of the detector improves. A good rear-end collision detection system needs a low false alarm rate and a high probability of detection [64] This may require a d on the order of 4 or higher. For example if the maximum deceleration of the lead vehicle is 8 m/s^{2}and the noise deviation is 3-5 m/s for the sensor and controller noise then $t > 0.5$ s gives d=4. This means that we require at least a half second after the vehicle ahead has started braking to make a good decision. Note that the brake actuator delay (0.2-0.3 s) increases the total time delay to around 0.75 seconds before the RECW warns the driver of a potential collision.

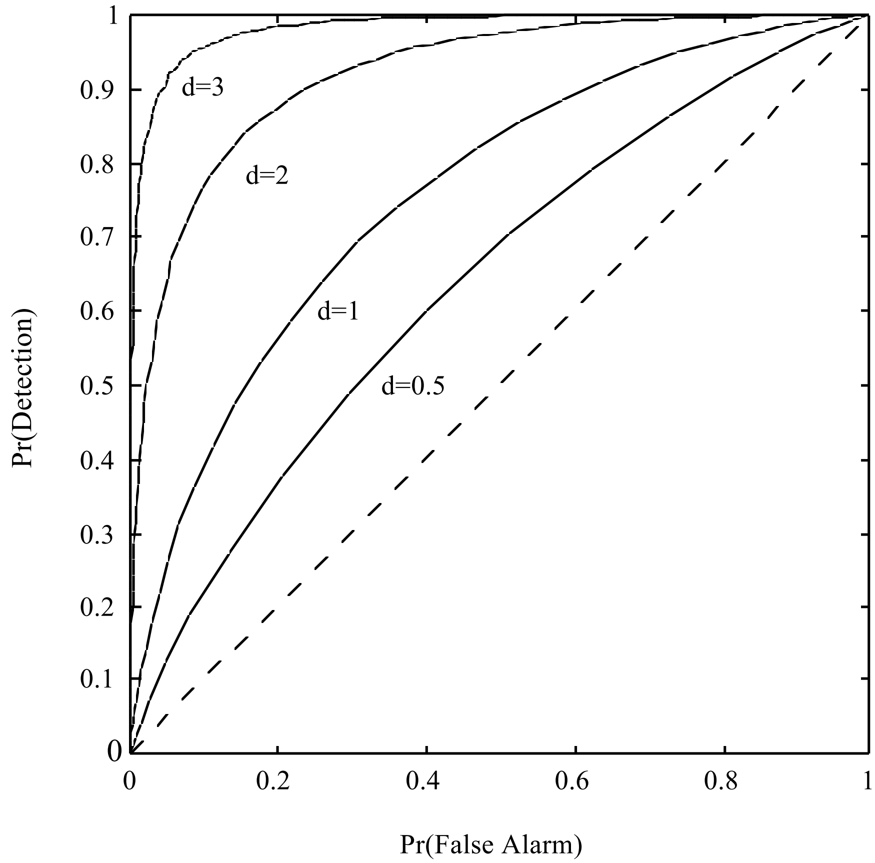


Figure 19. The probability of correctly deciding that the vehicle ahead is decelerating depends on the space between the two signals d. As d increases the detection-false alarm trade-off improves.

A vehicle-to-vehicle communication system sends braking data directly between vehicles. This lets the vehicle warn the driver quickly and reliably that an emergency is needed just as brake lights reduce human response times. The probability of false alarm is low. As the lead vehicle brakes it sends its brake data directly to the vehicle behind. This braking data only needs to say that the vehicle in front is braking hard. This communications system can have a very short delay on the order of 0.05 to 0.1 seconds.

Each vehicle sends its deceleration to the car behind it. This lets the car behind anticipate any braking before changes in the distance or velocity can be measured. This data may be in the form of brake line pressure or an accelerometer measurement. Studies by Ford and USC show that before skidding or for low line pressures brake line pressure is linearly proportional to brake force.[117]

$$F_b \approx P_b$$

The brake line pressure anticipates the actual deceleration. These measurements may be filtered to get a more accurate estimate of the deceleration. An accelerometer measures the actual deceleration of the vehicle. Vehicle-to-vehicle communications may also send data on the maximum braking capabilities of the target vehicle. This data could be computed from on-line tests or by the factory where the vehicle was built. Figure 20 shows how accident severity is affected by the deceleration capabilities of the vehicles.

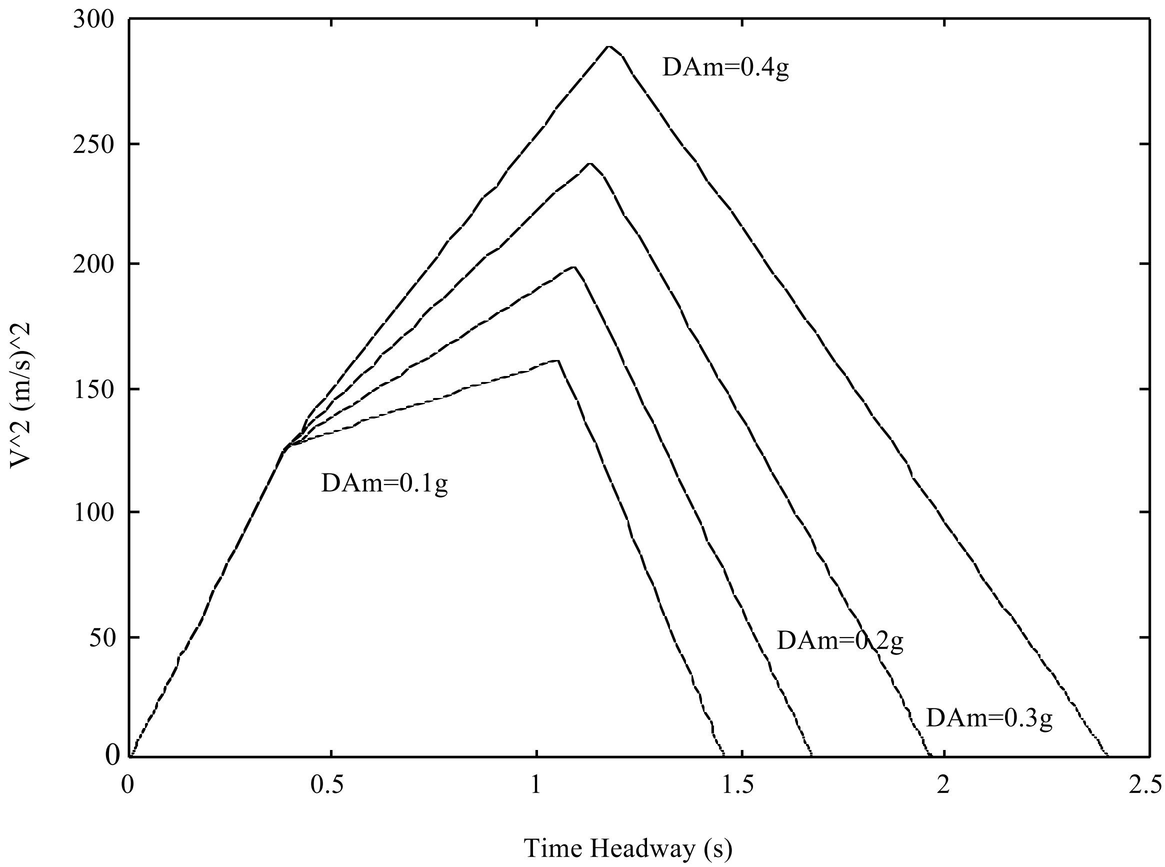


Figure 20. The deceleration difference between the vehicles Æ$A_m=A_{fm}-A_{lm}$ affects accident severity. As ÆA_m increases the potential accident severity increases.

Other forces that decelerate a vehicle are the aerodynamic drag coefficient, the friction between the car and the roadway, and the slope of the roadway. The aerodynamic drag stays constant over the life of the vehicle. It may be compensated for by calibrating each car model. The friction between the car and the road depends on the roadway, the tire condition, and the mass of the vehicle and passengers.[6] The road-tire friction coefficient may be estimated by measurements from an anti-lock braking system sensors .[39] This measurement coupled with an on-line estimate of the vehicle's maximum deceleration can give the vehicle's estimated braking capability.

The maximum deceleration for most passenger cars is around 0.9 g. This gives ten levels of quantization of braking data. This translates into 4 bits ($16=2^4$) of information. The maximum braking capability of the vehicle may also be encoded in a 4 bit field. This data may require on-line calibration to ensure that false braking signals are not sent out. The message between vehicles needs a length of around 50 bits in the worst case. This gives 16 bits for synchronization.[100] 8 bits each for the source and destination IDs if local addressing for a cell is used. The data field it 4 bits. 16 bits of error correction can help detect transmission errors.[100] If directional systems such as infrared (IR) or radio are used then the source and destination fields may not be necessary.[6]

The communications system must transmit over a range of at least 40 meters in a single lane. This allows the driver a 1.4 second reaction time to a rear-end collision warning at 60 mph. The signal delay is 0.05 seconds. The transmission rate is 20*M bits per second with a message length of M bits. The worst case transmission rate is 1000 bits per second. The transmission delays should be less than 20 ms since the brake data is time-critical. If the rear-end collision warning system decision time is 0.1 seconds, the rear-end collision warning system receives at least two messages before an emergency stop. The probability of message error (P_m) should be very low. Research at California PATH has produced IR systems that meet this data rate and accuracy requirement.[31] The tested system can transmit at 19.2 Kbits/second over a range of 30-40 meters.[31] As the distance between vehicles decreases the allowable data rate increases.

<u>Driver Interface</u>

The rear-end collision warning function provides levels of warning to the driver and provides a detector sensitivity adjustment for the driver. The different warning levels allow the vehicle to warn the driver without intrusive nuisance alarms. The detector sensitivity adjustment lets the driver adjust the range of the sensor to reduce sensitivity and false alarm rates.[64] Human factors studies show that there should be multiple levels of warning.[98] The severity and intensity of the warning depend on the immediacy of the threat. Lerner et al [64] suggest two levels of warning: cautionary and imminent. The warnings end when the driver takes action to end the threat.

The cautionary warning should be visual and located within 15-30° above the driver's line-of-sight for ordinary driving. [64] Visual signals are more detectable if they are near the center of the line-of-sight. The warning needs to give the driver informational feedback for headway maintenance.[37] A headway display could provide this type of feedback with a heads-up display.[116,83] This type of display could also assist the driver in selecting a safe headway.

The imminent rear-end collision warning should use two types of warnings. Lerner et al suggests a combination of auditory and visual warnings.[64] The auditory warning can attract the driver's attention if the visual warning is ignored. Other studies suggest that haptic warnings such as vibrations on the gas pedal or in the driver's seat may be effective for imminent collision warning.[105] However since ERSC 1 is designed to be "feet-off" during normal operations, haptic warnings may not be effective.

The rear-end collision warning system may have an adjustable threshold. This lets the driver reduce the sensor range to avoid excessive false alarms. For example, heavy traffic may cause the rear-end collision warning system to trigger frequently. Also the human reaction time of 1.5 s used for calculating the warning threshold is a worst case number. If a driver perceives himself as faster than average, then he/she may adjust the warning threshold at his own risk.

Issues and Risks

1 Sensor Capabilities

The RECW system may increase safety and reduce certain types of rear-end collisions by decreasing driver reaction time. But there are sensor and human factor issues that still must be resolved. The sensors must detect small vehicles or debris, such as motorcycles with few nuisance alarms. It will be very difficult for radar and ultrasonic sensors to decide if a motorcycle is present. A video system may be able to see small vehicles better during daylight. The video system sees what the driver sees so it may be more natural for human drivers to use. The performance of vision based systems may degrade at night and in rainy weather plus it is more expensive and complicated than radars of ultrasonic systems.

2 Warning system design

First the designers need to decide when the RECW function should be turned on: always on, only when the SHM function is on, or on only at higher speeds. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to get consistent and fast driver responses.

3 Multiple Warnings

ERSC 1 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

Blind Spot Warning

Most (95%) of lane change/merge crashes are angle or sideswipe collisions .[113] The driver of the merging car either did not see the other vehicle or misjudged the distance between the vehicles. These crashes usually happen in dry, clear, daylight conditions.[113] The driver “did not see” the other vehicles until too late. The blind spot or “lateral encroachment” warning system on the vehicle detects vehicles in adjacent lanes that are traveling in the same direction.[59] The blind spot detection warning system has a sensor and a system that warns the driver. Figure 21 shows a block diagram of the blind spot warning system.

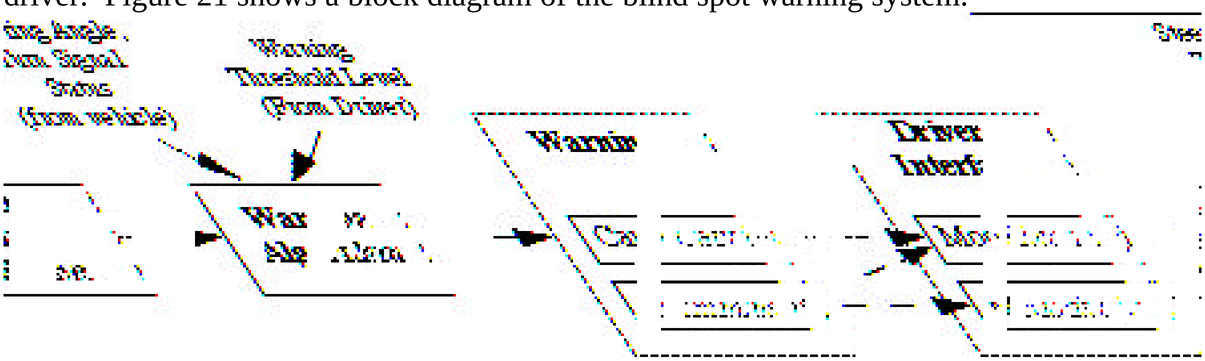


Figure 21. Block diagram for the blind spot warning system.

The blind spot warning system helps avoid "proximity" crashes in which the relative longitudinal locations and velocity differences between the vehicle and object are small.[21] This system

Table 10. Summary of requirements for blind spot warning system.

Requirement	Value	Background
Sensor Range	3-4 meters laterally 6-10 meters on side of vehicle	Sensors must cover both sides of the vehicle since accidents occurs equally on both sides of vehicle. Sensor looks for vehicle in blind spot.[64,21]
Obstacles detected	All types of motor vehicles	Sensor must detect small vehicles such as motorcycles and large vehicles such as trucks and buses.[64]
Cautionary Warning	0-15° from side mirror; visual warning	Warning must be non-intrusive; warnings should be near driver's primary line of sight [64]
Imminent Warning	Dual warning modes (Auditory and visual); >1.2 s before collision	Warning needs to give driver enough time to react to possible collision [64] Studies show that most(95%) drivers react within 1.2 s [21] for steering back into their lane

does not help with "fast approach" crashes. In this case there is a longitudinal gap between vehicles when the lane change begins and the relative velocity difference is large.[21]

Sensor

Since change/merge accidents occur with equal frequency on both sides of the vehicle there should be blind spot detection sensors on both sides of the vehicle.[64] Figure 22 shows the left-side blind spot for a vehicle. These sensors should increase safety as vehicles enter and exit the automated lane. The sensor needs to detect vehicles accurately with few unnecessary warnings or false alarms. Too many warnings will cause the driver to turn off the system or ignore its warnings.

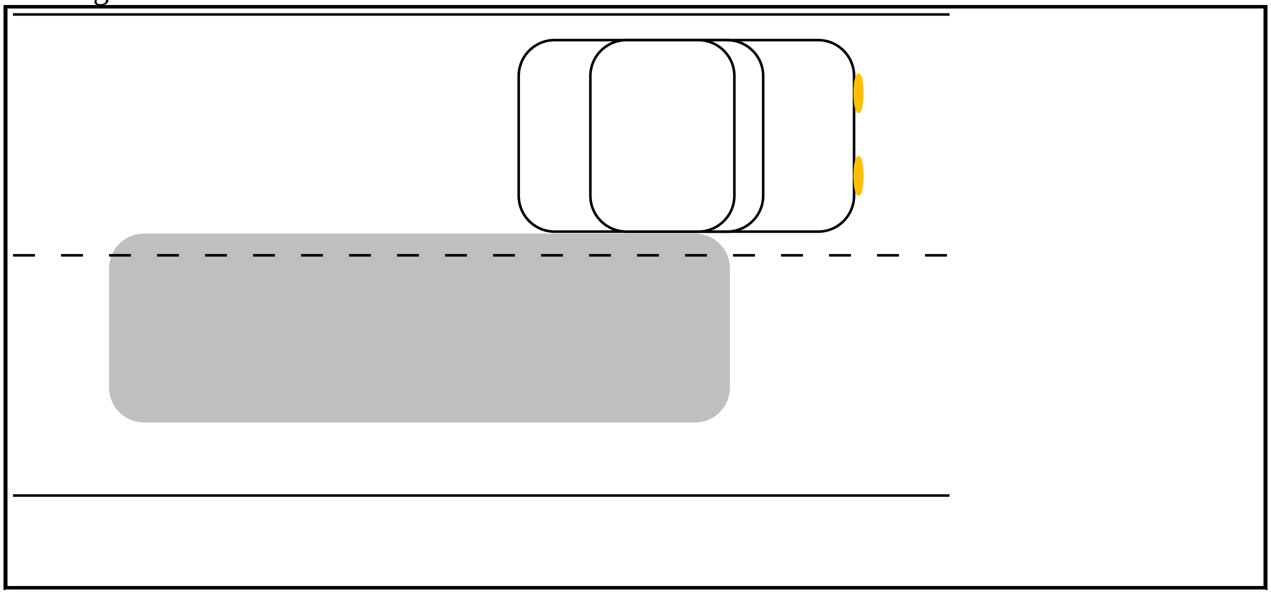


Figure 22. The shaded area shows the region of coverage for a blind spot sensor on the left side of the vehicle.

The blind spot detector should cover the adjacent lane to the side and behind the vehicle. This means a range of no more than 10-12 feet to the side and 20-30 feet rearward and along[64,21] the side of the vehicle. The size of the detection zone depends on the vehicle type and the size of its blind spot. The sensor should reliably detect small vehicles such as motorcycles in all likely lane positions.[64] The lateral detection zone comes from the standard highway lane width of 12 feet. If the lateral range is too large, the sensor could detect vehicles two lanes over leading to false alarms during lane changes.

Currently available blind spot sensor systems use ultrasound, radar and video systems.[76] Ultrasonic systems transmit ultrasound pulses to detect objects and measure their distance. Radar systems use frequency modulation and range-gating to find the range and relative velocity of objects. Video systems can show the driver a shot of the blind spot or they may add in computer vision technology to search for objects.

Ultrasonic sensors detect objects and their range with pulses of ultrasound. The sensor estimates the pulse time-of-flight. Sensor accuracy depends on local air properties, such as humidity and temperature. These sensors are short range (0.3-10 m) [76] with accurate range measurements.

Radar sensors measure the range and relative velocity of objects. The radar estimates the pulse time-of-flight with range gates that look for return pulses at different time ranges. Pulse doppler radars measure the relative velocity between vehicles. This lets the radar tell which vehicles are approaching and which are dropping back. Radar sensors have a longer range than do ultrasound sensors (15-45 m), but they are not as accurate. Extra range may not be good for the blind spot detection problem since the sensor may detect vehicles two lanes away and cause a nuisance alarm.

Video systems can show the driver an image of his/her blind spot. This system has no image processing that searches for vehicles. Newer systems use imaging devices mounted by the side view mirrors to track vehicles in the adjacent lanes. These systems use the continuity between image frames to track vehicles and estimate their distance.

Warning

The blind spot warning system may be active whenever the vehicle ignition is on and the vehicle is going forward.[64] This system may have many nuisance alarms caused by slow traffic or parked cars. Nuisance alarms occur when the sensor detects an object that is not there or an object more than one lane away. The system could also be active only if the driver indicates an intent to change course, such as with a turn signal. This system relies on the driver to signal lane changes. The blind spot warnings may also be triggered by a change in the vehicle's steering angle that signals a lane change. This warning would probably occur too late to avoid an accident.

The blind spot warning system should have at least two levels of warning: an imminent crash avoidance warning and a cautionary warning.[98,64] A cautionary warning tells the driver that there is a vehicle in the blind spot. This warning may operate when the vehicle is moving forward or only when the automated systems have been turned on by the driver. An imminent crash warning alerts the driver to an imminent crash avoidance situation that exists when an object is sensed in the blind spot and there is an indication that the vehicle's path may cause a collision with that object.(64) A turn signal or changes in the vehicle's steering angle can indicate a course change for the vehicle.

The imminent blind spot warnings should turn off when the hazard disappears or the driver responds to the warning. The cautionary warning stays on until there is no vehicle in the sensor field. The warning should give information on the location and speed of the threat without causing the driver to look away from the roadway. Directional audio systems can tell the driver the location of the threat.

The blind spot detector may turn on only when the driver turns on the turn signal to change lanes or it could be on the entire time the vehicle is in the automated lane. But if the blind spot sensor was on continuously, it would sound warnings every time the vehicle passed another vehicle. Another option is have the warnings sound only when the turn signal is on.

Driver Interface

The blind spot warning system provides levels of warning to the driver and provides a detector sensitivity adjustment for the driver. The different warning levels allow the vehicle to warn the driver without intrusive nuisance alarms. The detector sensitivity adjustment lets the driver adjust the range of the sensor to reduce sensitivity and false alarm rates.(64)

The cautionary warning should be visual and located within 15° above the line-of-sight of the side view mirror.(64) Visual signals are more detectable if they are near the center of the line-of-sight. Several of the commercial blind spot sensors mentioned in Najm use visual displays located by the side view mirror.(76) The imminent blind spot crash warning should use two types of warnings. Lerner et al suggests a combination of auditory and visual warnings.(64) The auditory warning can help the driver determine the direction of the imminent collision with a directional signal.

The blind spot warning system may have an adjustable threshold. This lets the driver reduce the sensor range to avoid excessive false alarms in which the driver perceives frequent hazards. For example, on multiple-lane highways the sensors may be triggered by objects across the adjacent lane or by vehicles two lanes away.

Issues and Risks

1 Sensor Capabilities

The blind spot sensor system may increase safety and reduce certain types of lane change/merge crashes. But there are sensor and human factor issues that still must be resolved. The sensors must detect small vehicles, such as motorcycles with few nuisance alarms. It will be very difficult for radar and ultrasonic sensors to decide if a motorcycle is present or if there is a large vehicle two lanes over. A video system may be able to track small vehicles better during daylight. The video system sees what the driver sees so it may be more natural for human drivers to use. The performance of vision based systems may degrade at night and in rainy weather plus it is more expensive and complicated than radars of ultrasonic systems.

2 Warning system design

First the designers need to decide when the system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to be directional to get fast driver response.

3 Multiple Warnings

ERSC 1 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

Driver Interface

The driver should be able to override the speed & headway maintenance function and adjust headway and set cruising speed as described in section 5 on the SHM function. The driver should also be able adjust the warning thresholds on the rear-end collision warning and the blind spot warning as described in the sections on the rear-end collision and blind spot warning functions. The driver also receives highway traffic information through the vehicle and may use it for speed/headway selection or route planning. The driver also monitors the vehicle's operational status and backs up failed vehicle functions. If the SHM system fails the driver takes over manual control of the vehicle in the fall-back mode.

The driver interface must show the driver that the automated functions are operating correctly or that the function has failed. This interface should be simple to understand and use. No adjustments should be required that take the driver's attention away from the driving task.

Head-up displays may be particularly useful for visual indicators of the system operation. For example a heads-up display could show the measured distance to the vehicle ahead as well as the minimum time headway and target speed. Other technologies include liquid crystal displays (LCDs), light-emitting diodes (LEDs), computer generated voice messages, sudden vehicle accelerations/decelerations (jerk), tactile feedback, and directional audio displays.[64,83,116]

The interface may be continuous or only active when a driver action is needed. The best design of the driver interface for human factors is an open issue and involves selecting a display technology, type and duration of warnings, user control types and locations, etc. User acceptance is crucial to user interface design.[54,67] The systems in each ERSC must be easy to use and understand and easy to adjust without the driver taking his eyes off the roadway for more than 2 seconds.[73]

Roadway/Vehicle Speed & Headway Commands

The roadway measures the average speed and traffic density, assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways. The vehicles should follow the target speeds using the speed and headway maintenance function. The vehicles should respond to headway recommendations for longer headways but not lower than those requested by the driver. The vehicles may also display relevant traffic information from the roadway to the driver for route planning purposes. This section covers roadway sensing systems, algorithms for smoothing traffic flow, and roadway to vehicle communications.

Roadway Sensing Systems

The roadway needs to sense the average traffic density and speed over sections of the roadway. This data can be measured by sensors that are part of the infrastructure or the vehicles can transmit their measured speed and headway to the roadway with a vehicle-roadway communication system. The vehicle may also transmit its operational status and identification to the roadway for check-in or incident management. The roadway also needs to measure roadway weather data to choose a safe target speed for the environmental conditions.[(57)]

Proximity sensors such as inductive loops count the number of vehicles that pass over them in a given time.[(112)] The data is collected over sections of roadway to monitor traffic flow.[(112)] The sensors can be hardwired to a roadway traffic control center or they can transmit their data electronically to the traffic control center. These sensors may require changes in the infrastructure and roadbed. These sensors have been in use on freeways for at least a decade and many urban areas already have them in place for traffic monitoring and incident management.[(112)]

Overhead infrared sensors have also been tested for traffic monitoring.[(80,48)] These sensors can measure vehicle speed, density, and vehicle type. This sensor type may allow the roadway to choose minimum headways based on the mix of vehicle capabilities. For example if there are many trucks in the dedicated lane at certain times of the day, then the roadway may lower the target speed and increase the minimum time headway.

The vehicle may send its current speed, headway to the roadway. This information could be used by the roadway to calculate average vehicle speeds and densities for traffic flow control. The vehicle may also communicate its operational status and identification to the roadway for check-in purposes or for incident management. Vehicles equipped with sensors for road-tire friction can report on road conditions on different sections of roadway. Types of communication systems are discussed later in this section.

The condition of the roadway surface also affects the safe headway in between vehicles. Figure 23 shows the time headway for different road-tire friction coefficients. Weather conditions can affect the friction coefficient.[(5)] If the follower vehicle decelerates slower than the vehicle in front then the minimum time headway increases. This figure assumes that both vehicles are on the same surface, for example it's raining and the roadway is equally wet for both vehicles. Localized patches of ice or puddles can cause large changes in the friction coefficient. This leads to fast changes in ÆA_m and the minimum time headway.

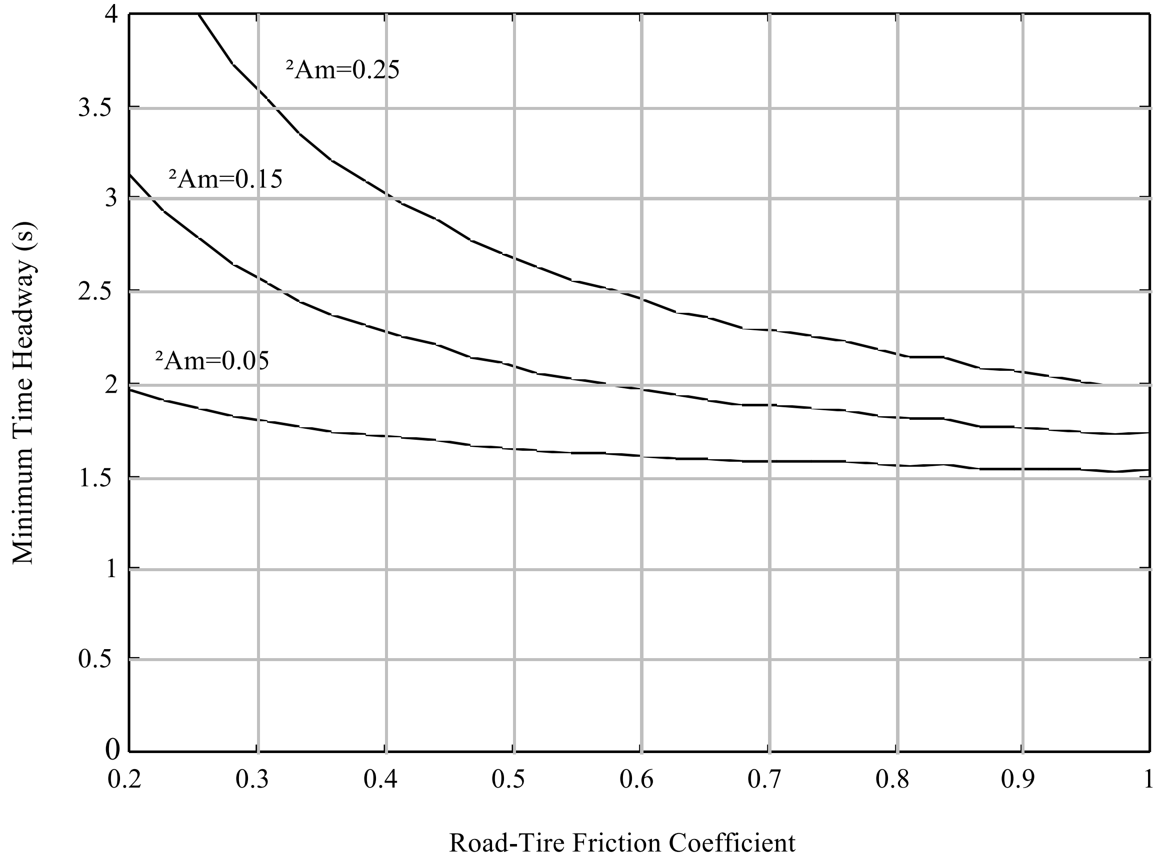


Figure 23. As the road-tire friction coefficient decreases (the road gets more slippery), the minimum safe time headway increases. Æ$A_m = A_{lm} - A_{fm}$ is the deceleration difference between the vehicles. A positive value means that the lead car has a larger deceleration than the follower vehicle.

Roadway weather conditions can give large changes in time headway. This may require roadway weather information systems (RWIS) that measure and estimate quantities such as water on the roadway, the possibility of ice patches, and snow.(57) The roadway may send this weather data to the drivers to help them choose a safe headway for the conditions. The RWIS described by Kelley only measures weather data at or near the sensor location. The system then interpolates conditions between sensors.

Roadway Traffic Control Algorithms

The roadway can increase the average velocity of the vehicles in an automated lane by smoothing traffic flow.(10,19) The roadway receives traffic flow data from sections of roadway in the form of speed and headway data. The roadway then sends target velocities to the vehicles in the automated lane. This lets the roadway compensate for variations in the traffic flow due to accidents or heavy traffic. Smoother flow can increase the traffic flow rate. The roadway also sends minimum time headways to the vehicles based on environmental conditions and vehicle capabilities. Constant velocity adjustments for each section would soon tire the driver. This means that the roadway must be able to set the speed of each vehicle in a section automatically with an electronic message. If the roadway sends automatic commands to the vehicle then vehicle compliance and overall roadway performance improves.

Traffic control experiments have been performed as part of the Prometheus project in Europe.[10] The traffic flow harmonization project in Gothenburg equipped a 3.5 km stretch of highway with short-range VRC beacons. These beacons transmitted data on speed limits, the status of traffic signals, and data on green lights. The vehicles could be operated in manual and automatic modes. The Aspen track project instrumented a 35 km long track of rural roads and motorways with short-range VRC beacons. The beacons transmitted data on speed limits, road curvature, recommended speeds on curves, and warnings for school areas and pedestrian crossings. Driver reaction to these systems was positive and vehicle safety was improved.

Other work by Chien et al “homogenizes” or smoothes traffic flow along a stretch of roadway.[19] The roadway measures the average speed and traffic density along each segment of the roadway. The roadway sends velocity commands to the vehicles on each section. This controller tries to keep traffic flow uniform over a length of roadway. This system can improve the average traffic flow rate along the highway and the traffic flow returns to a uniform density faster with control than without it. This type of roadway controller can give large benefits in terms of flow rates with very low technical risk and effort.

Vehicle to Roadway (VRC) Communications

The roadway sends speed data to the cars to smooth the traffic density. The vehicles may also send their measured velocity and headway to the roadway. This system may also be used for check-in. This allows the roadway to monitor the operational status of the vehicles and ensure that they are correctly operating in the automatic mode. These messages only need to be sent once per section.

VRC systems can be mounted on the side of the roadway, on overpasses, or embedded in the roadway .[85] These systems may use automated toll collection technology with variable registers or a system that covers a wider range.[22,53] Appendix A covers the operation of these systems. One-way systems from the roadway to vehicles include using subcarriers on existing FM or TV station signals to send data to vehicles .[16,33]

This message does not need a high data rate since it will not change very often. Each field will need 6-8 bits to give a resolution of 1 meter for the gap limit and 1 mile per hour for the velocity limit. Since the message goes to all cars a destination ID code is not needed. The source ID code indicates that the message is from the roadway. Error detection coding looks for bit errors in the message. Retransmission requests are unnecessary since we can rely on repeating the message. This message should be repeated at most one time per second. The bit error rate can also be high since the message changes slowly and rarely. Repetition of messages can compensate for the high error rate.

The VRC may also send messages from the vehicles to the roadway. Each vehicle sends its speed and the distance to the preceding vehicle (6-8 bits each) The vehicles may also send a unique identifying code (28 bits) to the roadway for check-in. The operational status of the automated system can be sent as well, this could take 8-16 bits depending on the amount of detail required by the roadway. Other variables such as estimates of the road-tire friction coefficient can take 4 or more bits. This gives a data length of around 70 bits.

A broadcast system with a range of 100 meters for a single automated lane needs to communicate with 0.3 to 0.75 vehicles per second. Analysis by Polydoros et al shows that the current Hughes VRC system and automatic toll collection systems can meet the data transmission requirements for VRC in ERSC 1.(85) This system scales up to the next ERSC that requires two way VRC for check-in and traffic management.

Issues and Risks

1 Dedicated Lane
An important issue for AHS is how to get a separate lane for automated vehicles. The driving public rebels when a lane is taken away from active use.(99) The solution for most highway departments has been to add a new lane on the shoulder or median strip, but most urban highways do not have any more space to spare for the sole use of automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

2 Legal/Liability
In this ERSC the roadway sends recommended target speeds directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the vehicles are going too fast. The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

3 Sensors
Roadway weather sensors only cover small regions of roadway. These sensors could easily miss patches of ice or puddles on the roadway. The roadway may recommend a headway that is not large enough. Research needs to continue into these sensors to improve their capabilities.

4 Privacy
This ERSC gives the vehicles the option to “Check-in” with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

5 Communication Protocols
The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

Fall-back Mode

In case of failures in the SHM or the RECW functions, the vehicle returns to manual brake and throttle control. The driver is responsible for the vehicle’s operation and for driving it out of the dedicated lane. It may be possible to continue operations in the dedicated lane if the RECW fails. The vehicle need only fall back to a larger headway since human drivers may have a longer reaction time without a warning system. However this option may cause “role confusion” and slow driver response if the driver is used to waiting for a warning before braking.(90)

If the blind spot warning system fails, the vehicle informs the driver and continues operations in the dedicated lane. Failure of this function does not impact the vehicle’s normal operations in the dedicated lane. The driver is still responsible for making lane changes into and out of the dedicated lane. The announcement of warning system failure may be repeated when the driver prepares to exit the dedicated lane to remind him/her to look in the blind spot.

Reliability Requirement Analysis

In ERSC 1, the automation technologies used in the AHS are mainly in the longitudinal control. The vehicle can perform speed and headway maintenance (SHM) using throttle and brake control. Automatic throttle control and brake control are limited within certain ranges so that the vehicle acceleration and deceleration will not cause driver discomfort. The driver is responsible for supervising the operation of the on-board SHM system and overriding it during emergencies. In particular, the driver is responsible for the rear-end collision avoidance. The driver performs the rear-end collision avoidance by applying hard braking to override the SHM system and/or steering maneuver. The driver’s rear-end collision avoidance function is assisted by the vehicle’s rear-end collision warning (RECW) system. The RECW system can receive braking data from the preceding vehicle to improve its detection accuracy.

The roadway sends target speed commands and time headway recommendations to improve the efficiency of the dedicated lane and the safety of vehicle following operation. The roadway calculates the target speeds and desired headways along sections of the dedicated lane according to the traffic and environmental conditions. The SHM system responds to the roadway target speed commands smoothly as long as the headway is larger than the one set by the driver. The RECW system responds to the roadway headway recommendations by adjusting the warning threshold setting. The safety of the longitudinal control depends on the reliability of the roadway speed/headway commands, the on-board SHM and RECW system, and the driver.

The driver is responsible for all vehicle lateral control functions. The driver is assisted by the on-board blind spot warning (BSW) system for lane changing and merging maneuvers during entry/exit of the dedicated lane. The BSW system gives warnings to the driver if a vehicle in the blind zone is detected. Once in the dedicated lane, the driver is fully responsible for steering to keep the vehicle in the lane. The driver’s reliability determines the safety of the vehicle lateral control.

Speed and Headway Maintenance

In ERSC 1, the on-board speed and headway maintenance (SHM) system assists the driver in vehicle longitudinal control. It maintains the speed and/or time headway chosen by the driver. The SHM system responses to the roadway target speed command if the resulting headway is not smaller than the one selected by the driver. The SHM system controls the throttle and brake. For the concern of riding comfort, only soft braking is applied by the SHM system. The driver can override the SHM system by pressing the throttle or brake pedal. Figure 24 shows a functional block diagram of the SHM system and its interface with the driver and roadway.

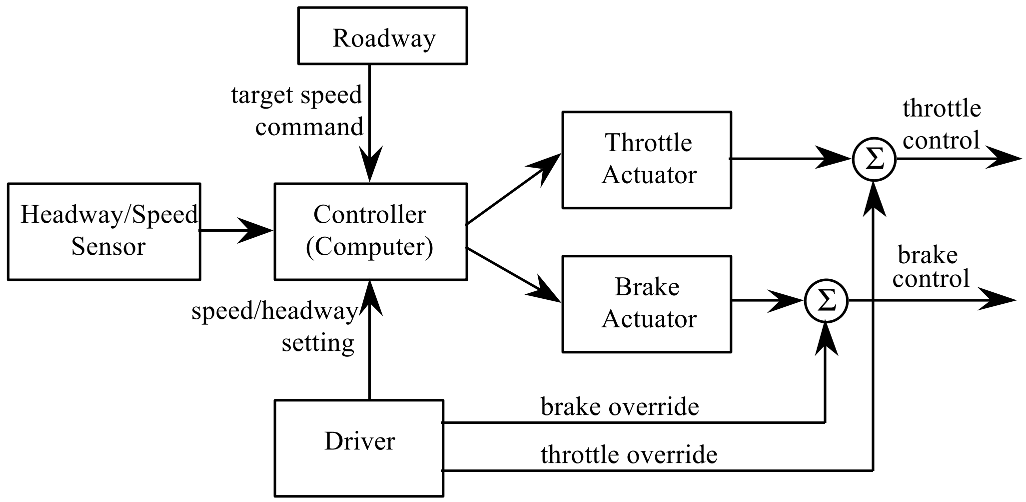


Figure 24. The functional block diagram of the SHM system.

The SHM system is composed of a headway/speed sensor, a controller (computer with control algorithms), a throttle actuator and a brake actuator. The headway/speed sensor measures the headway and the relative speed with respect to the preceding vehicle. The controller receives the speed/headway settings from the driver. The controller uses the data from the headway/speed sensor to generate throttle and brake commands for safe cruising or vehicle following. The controller can also smoothly respond to the roadway's target speed command when the vehicle has a headway larger than the one set by the driver. The throttle actuator takes the controller's throttle command to produce the desired throttle angle. The brake actuator uses the controller's brake command to generate the required force.

Safe longitudinal control depends on both the SHM system reliability and the driver's performance during emergencies. A rear-end collision may happen if the driver can not react to the danger such as abrupt braking by the preceding vehicle or a stationary vehicle in the lane. In addition, a SHM system failure may lead to a rear-end collision if the driver can not recover vehicle control in time. Drivers in the United States average a rear-end collision about every 50 years .[27] The SHM system needs to be designed in such a way that the operation of the combined SHM-driver system improves the manual driving safety standard significantly.

Reliability Requirement Estimation

Using the techniques developed in reliability engineering[11,65], one can estimate the required reliability of the SHM system, based on the safety standard in today's manual driving. Under normal operating conditions, the SHM-driver system can operate without rear end collisions if (1) the SHM system operates without failures; or (2) the SHM system fails but the driver successfully takes over the longitudinal control from the SHM system. Since the drivers are always responsible for supervising the vehicle's longitudinal control even when the SHM system is operational, one can consider the SHM-driver system as an active parallel system in the reliability analysis. In terms of reliability block diagram, the SHM-driver system can be represented by the parallel connected system as shown in figure 25.

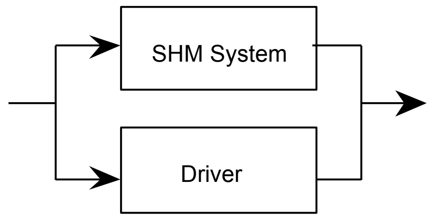


Figure 25. The reliability functional block diagram of the SHM-driver system.

It is reasonable to assume that the driver failure and SHM failure are two independent events. To simplify the analysis, we characterize the reliability properties of SHM system and driver with constant failure rate models. In this case, if we denote λ_S, $R_S(t)$, $MTTF_S$, λ_D, $R_D(t)$ and $MTTF_D$ as the failure rate, reliability function and mean time to failure of the SHM system and the driver respectively, we have

$$R_S(t) = e^{-\lambda_S t}, \quad R_D(t) = e^{-\lambda_D t}$$

and

$$MTTF_S = \frac{1}{\lambda_S}, \quad MTTF_D = \frac{1}{\lambda_D}$$

Using the reliability model in figure 25, we obtain the reliability function for the SHM-driver system

$$R_{SD}(t) = e^{-\lambda_S t} + e^{-\lambda_D t} - e^{-(\lambda_S + \lambda_D)t}$$

The mean time to failure for the SHM-driver system is

$$MTTF_{SD} = \frac{1}{\lambda_S} + \frac{1}{\lambda_D} - \frac{1}{\lambda_S + \lambda_D}$$

With the requirement that $MTTF_{SD}$ be much greater than 50 years, the above equation can be used to analyze the required SHM system failure rate λ_S.

Suppose that the driver's reliability in longitudinal control is not degraded while he/she is interfacing with the SHM system, i.e., we have $MTTF_D$ = 50 years and λ_D = 0.02 year^{-1}. Since

$$MTTF_{SD} - 50 = \frac{0.02}{\lambda_S(\lambda_S + 0.02)} > 0$$

we see that the reliability of SHM always produces a net improvement in the reliability of the overall SHM-driver system, if the driver's reliability is not degraded.

The SHM system is not available to the general public and experimental data about human factors in SHM-driver operation is limited. It is not clear that how the SHM system affects the driver's reliability. For drivers who are suspicious about the SHM system's reliability, they will tend to be more alert. These drivers will have higher reliability than the average in the SHM-driver operation. However, it is possible that some drivers are confident with the SHM system and become over reliant on the system. In this case, it is likely that driver's reliability will be degraded while interfacing with the SHM system.

For safety consideration, it is necessary to analyze how the driver's reliability degradation affects the reliability requirements of the SHM system. The case that the driver has a higher failure rate (or shorter mean time to failure) while interfacing with the SHM system should be considered. We require that

$$MTTF_{SD} > MTTF_a$$

where $MTTF_a$ >> 50 years. This requirement implies

$$\frac{{}_D^2 + {}_S({}_S + {}_D)}{{}_D\;{}_S({}_S + {}_D)} > MTTF_a$$

The above relationship allows one to evaluate the required SHM system reliability as a function of the driver's reliability. For a given driver's degraded reliability (with the value of failure rate λ_D), the SHM system is required to have reliability with λ_s stays below the curves in figure 26. The three curves are generated based on the assumption that the SHM systems average one hour operation daily and that the public will demand the SHM-driver system to be one, two or three times reliable as today's manual longitudinal control. These curves are plotted with the driver's reliability degradation up to 50%.

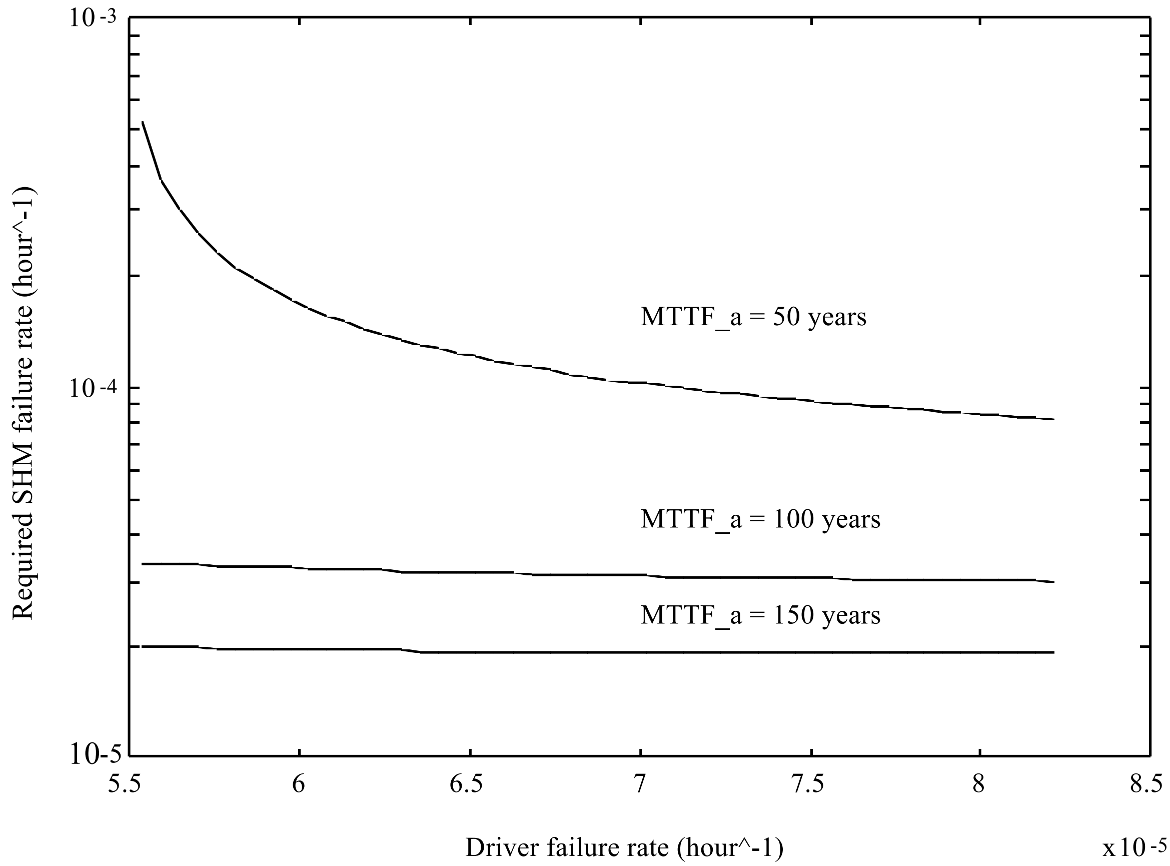


Figure 26. The required SHM system failure rates very as the driver's reliability degrades.

Reliability Functional Requirement

The SHM system is not designed for longitudinal collision avoidance. In ERSC 1, the driver has to be hands on the steering wheel for lateral control, monitor surrounding traffic, and supervise the operation of the SHM system. The driver has to take over longitudinal control during emergencies. Depending on the design, the SHM system may be disengaged temporarily or totally disabled when the driver's override takes place. The driver is essentially still driving the vehicle, and can be considered as a back-up to the SHM system during emergencies. Safe longitudinal control can be achieved by improving the man-machine interface between the driver and the SHM system. When the driver overrides the SHM system by pressing the throttle pedal to accelerate, the SHM system has to deactivate the brake control during the time interval in which the override takes place. When the driver presses the brake pedal, it is potentially an emergency. In this case, it is desirable to deactivate both throttle and brake control.

Since the driver is the ultimate back-up in the longitudinal control, it is imperative that the driver can always override the SHM system successfully when he/she does it. The vehicle can use redundant methods to guarantee safe transition of longitudinal control from the SHM system to the driver. To further ensure safety the redundant methods should be independent. This requirement can significantly reduce the probability of simultaneous failures in both methods caused by a single component/point failure. With the above discussion, it is reasonable to conclude that the essential reliability functional requirement for the SHM system design is:

"The SHM system should provide redundant, independent means to return the vehicle longitudinal control to the driver when he/she overrides the SHM system."

System Level Design Requirements

The above requirement can be fulfilled by implementing two independent, redundant methods (e.g., hardware and software based) to detect the driver's override action and to deactivate the throttle/brake actuators. It does not impose any requirement of major components (sensor, controller, and actuators) redundancy in the design of the SHM system.

Detailed design requirements for the SHM system can be obtained by exercising the failure mode and effects analysis (FMEA) Without doing the complete FMEA, one can still come up with important system level design requirements by simply examining the potential system level failure modes from the system functional block diagram figure 24 These potential major failure modes include

1. Headway/speed sensor failure
2. Controller failure
3. Actuator failure
4. Improper response to driver's override
5. Roadway interface failure

The SHM system should minimize the probability of above failure modes to ensure the fail-safe operation. If a potential failure is detected, the SHM system should be disabled and the driver should be notified to regain control. Some important system level design requirements can be derived by analyzing the above listed potential failure modes.

Potential Failure Mode 1: Headway/Speed Sensor failure

1.1 Headway/Speed Sensor computes incorrect headway or closing rate data.
Design requirements:

1.1.1 Headway/Speed Sensor needs to have an internal independent check of the reasonableness of the computed headway and closing rate data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response disables the SHM system and warns the driver to take over longitudinal control.

1.1.2 Controller should incorporate an independent check of the reasonableness of the computed data from Headway/Speed Sensor, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.2 Data from Headway/Speed Sensor is not communicated to Controller, or is corrupted in transmission through interface.
Design requirements:

1.2.1 Controller should verify that Headway/Speed Sensors are operating in a timely manner by verifying that new data is received from Headway/Speed Sensors every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

Potential Failure Mode 2: Controller failure

2.1 Controller computes incorrect throttle or brake command.
Design requirements:

2.1.1 Controller should incorporate an independent check of the reasonableness of the computed throttle/brake command before it is sent to the throttle/brake actuator, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.2 Throttle Actuator and Brake Actuator should incorporate an independent check of the reasonableness of the throttle/brake command computed by Controller, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.3 Controller should incorporate circuitry, such as a watchdog timer, to detect failure and to ensure the processor functions in a timely manner. If a failure is detected, the circuitry should deactivate Controller, and the System Failure Response should be executed.

2.2 Controller's command is not communicated to Throttle/Brake Actuator at appropriate time or is corrupted in transmission through interface.
Design requirements:

2.2.1 Throttle/Brake Actuator should verify that it is receiving updated command from Controller in a timely manner. If an error is detected, the System Failure Response should then be executed.

Potential Failure Mode 3: Actuator failure

3.1 Brake Actuator does not generate correct brake force for the given brake commands.
Design requirements:

3.1.1 Brake Actuator should incorporate built in tests to be performed on the vehicle startup and during headway maintenance operation to verify that brake force can be produced and is within the allowable range. If an error is detected, the System Failure Response should be executed.

3.2 Throttle Actuator produces incorrect throttle angle.

Design requirements:

3.2.1 Throttle Actuator should incorporate built in tests to be performed on the vehicle startup and during headway maintenance operation to verify that throttle angle can be produced and is within the allowable range. If an error is detected, the System Failure response should be executed.

Potential Failure Mode 4: Improper response to driver's override

4.1 Brake Actuator is not disengaged temporarily in response to the movement of the accelerator pedal by the driver.
Design requirements:

4.1.1 The SHM system should incorporate independent, redundant devices for detecting the driver's pressing of the accelerator pedal and means to detect failure of these detection devices.

4.1.2 The SHM system should provide for independent, redundant means to deactivate Brake Actuator.

4.2 Controller and Throttle/Brake Actuators are not disabled (or disengaged temporarily) when the driver presses the brake pedal.
Design requirements:

4.2.1 The SHM system should incorporate independent, redundant devices for detecting the driver's pressing of the brake pedal and means to detect failure of these detection devices.

4.2.2 The SHM system should provide for independent, redundant means to deactivate Throttle Actuator.

4.2.3 The SHM system should provide for independent, redundant means to deactivate Brake Actuator.

Potential Failure Mode 5: Roadway Interface failure

5.1 The target speed commands are not received by the SHM system or are corrupted in transmission.
Design requirements:

5.1.1 The SHM system needs to verify that the target speed commands are received in a timely manner. If an error is detected, the SHM system should warn the driver of the missing speed commands and smoothly switch the operation to the desired speed set by the driver.

5.1.2 The SHM system should incorporate an independent check of the reasonableness of the message received from the roadway, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the SHM system should warn the driver of the error, and smoothly switch the operation to the desired speed set by the driver.

Key findings:

1. The driver can be regarded as a back-up to the SHM system.

2. The reliability functional requirement for the SHM system is to reliably return the control to the driver when the driver overrides the SHM system.

Issues and Risks:

1. The driver may become over-reliant on the SHM system and degrade his/her reliability/performance during emergencies.

2. The vehicle's automatic response to the roadway's target speed command imposes safety concerns in ERSC1. For example, the SHM system headway/speed sensor fails while the controller is responding to a target speed command by accelerating the vehicle. In this case, the driver may perceive that the SHM system is properly following the roadway's command and fails to sense a rear-end collision danger. The driver's reliability as a back-up to the SHM system may be seriously degraded since the SHM operation puts the driver into a situation that he/she can not handle safely. This potential failure mode has serious reliability implications.

3. If the driver can not be regarded as a back-up to the SHM system, a fail-safe SHM system design will require considerable amount of redundant components. This will increase the cost and difficulties in deploying the SHM system in ERSC 1.

4. The above safety concerns can be relieved if we do not allow the vehicle to respond to the roadway's speed commands automatically. In this case, the driver can take the target speed commands from the roadway and input it to the SHM system. However, the effectiveness of the roadway traffic flow control will be much affected since the driver may not always adjust the speed exactly the same way as the roadway demands.

Rear-End Collision Warning

The rear-end collision warning (RECW) system improves the safety of vehicle longitudinal control by warning the driver of potential rear-end collisions. The RECW system measures the vehicle's and the lead vehicle's dynamics including headway, velocities, braking actions and braking capabilities. It uses these data to evaluate the time to collision (TTC). If the computed TTC is larger than the time headway, the RECW system sends warning to the driver. The driver reacts to the warning by overriding the SHM system to avoid rear-end collisions. The vehicle's braking capabilities depend on the road-tire friction that is affected significantly by the road surface condition. The roadway senses the road surface condition to estimate a headway for collision free vehicle following. The RECW system adopts the headway recommended by the roadway as TTC if it is longer than the existing TTC computed by the RECA system. Figure 27 shows the interaction between the RECW system and the driver.

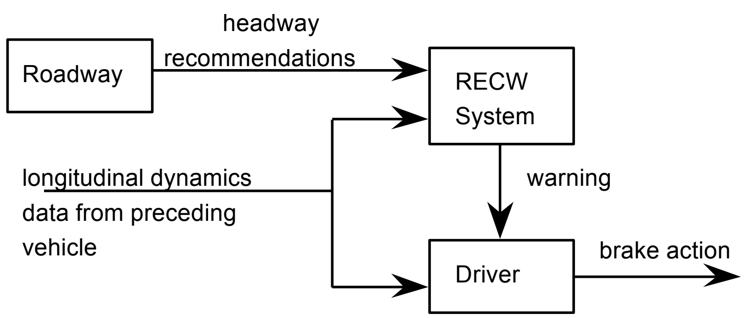


Figure 27. The functional block diagram of the RECW system.

The RECW system uses a headway/speed sensor and vehicle-to-vehicle communication to collect the dynamic data required for computing TTC. The headway and closing rate data measured by the headway/speed sensor is essential for the RECW system operation. A malfunction in the headway/speed sensor will result in the RECW system failure and cause non-detections or false alarms. The brake data provided by vehicle-to-vehicle communication can be used to improved the accuracy of the predicted TTC. The RECW system degrades its reliability, i.e., may have lower detection rates and higher false alarm rates, if the processor does not correctly receive the preceding vehicle's brake data from the vehicle-to-vehicle communication. Incorrect headway recommendations received from the roadway will result in improper TTC. This will also cause non-detections or false alarms.

Warning Levels

It has been recommended that at least two levels of warnings be used in the RECW system,[64,34] an imminent collision warning and a cautionary collision warning. The imminent collision warning informs the driver that it is necessary to take evasive action to avoid rear-end collision. If the imminent collision warning can not be sensed by the driver promptly, the driver may not be able to react to the danger in time. The RECW system is therefore required to provide redundant imminent collision warnings. Since the driver may become less attentive to a specific type of signals, it is desirable that the redundant imminent collision warning signals be different in modality, e.g., visual and audio.

Reliability Functional Requirement

The RECW system is not designed to replace part of the driver's longitudinal control function. It is to increase safety by effectively alerting the driver when there is a rear-end collision danger. The effectiveness of the RECW system is affected by many factors including the detection rates, the false/nuisance alarm rates, types of warning signals, and the driver's reaction to different warning signals, etc.

In ERSC 1, the driver is interfacing with SHM and RECW systems for longitudinal control. The driver is feet-off the throttle and brake pedals except during emergencies. It is possible that some drivers become over relaxed and rely on the RECW system for sensing the rear-end collision danger. For these drivers, high detection rates of the RECW system will be vital and a non-detection may contribute to a rear-end collision. The design of the RECW system thus is required to minimize the possibility of non-detection.

Nuisance alarms may irritate the driver. By allowing the driver to adjust the warning sensitivity within a limited range, the RECW system can reduce its nuisance alarm rates and still accommodate the driver's skill. False alarms can be caused by noise, environmental conditions, internal system malfunctions, etc. Frequent false alarms may be disturbing to the driver, and delay his/her reaction to the danger. The driver may even reject the false alarms by turning off the RECW system. A sudden false imminent collision warning may make the driver panic and even endanger his/her vehicle control.

The above discussion suggests that the reliability functional requirement for the RECW system be:

"The RECW system should have high detection rates and low false alarm rates."

<u>System Level Design Requirements</u>
To achieve this requirement, the RECW system needs to have self-diagnostic element to detect potential internal failures. If a failure is detected, the driver should be notified and the RECW system may have to be deactivated. More specific system level design requirements can be identified by analyzing major potential failure modes and causes based on the system framework shown in figure 28.

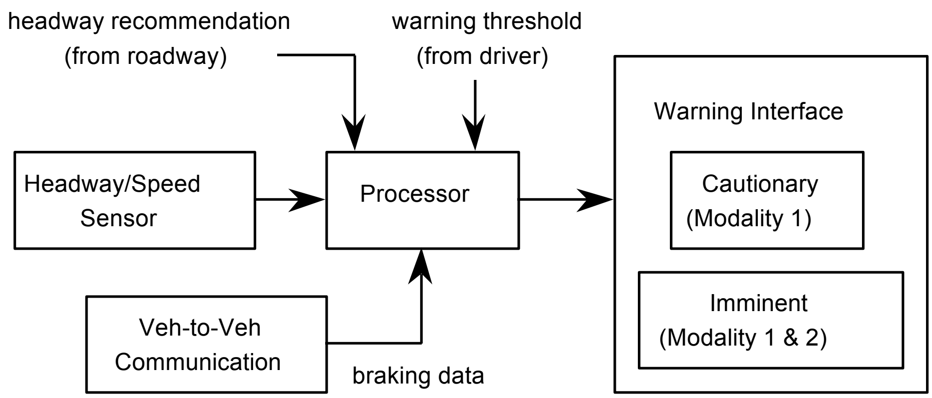


Figure 28. The RECW system framework for reliability design.

Potential Failure Mode 1: Headway/Speed Sensor failure

1.1 Headway/Speed Sensor computes incorrect headway or closing rate data.
Design requirements:

1.1.1 Headway/Speed Sensor needs to have an internal independent check of the reasonableness of the computed headway and closing rate data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response warns the driver of the potential failure and asks him/her to turn off the RECW system.

1.1.2 Processor should incorporate an independent check of the reasonableness of the computed data from Headway/Speed Sensor, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.2 Data from Headway/Speed Sensor is not communicated to Processor, or is corrupted in transmission through interface.
Design requirements:

1.2.1 Processor should verify that Headway/Speed Sensor is operating in a timely manner by verifying that new data is received from Headway Sensor/Speed every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

1.2.2 Same as for 1.1.2.

Potential Failure Mode 2: Braking data reception failure

2.1 Braking data of the preceding vehicle is not communicated to Processor, or is corrupted during transmission.
Design requirements:

2.1.1 Processor should verify that it is receiving preceding vehicle's braking data in a timely manner by verifying that new data is received every tbd time interval. If an error is detected, Processor should notify the driver of the failure and take it into account to modify the estimation of TTC.

Potential Failure Mode 3: Processor failure

3.1 Processor computes incorrect time to collision.
Design requirements:

3.1.1 Processor should incorporate an independent check of the reasonableness of the computed time to collision, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

3.2 Processor command is not communicated to Warning Interface at appropriate time or is corrupted in transmission through interface with Processor.
Design requirements:

3.2.1 Warning Interface should verify that it is receiving updated command from Processor in a timely manner. If an error is detected, the System Failure Response should then be executed.

Potential Failure Mode 4: Warning Interface failure

4.1 Warning Interface fails to give warnings or generate incorrect level/modality of warnings, after receiving a warning command from Processor.
Design requirements:

4.1.1 Warning Interface should incorporate built in tests to be performed on the vehicle startup and during headway maintenance operation to verify that proper warning signals can be generated. If an error is detected, the System Failure Response should be executed.

Key findings

1. Two levels of warning may be required. Imminent collision warning may require redundancy with different warning modalities.

2. The reliability functional requirements for the RECW system are high detection rates and low false alarm rates.

Issues and Risks

1. The driver may become over-reliant on the RECW system and degrade his/her reliability/performance in rear-end collision avoidance.

2. The driver may experience warning overload and warning confusion problems while interfacing with other vehicle and roadway functions.

Blind Spot Warning

The blind spot warning (BSW) system helps the driver change lanes or merge safely. It helps the driver detect other vehicles in the blind spots on both sides of the vehicle. The BSW system gives the driver a warning if a vehicle in the blind zone is detected. Figure 29 shows the BSW system interfacing with the driver.

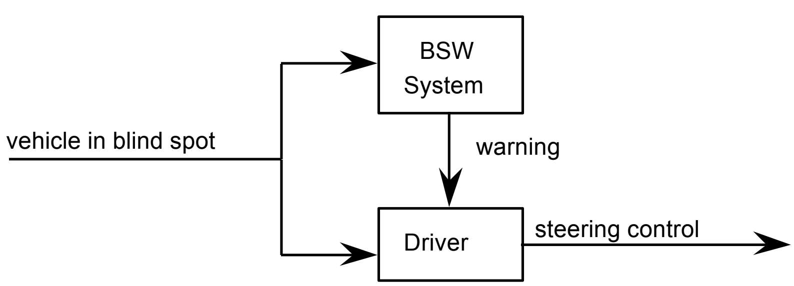


Figure 29. The functional block diagram of the BSW system.

The BSW system will be most effective if the warning is sent before the vehicle's lane changing motion starts. In this case, the driver will probably cancel or delay his plan of change lanes. However, it is possible that other vehicles may suddenly move into the blind spot after the driver has started turning the steering wheel. In this case, even if the BSW system sends out the warning in time, the driver may not have enough time to react to the danger. The BSW system is not designed to replace the driver's detection function in lane changes or merges. It is mainly to improve the driver's reliability.

Warning Signals

It is suggested that at least two levels of warning be provided in the BSW system, i.e., imminent collision warning and cautionary collision warning .[98,64] To ensure that the imminent collision warning can always be perceived by the driver, it should contain redundant signals with different modalities such as auditory and visual.

The warning signal generated by the BSW system needs to be distinct from those by other function so that the probability of driver confusion is minimized. It is also important that the driver can always perceive the warning message as soon as it is sent out by the BSW system. Visual or audio warnings can be used to warn the driver. If visual warning is used, it needs to be able to guide the driver's attention to the danger in blind spot. "Sound icons" may provide effective audio warnings.[105] It simulates the sounds that might be heard in real life. With sound icons, the BSW system can sound a horn from the rear right/left hand side of the vehicle.

Reliability Functional Requirements

In ERSC 1, the driver is still in charge of the entire lane change and merge process. As shown in figure 29, the BSW system senses the traffic in blind spot and processes the data to determine if a warning should be delivered to the driver. Since the BSW system does not take over control from the driver, a BSW system failure is not likely to cause immediate catastrophe. However, the safety in changing lanes and merging can be improved by well-designed man-machine interface. The BSW system should sense the object in the blind spot, deliver a timely warning, and use effective warning signals. Design of reliable BSW systems should be focused on both the component/hardware reliability and the human factors engineering.

The BSW system should not deliver warnings not too often so that the driver will not be irritated. Warnings should not be too late so that the driver has enough time to react to the collision threat. Since drivers have different levels of driving skill and reaction time, it is desirable to allow drivers to select warning thresholds.[26] Such a design can allow the driver to minimize nuisance alarms without compromising his/her reaction time.

Since the driver may become over-reliant on the BSW system, a missed detection could lead to a lateral collision. Frequent false detections are not desirable since they may make the driver ignore the warning or even turn off the BSW system. The reliability functional requirement of the BSW system is thus proposed as:

"The BSW system should have high detection rates and low false alarm rates."

System Level Design Requirements

Missed detections and false alarms can occur due to BSW system internal failures or environmental causes. High detection and false alarm rates will require reliable components (sensor, processor and warning interface, etc.) and self-diagnosis elements implemented in the BSW system. More specific design requirements at system level can be identified by analyzing major potential failure modes and causes based on the system framework shown in figure 30.

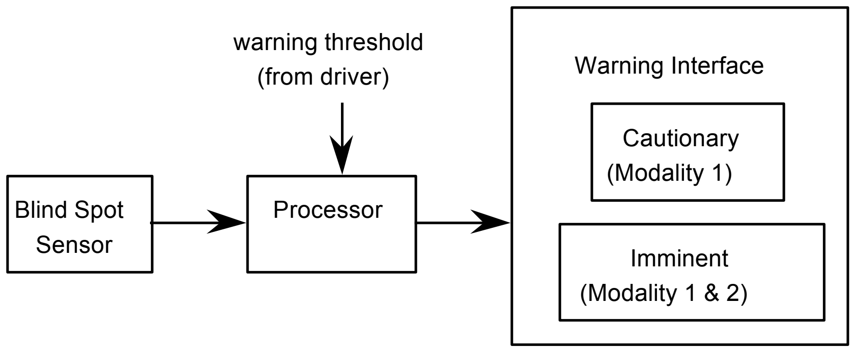


Figure 30. The BSW system framework for reliability design.

Potential Failure Mode 1: Blind Spot Sensor failure

– Blind Spot Sensor computes incorrect range or direction of the threat.

Design requirements:

Blind Spot Sensor needs to have an internal independent check of the reasonableness of the computed range and direction data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response warns the driver of the potential failure and asks him/her to turn off the BSW system.

Processor should incorporate an independent check of the reasonableness of the computed data from Blind Spot Sensor, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

– Data from Blind Spot Sensor is not communicated to Processor, or is corrupted in transmission through interface.

Design requirements:

Processor should verify that Blind Spot Sensor is operating in a timely manner by verifying that new data is received from Blind Spot Sensor every tbd time interval. If an error is detected, the System Failure Response should be executed.

Same as for above.

Potential Failure Mode 2: Processor failure

– Processor command is not communicated to Warning Interface at appropriate time or is corrupted in transmission through interface with Processor.
Design requirements:

Warning Interface should verify that it is receiving updated command from Processor in a timely manner. If an error is detected, the System Failure Response should then be executed.

Potential Failure Mode 3: Warning Interface failure

– Warning Interface fails to warn or generate incorrect level/modality of warnings after receiving a warning command from Processor.
Design requirements:

Warning Interface should incorporate built in tests to be performed on the vehicle startup and during headway maintenance operation to verify that proper warning signals can be generated. If an error is detected, a System Failure response should be executed.

Key findings

1. Two levels of warning may be required. Imminent collision warning may require redundancy with different warning modalities.

2. The reliability functional requirements for the BSW system are high detection rates and low false alarm rates.

Issues and risks:

1. If the warning signal of the BSW system is to be activated only by the turn signal or steering wheel motion, there might not be enough time for the driver to react to the danger. This is because some drivers may perform changing lanes without turning on the turn signal. Warnings may be too late if the driver has already started turning the steering wheel. If the warning signal is to be generated without activation from the driver, the warnings created by the adjacent lanes traffics moving into and out of the blind zone will be irritating to the driver.

2. The effectiveness of the blind spot warning may be discounted since the driver has to deal with the potential warning/information overload problem while traveling in the AHS.

Roadway to Vehicle Speed and Headway Commands

The roadway sends target speed commands to the on-board SHM system to smooth the traffic flow in the dedicated lane. The roadway also sends headway recommendations to the on-board RECW system to enhance the safety in longitudinal control. The roadway has traffic flow sensors to measure the average traffic speed/density and the environmental conditions. The roadway traffic controller uses this data to evaluate target speeds and minimum time headways along sections of the dedicated lane for efficient and safe traveling.[19,10] The speed and headway commands are sent to the vehicle through the roadway-to-vehicle communication. Figure 31 shows a block diagram of the roadway to vehicle speed and headway command function.

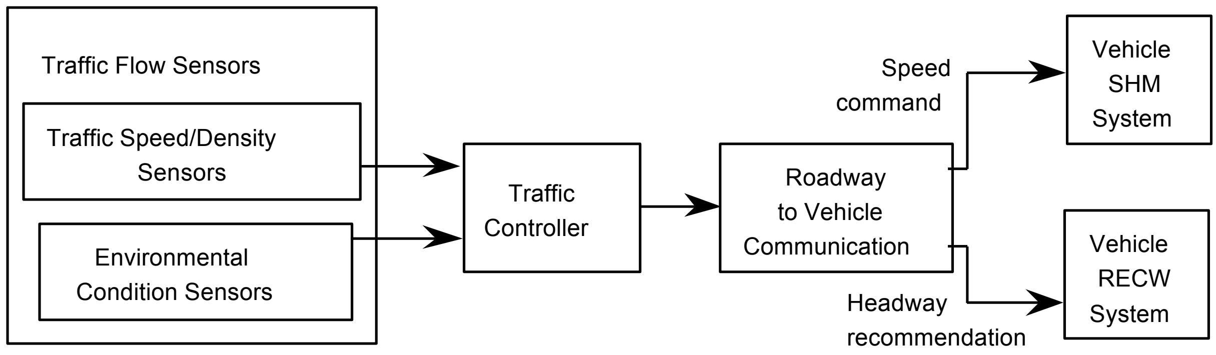


Figure 31. A block diagram of the roadway to vehicle speed/highway command function.

The on-board RECW system adopts the headway recommended by the roadway as TTC if it is larger than the one adjusted by the driver. The SHM system follows the roadway target speed command if the resulting headway is not smaller than the one selected by the driver.

Reliability Functional Requirement

Since the headway used by the SHM system for longitudinal control is constrained by the one chosen by the driver, incorrect speed commands from the roadway introduce no immediate danger to the SHM operation if the driver properly sets the headway based on the traffic and environmental conditions. However, if the driver relies on the roadway to determine the speed and headway used by the SHM system and RECW system, (i.e., the driver chooses the maximum allowable speed and minimum allowable headway,) the incorrect target speed command and minimum time headway recommendation will affect vehicle safety in longitudinal control. This can happen when the vehicle enters a roadway section that has slippery roadway surface. Without increasing the headway and/or decreasing the speed, the driver may have difficulties stopping the vehicle safely during emergencies. Incorrect commands from the roadway may affect the safety and efficiency of traffic flow. The above discussion suggests that the reliability functional requirement for the roadway to vehicle speed/headway commands be:

> *"The traffic flow sensors should be accurate and the target speed commands and minimum time headway recommendations should have low error rates."*

System Level Design Requirements

To achieve this requirement, the roadway needs to incorporate reliable sensors to measure traffic flow condition along the roadway.(112), and to detect the roadway surface condition.(57) The roadway traffic controller needs to have efficient and reliable algorithms to process the collected information and generate target speed commands and minimum time headway recommendations for smoothing the traffic flow over sections of the dedicated lane. The roadway-to-vehicle communication should provide communication protocols that allow reliable data transmission from the roadway to the vehicle.

More specific system level design requirements can be identified by analyzing major potential failure modes and causes, based on the system framework shown in figure 31.

Potential Failure Mode 1: Traffic Speed/Density Sensors failure

– Traffic Speed/Density Sensors at some roadway section(s) fail to provide correct traffic speed/density.

Design requirements:

The sensors should have an internal independent check of the reasonableness of the computed traffic speed/density data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, Traffic Controller should be notified and should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

Traffic Controller should incorporate an independent check of the reasonableness of the average speed/density data provided by the sensors, based on the physical attainability and valid known ranges of the system variables. If an error is detected, Traffic Controller should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

– Speed/density data is not communicated to Traffic Controller, or is corrupted in transmission through interface.

Design requirements:

Traffic Controller should verify that all Traffic Speed/Density Sensors are operating in a timely manner by verifying that new data is received every to be determined (tbd) time interval. If an error is detected, Traffic Controller should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

Potential Failure Mode 2: Environmental Condition Sensors failure

– Environmental Condition Sensors at some roadway section fail to provide correct roadway surface condition information.

Design requirements:

The sensors should have an internal independent check of the reasonableness of the estimated data of road surface condition, visibility, etc., based on the physical attainability and valid known ranges of the system parameters. If an error is detected, Traffic Controller should be notified and should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

Traffic Controller should incorporate an independent check of the reasonableness of the data provided by Environmental condition Sensors, based on the physical attainability and valid known ranges of the system parameters. If an error is detected, Traffic Controller should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

- Data from some Environmental Condition Sensors is not communicated to Traffic Controller, or is corrupted in transmission through interface.
  Design requirements:

  Traffic Controller should verify that all Environmental Condition Sensors are operating in a timely manner by verifying that new data is received every tbd time interval. If an error is detected, Traffic Controller should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

  Traffic Controller should incorporate an independent check of the reasonableness of the data provided by Environmental condition Sensors, based on the physical attainability and valid known ranges of the system parameters. If an error is detected, Traffic Controller should use the validated data provided by the sensors from the neighboring roadway sections to estimate.

Potential Failure Mode 3: Traffic Controller failure

- Traffic Controller computes incorrect target speed commands and/or minimum time headway recommendations.

  Design requirements:

  Traffic Controller should incorporate an independent check of the reasonableness of the computed target speed commands and minimum time headway recommendations before they are sent to Roadway-to-Vehicle Communication, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the vehicle/driver should be notified and the roadway to vehicle speed/headway commands should be canceled.

  Roadway-to-Vehicle Communication should incorporate an independent check of the reasonableness of the commands/recommendations provided by Traffic Controller, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the vehicle/driver should be notified and the roadway to vehicle speed/headway commands should be canceled.

- Traffic Controller commands are not communicated to Roadway-to-Vehicle Communication at appropriate time or are corrupted in transmission through interface.

  Design requirements:

  Roadway-to-Vehicle Communication should verify that it is receiving updated commands from Traffic Controller in a timely manner. If an error is detected, the vehicle/driver should be notified and the roadway to vehicle speed/headway commands should be canceled.

Potential Failure Mode 4: Roadway-to-Vehicle Communication failure

– The target speed commands and minimum time headway recommendations are not communicated to the vehicle or are corrupted in transmission.

Design requirements:

The vehicle should verify that the target speed commands and minimum time headway recommendations are received in a timely manner. If an error is detected, the vehicle should warn the driver of the failure.

The target speed commands and minimum time headway recommendation should be sent frequently enough to minimize the effects of no communication.

Roadway-to-Vehicle Communication should provide communication protocol that contains error detection and correction codes to minimize the probability of incorrect message reception by the vehicle.

The vehicle should incorporate an independent check of the reasonableness of the message received from the roadway, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the vehicle should warn the driver and the roadway to vehicle speed/headway commands should be canceled.

<u>Key Findings</u>:

1. Incorrect speed commands from the roadway introduce no immediate danger to the vehicle/driver. However, incorrect commands from the roadway may affect the safety and efficiency of traffic flow.

2. The reliability functional requirement for the roadway to vehicle speed/headway commands is to have low error rates.

<u>Issues and Risks</u>:

1. The roadway may be liable for the accidents in the dedicated lane since it sends speed commands and headway recommendations to the vehicle.

2. Safer and more efficient traffic control can be achieved by installing more sensors to collect more accurate traffic and environmental data. This may substantially increase the cost of deployment.

ERSC 1 Driver Tasks and Workload

The driver drives the car to the automated lane. The driver turns on the turn signal and the blind spot warning system. The driver enters the lane when a safe gap appears in the traffic flow. The driver steers the car into the lane and turns on the SHMS and rear-end collision warning systems. The driver may set a minimum time headway for the vehicle. The vehicle takes over the throttle and brakes when the car is in the lane or as the car enters the lane. The driver steers the car while in the automated lane. The driver supervises the vehicle control of the brake and throttle. The driver workload in ERSC 1 is very similar to that of today’s driving.

The driver turns on the turn signal and blind spot warning system to leave the automated lane. The driver then resumes control of the throttle and changes lanes out of the automated lane. The driver turns off the communications links when he leaves the automated lane.

The driver performs all emergency stops and steering maneuvers. The driver can change the threshold of the rear-end collision warning since drivers have different reaction times and tolerances for risks and false alarms. The vehicle may begin soft braking, but the driver must complete the stop. The driver can override the vehicle SHMS at any time to avoid an accident or hazardous situation.

The vehicle's rear-end collision warning system and blind spot detector give warnings to the driver. The driver then reacts to the warnings. Driver response time varies with conditions such as age, fatigue, medical condition, and substance use.

Task Analysis–Normal Driving

In normal operations, the vehicle controls the throttle and soft braking. The driver steers the vehicle in the lane and sets the speed and time headway. The roadway sends speed commands electronically to the vehicle and the driver. The task analysis in tables 11 and 12 below shows the driver cues for these two tasks.

The most common problem is that the driver may set the headway too short or too long. The cost of this error could be turbulence in the traffic stream, a rear-end collision, or reduced highway capacity. Tests on vehicles with gap control show that headway may need to be adjustable by the driver.(26) Most drivers dislike "cut-ins" on crowded freeways, so they use short headways to prevent them.

After extended driving, the driver may accidentally turn the speed and headway maintenance system off. The speed and headway maintenance system needs to clearly indicate that it is on or off. The SHMS may require standardization to make this system less confusing to the driver. If the SHM function fails, then the driver returns to manual driving

Table 11. Driver task description for normal ERSC 1 driving

Task	Monitor Vehicle Operation and Steer Vehicle in Normal Driving
General	Task similar to manual driving
Initiating Cue	Enter Dedicated Lane and Turn on SHM–Set time headway or cruising speed
Feedback	Visual, auditory, and kinesthetic cues of accelerating, braking, slowing, and steering
Task Standards	Duration is the same as manual driving
Task Conditions	Weather, road conditions, or traffic
Skills Required	Reaction times appropriate to speed, following distance, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Set to wrong speed or unsafe headway Driver inattention causes vehicle to leave road Turn off headway maintenance system accidentally Vehicle fails to maintain speed or proper headway
Causes of Error	Fails to perceive or misinterprets system feedback Poor judgment of distance and closing rate or speed and road curvature Hit wrong button or brake pedal Sensor or actuator failure on vehicle
Consequences of Error	Disrupt traffic flow and lower capacity Rear-end collision Rear-end collision by vehicle in back Lane departure collision
Recovery Points	Minimum safe headway setting on vehicle to avoid tail-gating Rear-end collision warning Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off Blind spot warning
Individual Differences	Education Age Driving Skill
Criticality	Essential

Table 12 Driver task description for speed and headway adjustments while driving.

Task	Adjust Vehicle Cruising Speed or Headway In Normal Driving
General	Task may be similar to setting a radio in a vehicle or turning on the headlights
Initiating Cue	Driver enters dedicated lane Driver receives signal from roadway to change speed or headway Driver feels uncomfortable with headway or speed
Feedback	Dial or indicator that gives chosen speed and headway
Control Functions	Depend on system design, must be easy to use
Task Standards	Change speed or headway while steering vehicle in dedicated lane
Task Conditions	Weather, road conditions, suggestions from traffic control center
Skills Required	Understand signs in or out of vehicle (literacy) Perceptual judgment of vehicle kinematics
Potential Errors	Change to wrong speed or headway Ignore request for speed change from traffic control center (option) Turn off vehicle speed and headway maintenance system accidentally Vehicle fails to maintain speed or proper headway Vehicle does not receive target speed and minimum headway from roadway (option)
Causes of Error	Fails to perceive or misinterprets the request for a headway change Driver hits wrong button or brake pedal Sensor or actuator failure on vehicle Communication link failure between vehicle and roadway
Consequences of Error	Disrupt traffic flow–lower capacity Rear-end collision Rear-end collision by vehicle in back
Recovery Points	Minimum allowable headway setting on vehicle to avoid tail-gating or unsafe headway Rear-end collision warning Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off
Individual Differences	Education Age Driving Skill
Criticality	Critical

Task Analysis–Rear-End Collision Warning

Human factors studies suggest that collision avoidance systems need multiple levels of warning.[64,98] In the first level the collision warning system shows the driver that it is operating with a heads-up display or other indicator that shows the distance to the car ahead. In the second level the collision warning system warns of a possible collision with a visual warning such as changing the color or intensity of the display. In the third level the collision warning tells the driver to brake with combined auditory and visual warnings. These levels could correspond to no threat, a distance warning and a conservative time to collision based warning set by the driver. Table 13 lists the driver's tasks for stopping distance and collision avoidance warnings.

Most rear-end collisions are caused by driver's failure to detect objects or other vehicles or by misjudgments of the vehicle's movements.[60] Collision avoidance systems(CAS) warn the driver of impending collisions. These systems should reduce accident frequency .[59] The driver must decide whether to brake and how much to brake. This leads to the human factors problem of what criterion to use for driver warning.

Task Analysis–Blind Spot Warning

The blind spot warning looks for vehicles in the blind spot of the driver when the turn signal is on. If the sensor detects a vehicle then it warns the driver. This sensor backs up the driver when he changes lanes. Table 14 below shows driver-blind spot warning system operation. The blind spot detector may lead to driver carelessness in lane changing. The blind spot warning system should ideally warn the driver before the lane change begins to avoid a strong swerve to avoid an accident. The blind spot warning system may warn the driver in the middle of a lane change since the detector does not look for potential collisions such as a faster car approaching on the side. This could cause an accident if the driver does not respond quickly enough.

Good traffic engineering designs use the “one task at a time” rule to decrease driver response time. The blind spot sensor warning must give the direction of the problem early enough for the driver to evade the crash. These conditions violate the idea of one task at a time and may cause problems.

Table 13 Driver task description for hard or emergency braking.

Task	Perform Hard or Emergency Braking
General	Task similar to manual driving
Initiating Cue	Warning from rear-end collision warning system to emergency brake Driver detects: preceding vehicle braking Vehicle ahead stopped or object in roadway Vehicle cuts in and brakes or slows
Feedback	Visual, auditory, and kinesthetic cues of braking and slowing
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking
Task Standards	PRT studies have shown for a wide population segment (young and old) PRT's on the average of about 1.5 sec are required to respond to an unexpected hazard, most respond under 2.0 sec [64] However it is not certain that these data are directly applicable to the car-following scenario.
Task Conditions	Weather, traffic conditions, position of following vehicle
Skills Required	Reaction times appropriate to speed, following distance, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Respond too slowly to emergency Not brake hard enough Brake too often or too much
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Poor judgment of distance and closing rate Rear-end collision system does not detect emergency braking situation Rear-end collision system has a high false alarm rate
Consequences of Error	Rear-end collision with potentially severe results for the system Disrupt of traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it
Recovery Points	Driver sets longer headway or lower warning threshold for slow reactions Improve vehicle braking capabilities Warn driver sooner of a "cut-in" Redundant sensors to improve detection
Individual Differences	PRTs for older drivers have not shown them to be less alert or significantly slower in responding to unexpected hazards. As noted above, it is not clear that this pertains to the car following scenario and especially under a variety of highway conditions
Criticality	Very Critical

Table 14 Driver task description for blind spot warning.

Task	Respond to Blind Spot Warning
General	Task similar to that in manual driving
Initiating Cue	Warning from vehicle that vehicle is in blind spot Driver turns on turn signal to enter or leave dedicated lane Vehicle detects change in steering angle
Feedback	Visual, auditory, and kinesthetic cues of steering and braking
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking
Task Standards	Steer back into lane when warned (~1 second) Look in blind spot
Task Conditions	Type and timing of warning Environmental conditions, traffic speed and density
Skills Required	Reaction times appropriate to speed, lane change speed, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Overconfidence in system-driver does not look Driver does not use turn signals Driver does not respond to the warning or responds too late Sensor false alarms (No vehicle in blind spot, system warns driver anyway) Sensor does not detect another vehicle in blind spot
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Driver delay in response to warning Blind spot sensor warning threshold too high or low, malfunction
Consequences of Error	Lane change/Merge collision with potentially severe results for the system (Approximately 4% of crashes and 0.5% of fatalities are lane change/merge crashes. Some 95% of these crashes are angle/sideswipe crashes [(113)]) Disrupt of traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it
Recovery Points	Vehicle reminds driver to look before lane change Multiple warnings from detector
Individual Differences	Accident statistics, citations and self report data indicate that older drivers have difficulty in merging, changing lanes, and exiting maneuvers. Data suggests that persons over 65 may be over represented in lane change/merge crashes [(113)] Size of vehicle's blind spot
Criticality	Critical

Task Analysis–Fall-back mode

The vehicle warns the driver when the SHM or the RECW functions fail. The driver then takes over manual control other vehicle and exits at the next exit. Table 15 shows the task analysis.

Table 15 Driver task description for fall-back mode to manual driving.

Task	Resume manual control of vehicle
General	Task similar to manual driving
Initiating Cue	Warning from vehicle that SHM or RECW has failed or is degraded
Feedback	Visual, auditory, and kinesthetic cues of braking and slowing
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking
Task Standards	PRT studies have shown for a wide population segment (young and old) PRT's on the average of about 1.5 sec are required to respond to an unexpected hazard, most respond under 2.0 sec [64]. However it is not certain that these data are directly applicable to the car-following scenario. Driver must take over vehicle throttle and brake control in a specified time.
Task Conditions	Weather, traffic conditions, position of following vehicle
Skills Required	Reaction times appropriate to speed, following distance, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Respond too slowly to transfer of control from vehicle to driver Vehicle slows Not brake hard enough Brake too often or too much
Causes of Error	Fails to perceive or misinterprets the indication of a failure and transfer of control Driver does not take over throttle control Driver waits for warning before braking Poor judgment of distance and closing rate Vehicle does not detect SHM or RECW failure
Consequences of Error	Rear-end collision with potentially severe results for the system Disrupt of traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it
Recovery Points	Driver sets longer headway or lower warning threshold for slow reactions Improve vehicle braking capabilities Warn driver sooner of a "cut-in" Redundant sensors to improve detection Reliability in SHM and RECW functions
Individual Differences	PRTs for older drivers have not shown them to be less alert or significantly slower in responding to unexpected hazards. As noted above, it is not clear that this pertains to the car following scenario and especially under a variety of highway conditions
Criticality	Very Critical

Issues and Risks

1. Driver confidence in warning

If the driver has too much confidence in the collision warning systems then she may not pay enough attention during lane changes or while following another vehicle. This could lead to accidents if the warning system does not detect an object or the system fails. Driver lack of confidence could cause the driver to disable or ignore the warning system. Research needs to be done on how many false alarms and detection failures are acceptable.

2. Enabling/Disabling Automatic Systems

This ERSC includes a speed and headway maintenance system, rear-end and blind spot collision warnings, and communication systems. Research needs to be done on the instrumentation needed to control these different systems. The question of whether all the automatic systems need to be controlled with one switch or many needs to be answered.

3. Multiple Warnings

The blind spot and rear-end collision warnings may occur simultaneously. The vehicle must prioritize the alarms so that the driver only has to work with one task at a time.

Key Results

Traffic Flow Control

In this section, we study the potential AHS capacity improvement due to roadway controllers that smooth traffic. Traffic tie-ups occur daily on traffic networks due to accidents and congestion. This degrades the performance of the highway system in terms of safety and average travel times. Roadway authorities have installed traffic detectors and communication links to get real-time information to central traffic control centers .[112] To date this data has only been used in the form of real-time signs that display traffic information. Studies by Chien et al. show that a more active approach can help smooth traffic after incidents .[17,19]

One of the major factors that contributes to congestion on today's freeway is disturbances or inhomogeneities of the traffic streams. Examples of these inhomogeneities are speed differences between consecutive vehicles in one lane, speed differences between lanes, and flow rate differences between lanes. In an inhomogeneous traffic stream, when the traffic volume approaches the maximum capacity, drivers are forced to drive close together and compete for the available space. Hence, gaps are immediately filled up. Shock waves may occur that originate in a chain of vehicles closely following each other at high speed and competing for available gaps. In this situation small disturbances are amplified. Traffic flow instability may occur and lead to a standstill or congestion.

If the roadway sends speed commands to the vehicles on sections of the roadway, the traffic flow recovers from incidents faster and the traffic resumes full speed in a shorter amount of time. This controller sends speed commands so that the density distribution of the dedicated lane tracks a desired or optimal density distribution based on overall traffic considerations. If the traffic density distribution along the dedicated lane could be smoothed, then the formation of the congestion due to the inhomogeneities of the traffic streams can be avoided and the time delays can be reduced. In case of incidents, the traffic density distribution could be controlled to minimize the effects of the incident on traffic flow. Thus, if the traffic density distribution could be re-shaped to a uniform profile (in case of normal traffic conditions) or a suitable one (in case of incident), the congestion can be reduced and the traffic flow rate can be increased.

To reshape the traffic density distribution along the dedicated lane, one approach is to provide proper target velocity commands to the vehicles in the dedicated lane. In this section, we propose control strategies to provide target velocity commands. We show that if the vehicles in the dedicated lane follow the recommended target speed, the traffic density distribution along the dedicated lane converges to a desired density profile. The benefit of this approach is demonstrated by simulations.

By definition, the traffic density *k* is the number of vehicles occupying a unit length (No. of vehicle/km), the spaces mean speed *v* is the instantaneous average speed of vehicles in a length increment (km/hour) and the traffic volume *q* is the number of vehicles passing a specific location in a unit time (No. of vehicles /hour). As a direct consequence of the continuum variables' definitions, we have the following equation

$$q = k\,v$$

which is called the fundamental equation. The traffic density controller models a freeway system with a single dedicated lane that is subdivided into N sections with lengths L_i, $(i = 1, \ldots, N)$ each having at most one on-ramp and one off-ramp as shown in figure 32 .

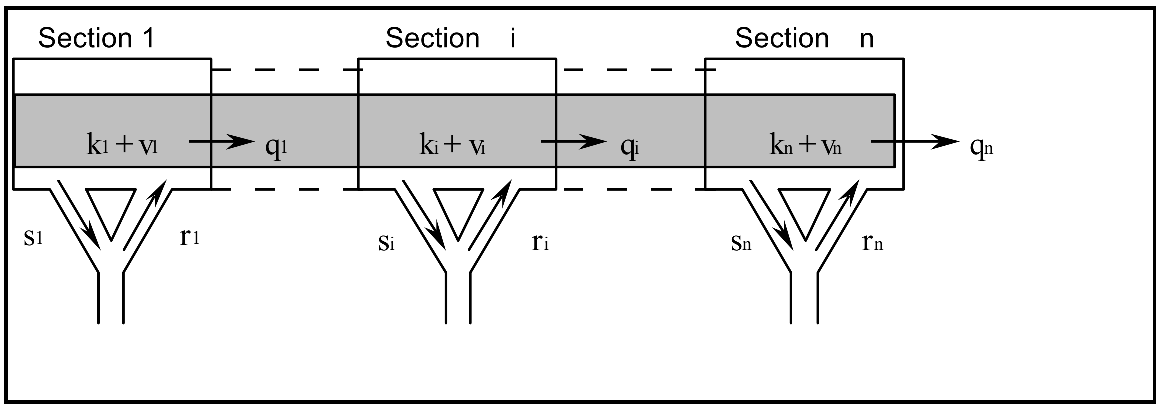


Figure 32. A freeway system subdivided into sections.

At time *t*, $k_i(t)$ is the number of vehicles in the freeway section *i* at time *t* divided by the length L_i of the section; $v_i(t)$ is the mean speed of vehicles on the freeway section *i* at time *t*; $q_i(t)$ is the number of vehicles leaving sections *i* per unit time; and $r_i(t)$ and $s_i(t)$ are on-ramp and off-ramp traffic flow rates of section *i* respectively.

Consider a dedicated lane as shown in figure 32. In general, the higher the desired traffic density, the higher the achievable input traffic flow rate. However, the upper bound of the traffic density is limited by the inter-vehicle safety distance adopted by the vehicles in the dedicated lane.

Assume a constant time headway safety policy is adopted by the vehicles in the dedicated lane

$$S = h\,v$$

S is the safety distance and *h* is the time headway. For steady-state uniform traffic flow, it is known that the traffic density is inverse proportion to the inter-vehicle safety distance. Hence, for fixed speed, the traffic density is also inversely proportional to the time headway. Therefore, the smaller the time headway *h*, the higher the traffic density that can be achieved and higher input traffic flow rates can be achieved.

<u>Dynamic Traffic Flow Control</u>

Due to variations in traffic flow such as entering and exiting (the dedicated lane) maneuvers, the traffic stream is seldom in the steady-state. Therefore, a dynamic control strategy should be employed to constantly provide dynamic target speed commands for the vehicles in the dedicated lane.

We propose a dynamic control strategy based on a traffic model proposed by Karaaslan, Varaiya and Walrand(56). Appendix B gives the details of the proposed control strategy and this traffic model. This control strategy continuously provides speed commands to the vehicles in the dedicated lane. The traffic density distribution along the dedicated lane could be controlled to a uniform density or any other desired density profile.

Simulation Study

Consider a long segment of dedicated lane that is divided into 12 sections as shown in figure 32. The length of each section is 500 meters. Assume that an accident occurs at section 8 and interrupts traffic. In this situation, vehicles accumulate upstream of section 8. The accident is removed quickly. Due to the direct impact of the accident, the traffic density at section 8 is high after the accident has been removed. And the traffic density at section 6, 7 increases to an intermediate-high value due to the indirect impact of the accident. In addition, since section 8 is blocked by the accident, no vehicle can enter sections 9 - 12. The traffic density of these sections is very low. The initial traffic conditions after the accident is shown below.

Section	1	2	3	4	5	6	7	8	9	10	11	12
Initial Density (Veh/km/lane)	30	30	30	30	30	40	70	80	10	10	10	10
Initial Velocity (km/hour)	10	10	10	10	10	7.5	4.3	3.7	30	30	30	30

In ERSC 1, the traffic flow entering section 1 is in a moderate value. The traffic flow entering section 1 is shown in Figure 33. Since the accident was removed quickly, its impact to the traffic is not very severe. The figures below compare the effects of control with the case of no control. All the simulations use the traffic model described above. The first case shows a situation where an accident occurs in section 8 when there is a moderate flow rate of traffic onto the highway.

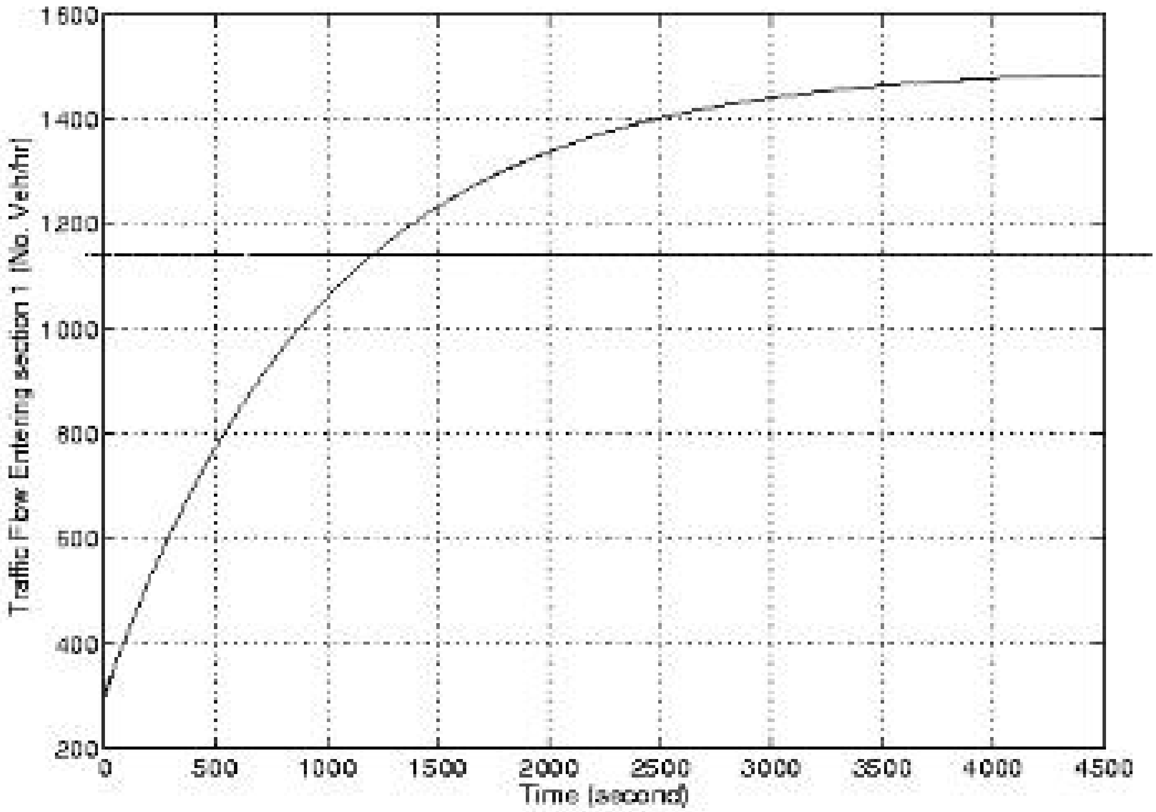
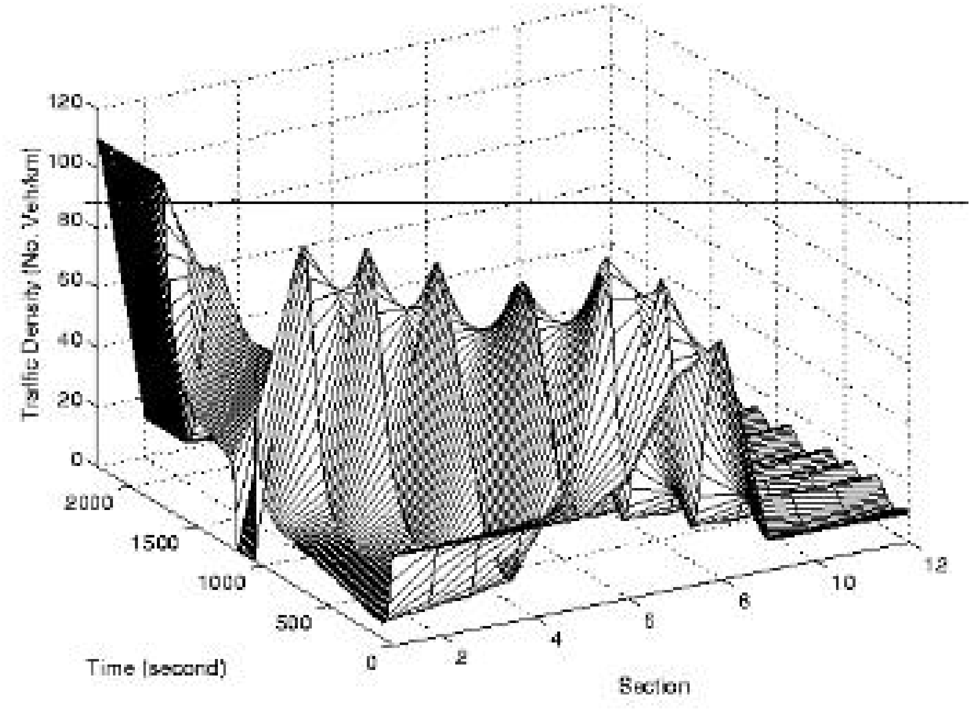
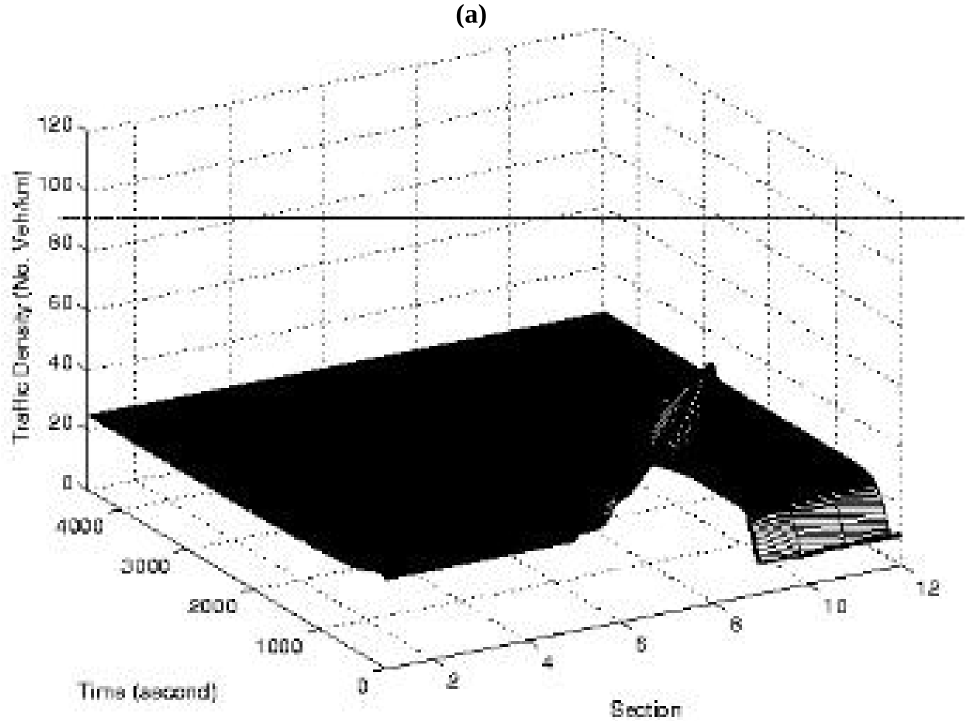


Figure 33. Traffic flow entering section 1 during case with a low input traffic flow.

Figure 34(a) shows the evolution of the traffic density without control. The disturbance in section 8 propagates back down the highway as it slowly dies out. The disturbance in traffic density is still very strong in section 1 more than 30 minutes after the original accident is cleared. Figure 34(b) shows the evolution of the traffic density when the controller is operating. The disturbance in section 8 propagates back down the highway but dies out quickly. This lets the highway quickly return to a constant flow rate. Figure 35(a) shows the velocities for each section of the roadway over time without control. Figure 35(b) shows the velocities for each section of the roadway over time with control. Figure 36(a) shows the evolution of the traffic flow rate for the roadway sections. Section 8 is the section where the accident originally occurred. The traffic flow is very jerky and inhomogeneous as the accident effects propagate. Figure 36(b) shows the evolution of the traffic flow rate for the roadway sections. The traffic flow quickly returns to its original rate. Since the traffic flow rate quickly smoothes out the highway can handle more vehicles smoothly.

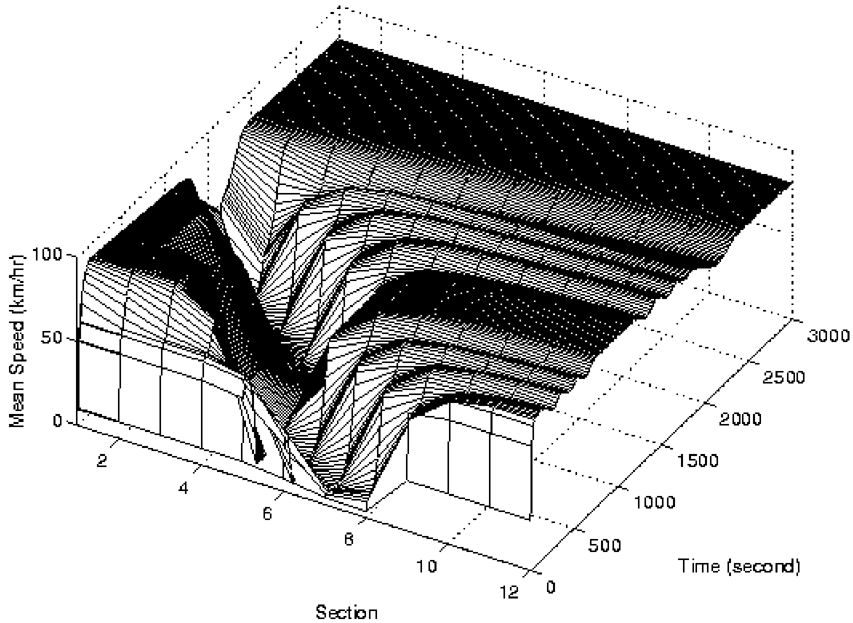


(a)



(b)

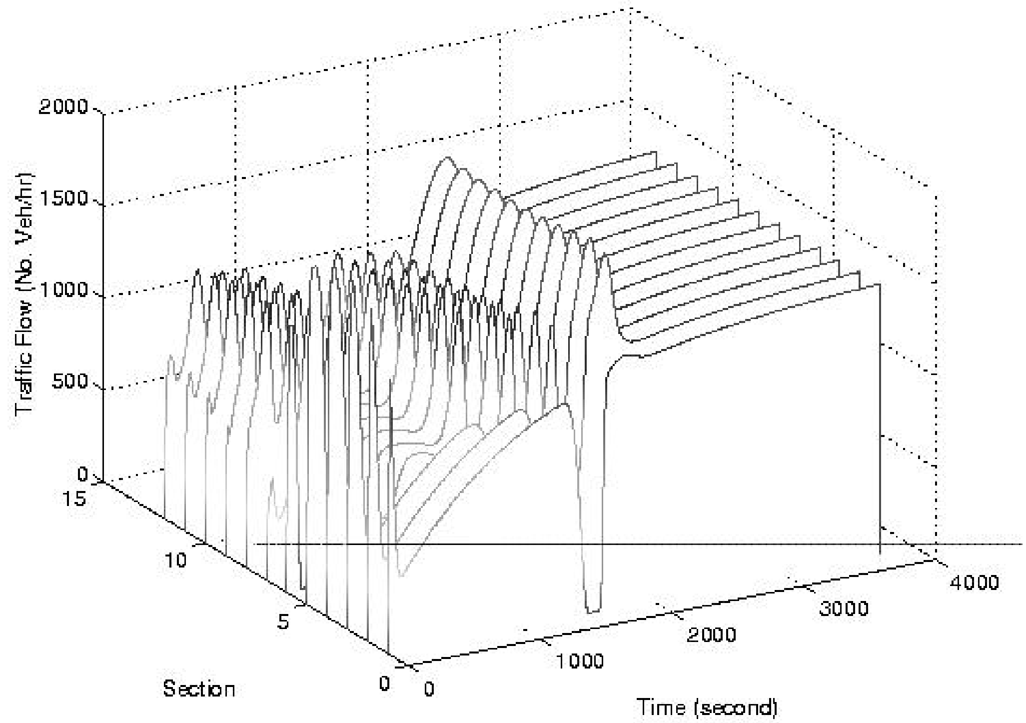
Figure 34. (a) Evolution of traffic density when no roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8. (b) Evolution of traffic density when the roadway controller is present. The disturbance quickly dies out after the accident is removed from section 8.



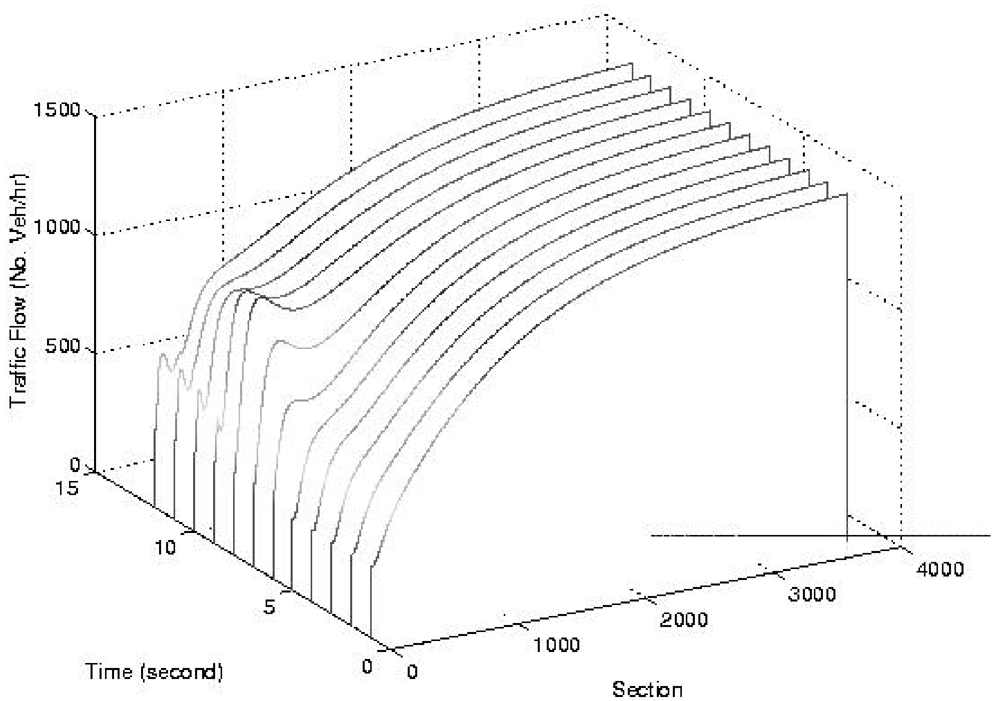
(a)

(b)

Figure 35. (a) Evolution of traffic velocity when no roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8 causing changes of speed back to section 1. (b) Evolution of traffic velocity when the roadway controller is present. The disturbance quickly dies out after the accident is removed from section 8 and the vehicles resume a constant speed.



(a)



(b)

Figure 36. (a) The traffic flow evolution with respect to time with no roadway control. It takes more than 30 minutes (2000 s) for the traffic flow disturbances to subside. (b) The traffic flow evolution with respect to time for the roadway with roadway control. The traffic flow quickly smoothes out to the steady state velocity.

Severe Congestion and High Entering Traffic Flow Rate

In this example, the accident at section 8 occurs during rush hour and it takes longer to be removed. Due to the direct impact of the accident, the traffic density at section 8 is high after the accident has been removed. And the traffic density at section 6, 7 increases to an intermediate-high value due to the indirect impact of the accident. In addition, since section 8 is blocked by the accident, no vehicle can enter sections 9-12. The traffic density of these sections is very low. The initial traffic conditions after the accident are shown below.

Section	1	2	3	4	5	6	7	8	9	10	11	12
Initial Density (Veh/km/lane)	30	30	30	30	30	70	80	97	10	10	10	10
Initial Velocity (km/hour)	10	10	10	10	10	4.3	3.7	3.0	30	30	30	30

In ERSC 1, the traffic flow entering section 1 is a higher value like in rush hour. The traffic flow entering section 1 converges to 2000 vehicles per hour. Since the accident took a long time to remove, its impact to the traffic is severe. The figures below compare the effects of control with the case of no control. All the simulations use the traffic model described in appendix B. The first case shows a situation where an accident occurs in section 8 when there is a moderate flow rate of traffic onto the highway.

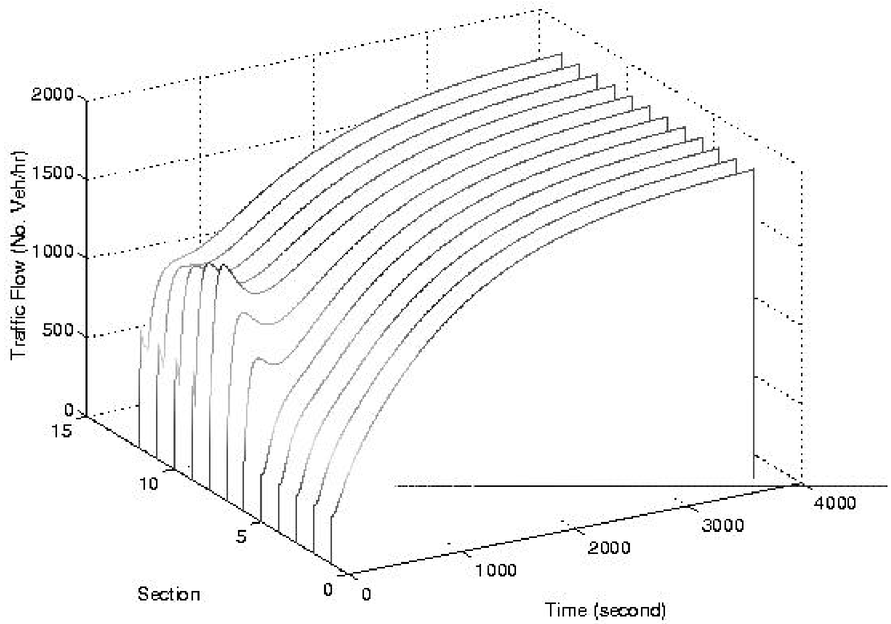
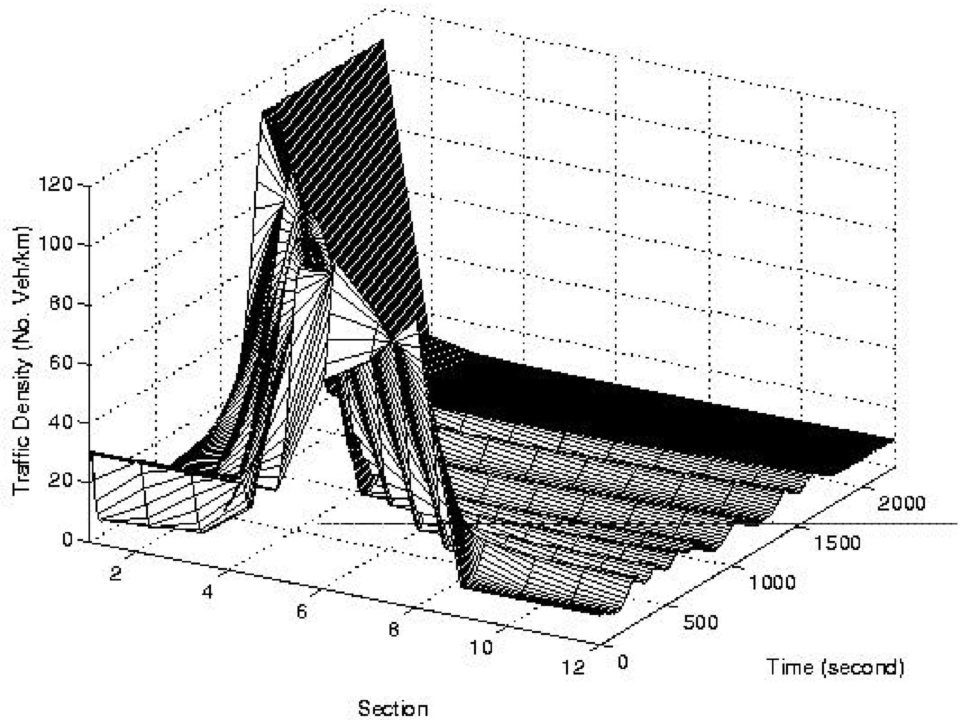
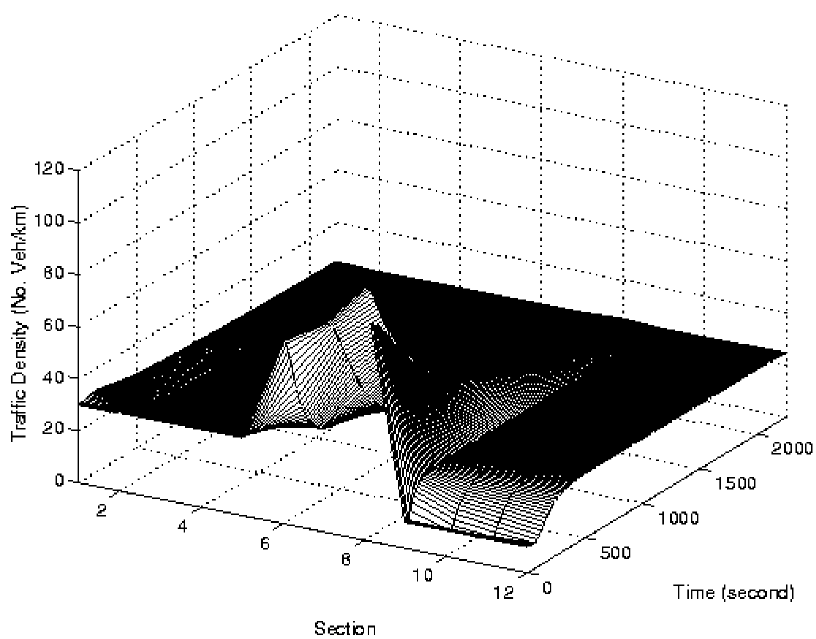


Figure 37. The traffic flow evolution with respect to time for the roadway with roadway control. The traffic flow quickly smoothes out to the steady state velocity.

Figure 37 shows the evolution of the traffic flow for the case with control. Figure 38(a) shows the evolution of the traffic density without control. The disturbance in section 8 propagates back down the highway and causes serious congestion. The disturbance in traffic density is still very strong in section 1 more than 30 minutes after the original accident is cleared. Figure 38(b) shows the evolution of the traffic density when the controller is operating. The disturbance in section 8 propagates back down the highway but dies out quickly. This lets the highway quickly return to a constant flow rate. Figure 39(a) shows the velocities for each section of the roadway over time without control. Figure 39(b) shows the velocities for each section of the roadway over time with control.

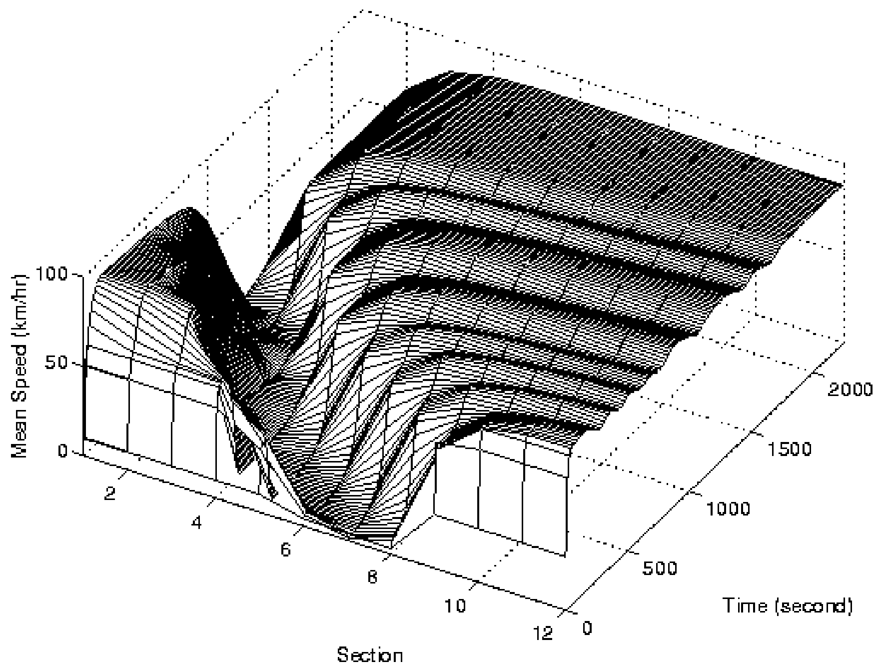


(a)

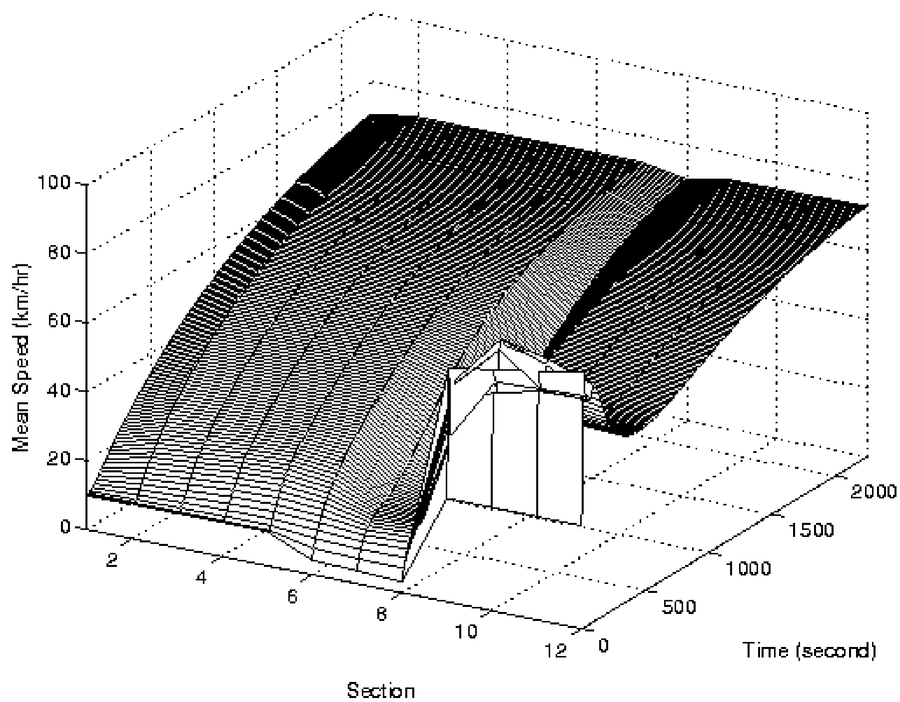


(b)

Figure 38. (a) Evolution of traffic density when no roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8. (b) Evolution of traffic density when the roadway controller is present. The disturbance quickly dies out after the accident is removed from section 8.



(a)



(b)

Figure 39. (a) Evolution of traffic velocity when no roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8 causing changes of speed back to section 1. (b) Evolution of traffic velocity when the roadway controller is present. The disturbance quickly dies out after the accident is removed from section 8 and the vehicles resume a constant speed.

Safety

A rear-end collision warning system needs to be able to accurately predict the likelihood of a collision. If a collision is likely, then the system warns the driver to respond to the threat. Analysis of minimum time headways between vehicles suggests that small reductions in driver reaction times can dramatically decrease the minimum safe headway. Reductions in the reaction time may be achieved by warning the driver. Many accidents are due to failures in human information processing.(59) In many cases the other vehicle was clearly visible. This again suggests that a rear-end collision warning system may increase driver safety.

Most (95%) of lane change/merge crashes are angle or sideswipe collisions .(113) The driver of the merging car either did not see the other vehicle or misjudged the distance between the vehicles. These crashes usually happen in dry, clear, daylight conditions.(113) The driver "did not see" the other vehicles until too late. The blind spot or "lateral encroachment" warning system on the vehicle detects vehicles in adjacent lanes that are traveling in the same direction.(59) The blind spot detection warning system has a sensor and a system that warns the driver.

Issues and Risks

1 Controller Algorithms

The controller algorithms need to smoothly adjust the brake and throttle to avoid sudden accelerations when the vehicle ahead leaves the lane. Driver tests indicate that drivers feel unsafe when the controller suddenly accelerates.(26) The SHM controller needs to use alternative algorithms that limit accelerations.(51,25)

2 Electromagnetic Interference

Full deployment of ERSC 1 means that most vehicles will have active sensors such as radar. When multiple radar operate in a small area at similar frequencies the radar may interfere with one another. This interference could lead to shorter sensor ranges and poor performance.

3 Driver Interface

Research needs to be done on the driver interface with the SHM, RECW, and blind spot warning functions. Each function may have separate controls for enable/disable and adjustments. It may be too much of a burden on the driver to expect him/her to change lanes and start the automated systems immediately. The driver may need to preset the target speed, minimum headway, and warning thresholds when he/she starts the vehicle.

4 Sensor Capabilities

The RECW and blind spot warning functions may increase safety and reduce certain types of collisions by decreasing driver reaction time. But there are sensor and human factor issues that still must be resolved. The sensors must detect small vehicles or debris, such as motorcycles with few nuisance alarms.

5 Warning system design

First the designers need to decide when the warning system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to be directional to get fast driver response. ERSC 1 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

6 Dedicated Lane

The biggest social issue for AHS is how to get a separate lane for automated vehicles. The driving public rebels when a lane is taken away from active use.(99) The solution for most highway departments has been to add a new lane on the shoulder or median strip, but most urban highways do not have any more space to spare for the sole use of automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

7 Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short.(102) The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

8 Privacy

This ERSC gives the vehicles the option to “Check-in” with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

9 Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

Key Findings

1 The SHM function does not have to be very accurate in this ERSC (5-10%). The human driver takes over all hard braking and collision avoidance. Human drivers have relatively slow perception and reaction times. This suggests that SHM systems at this level may come from the intelligent cruise control systems planned by several companies .(74,26) The next ERSC requires a more accurate SHM function. The components for a more accurate SHM function may need to be designed with AHS requirements in mind instead of taking commercial technology off the shelf.

2 There are significant safety and performance benefits even with low levels of automation. Simple systems like the roadway velocity controller can give large increases in capacity and traffic flow volumes. This system uses technology available today in traffic control centers and toll roads.

3 The reliability functional requirement for the warning systems is that they have high detection rates and low false alarm rates. Vehicle to vehicle communications systems can reduce

the number of false alarms in the collision warning systems without reducing the probability of detection.

4 The driver can serve as a back up to the automated systems at this level. If either the SHM or the RECW system fails, then the driver takes over.

5 There are significant human factors issues for warnings and the driver interface that must be researched for even low levels of automation. The warning systems will require multiple levels of warnings.

6 The reliability functional requirement for the SHM function is that it must safely return control to the driver in case of override.

SECTION 6: ERSC 2 ANALYSIS

Description of ERSC 2

In ERSC 2, the roadway provides a dedicated lane with the same vehicle accessibility as in ERSC 1. The roadway assists in keeping non-fit vehicles out of the dedicated lane. The roadway receives speed and headway data from the vehicles. It computes the desired target speed at each section of the lane for smoother traffic flow. It sends minimum time headway information to the vehicles based on environmental conditions. It uses the operational status and identification of the vehicle for check-in purposes and for roadway emergency response in case of disabled vehicles.

The vehicle has all the capabilities as in ERSC 1, with the rear-end collision warning being upgraded to rear-end collision avoidance. The SHM function and rear-end collision avoidance allow the driver complete “feet-off” driving in the dedicated lane. The vehicle provides steering assist to smooth the driver's steering by compensating for roadway disturbances, wind gusts, and small driver steering errors. The vehicle also has a lane departure warning to warn the driver of large deviations from the center of the lane. The vehicle sends its speed and headway, operational status and identification to the roadway. It sends its braking capabilities and acceleration/deceleration intentions to the vehicle behind. It receives the braking capabilities and acceleration/deceleration intentions of the vehicle in front. As in ERSC 1 the vehicle has on-board diagnostics that are used to detect malfunctions and alert the driver. The vehicle provides a fall-back mode to ERSC 1 in case the rear-end collision avoidance or speed and headway maintenance functions fail.

The motivation behind ERSC 2 is to

- increase capacity by using smaller headways mad e possible by the rear-end collision avoidance function.

- improve safety and driver comfort by introducing lane departure warnings and steering assist

- smooth traffic flow with roadway specified vehicle target speeds.

Table 16. ERSC 2 functions and driver/vehicle/roadway performance requirements.

Function	Requirement	Driver/Vehicle/Roadway Tasks
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead. - Calculate and maintain a headway for collision-free vehicle following.	– Respond to driver commands for setting the minimum headway and maintain at least that minimum headwa – Respond to driver commands for enabling and disabling the SHM function safely – Respond to roadway commands for following target speeds in a smooth manner – Respond to roadway commands for increasing the minimum headway in a smooth manner – Compute a safe minimum headway based on vehicle braking characteristics and those of the preceding vehicle, and environmental conditions
Rear-end Collision Avoidance	The rear-end collision avoidance function should avoid rear-end collisions due to moving or stationary obstacles in the lane under all road and environmental conditions.	– Detect any obstacle in the lane ahead in time to stop or avoid the obstacle. – Actuator response should be fast and free of failures – Low rate of false or nuisance alarms – Deceleration and jerk may reach maximum possible values in emergency stop – Communicate braking capabilities, decelerations, and intentions between vehicles to reduce false alarms and increase safety
Blind spot warning (described in Section 5)	Warn the driver of a potential lane change/merge collision due to moving or stationary obstacles in the vehicle's blind spot	Same as in ERSC 1.
Lane Departure Warning	Warn the driver when the vehicle is in danger of leaving the lane	– Sense the vehicle's position in the lan and estimate its course – Senses roadway preview information – Sends driver cautionary and imminen threat warnings of potential lane departures – Have a high detection rate and a low rate of false alarms
Steering Assist	Works in series with driver to compensate for disturbances due to wind gusts and road surface conditions	- Sense vehicle's yaw rate and slip angl to compensate for high frequency disturbances - Increase control bandwidth and make vehicle easier to drive.

Driver Interface	- Adjust thresholds on warnings - Enable/Disable automatic functions - Adjust headway - Steer vehicle with help from steering assist	– Driver should be able to: » adjust headway » adjust warning thresholds » enable/disable automatic functions » steer vehicle – Interface should be simple to understand and use – No adjustments should be required that take driver's attention away from driving
Roadway/Vehicle speed & headway commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow	– Roadway measures the average speed and traffic density, and assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways – Vehicles may display relevant traffic information to driver – Roadway monitors vehicle status at check-in
Fall-back Mode to ERSC 1	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- Sense status of different vehicle control channels - Safely transfer control to the driver if SHM function or rear-end collision avoidance fails

Performance Requirements

Speed and Headway Maintenance

<u>Functional Requirement</u>

The speed and headway maintenance (SHM) function should maintain the selected cruising speed when no vehicle is ahead. It should calculate and maintain a minimum headway for collision-free vehicle following. The SHM must smoothly switch between vehicle following mode and constant speed cruising. The SHM function in ERSC 2 performs the same tasks as in ERSC 1, but they have to be more accurate if smaller headways are used for higher capacity.

The vehicle receives and responds to target speed commands and headway recommendations sent by the roadway in the same way as in ERSC 1. The braking capabilities and acceleration/deceleration intentions of the vehicle in front as well as the headway recommendations sent by the roadway are used by the vehicle to calculate the minimum time headway for collision-free vehicle following. The SHM function chooses a headway that is larger than the calculated one based on some tolerance for additional safety. Since the driver is not considered to be a back up in a rear-end collision avoidance situation the calculated headway does not take into account the driver reaction time and is therefore smaller than the one used for collision warning in ERSC 1. The vehicle responds to driver commands for changing the headway. It also enables/disables the SHM and rear-end collision avoidance functions upon driver commands. If the driver disables the rear-end collision avoidance function the vehicle initiates a smooth transition sequence that does not put the driver in a dangerous situation. This transition may require a larger headway since human drivers have a longer reaction time compared to an automatic rear-end collision avoidance system.

The SHM function operates by measuring the relative speed and spacing, then sending commands to the throttle and brake actuators. Figure 40 shows the structure of the SHM function. This section will discuss the sensor and actuation requirements, control algorithms, selection of a safe headway, and driver/roadway interface for the SHM function.

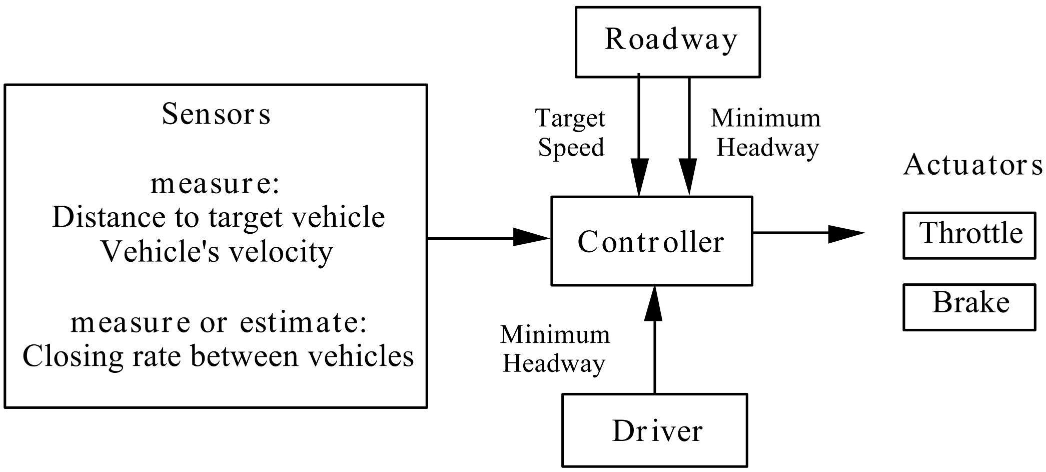


Figure 40. Block diagram of the speed and headway maintenance function. The sensors measure the relative speed and spacing of the vehicles, then the controller sends commands to the brake and throttle actuators so that the vehicle maintains the target speed or minimum headway.

<u>Sensor Requirements</u>
To maintain a target velocity the vehicle must be able to measure its own speed. The sensor must measure speeds up to 160 km/h (100 mph) or any speed that may be used in the dedicated lane. The sensor needs to be accurate within about 3 km/h (1.8 mph) since the SHM function needs an accurate velocity measurement to select a safe headway for vehicle following.

To maintain a constant time headway the vehicle must be able to measure the distance to the target vehicle ahead. The vehicle must also estimate or measure the closing rate between vehicles. Figure 41 shows the sensor region for headway maintenance. The sensor region shows the sensor requirement for a vehicle with a rear-end collision avoidance system that must detect obstacles as soon as they become a threat.

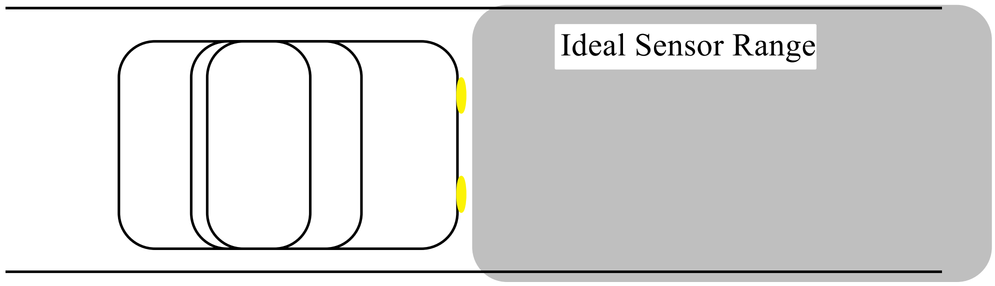


Figure 41 Sensor requirements for range and closing rate detection for the speed and headway maintenance system.

There are several requirements that determine the maximum sensor range. The sensor needs to work for the collision avoidance and the fall-back mode to ERSC 1 functions as well. The sensor range needs to be the maximum value for these requirements. [29] The first requirement is that the vehicle must be able to safely return control to the human driver if the driver decides to turn off or override the SHM function and return to manual driving. The California Driver's Handbook states that 3-4 seconds is a safe time headway for human drivers. If we assume a speed of 60 mph (26 meters/s) this gives a distance of 78-104 meters. Therefore the vehicle range sensor should work over a distance of at least 80-105 meters. The second requirement is that the system be able to stop when there is debris or another vehicle stopped in the roadway ahead. This scenario is known as the "brick wall" scenario. Rear-end collisions with a stationary vehicle outnumber rear-end collisions where the lead vehicle is moving by 2:1. [60] Figure 42 shows some range curves for the brick wall scenario for different velocities and a detection time of 0.5 seconds for the rear-end collision avoidance system. For example, at 60 mph we get a range of 80 meters for a vehicle with a maximum braking capability of -0.55 g. Table 17 gives the parameters used in this calculation. This calculation does not take human reaction times into account since fully automated longitudinal control is achieved by the SHM and rear-end collision avoidance functions.

For the vehicle to operate in the "fall-back" mode, the sensor needs to meet the range requirements for ERSC 1 as well. In the fall-back mode the vehicle returns to ERSC 1 if one of the control channels for the rear-end collision avoidance function fails. This implies a range of 120 meters as calculated in section 5.

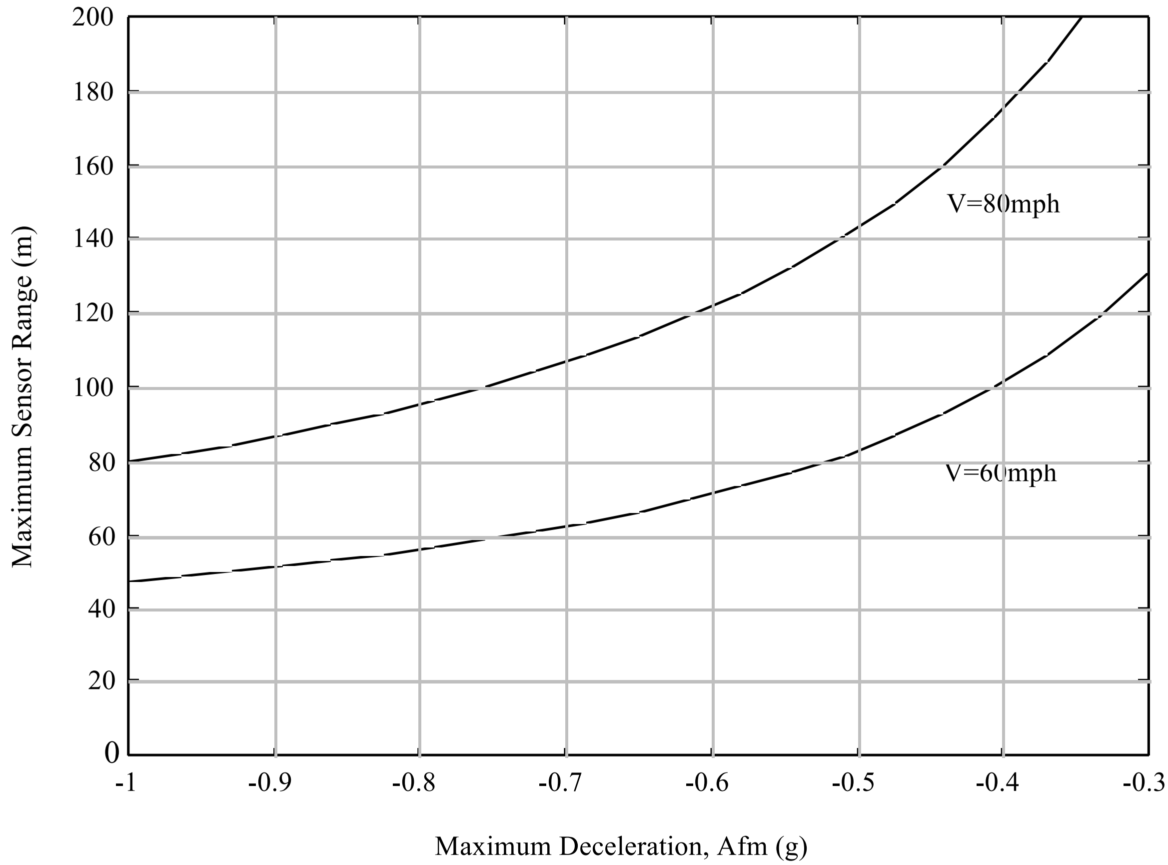


Figure 42. The maximum distance sensor range versus the maximum vehicle deceleration for the "brick wall" scenario at two different velocities. The maximum vehicle deceleration is the vehicle capability on the roadway at a given time. It reflects the road-tire friction coefficient and vehicle's capabilities.

The sensor must cover the lane so it does not miss the target vehicle. But it must also minimize interference from adjacent lanes which means that the sensor beam cannot spread out too much or it must use multiple beams to reject interference. The sensor must be able to track the vehicle around highway curves without losing the target. Reliable sensing may require roadway curvature preview data to track vehicles around curves.

The vehicle must also detect or estimate the closing rate between itself and the target vehicle. This may be done directly with a pulse-doppler radar or it may be estimated by taking the derivative of the distance measurement over time. The sensor accuracy needs to be within 5% of the true value.

The most common type of distance sensor measures the time-of-flight from the time that a pulse is sent out to the time that the pulse returns. These time-of-flight sensors can measure the range, relative speed, and angular position of the target vehicle. These sensors are commercially available for automotive use today. [12; 33; 76] Other sensors use triangulation techniques such as stereo to measure the distance to the vehicle ahead. These sensors include vision-based systems and radar. [68; 86]

Control Algorithms

The vehicle must respond quickly and smoothly to commands from the driver and roadway. The controller must also limit the jerk and accelerations in normal operation. Humans find longitudinal accelerations above 0.17 g and jerks above 0.2 g/s uncomfortable at low speeds.[15] At high speeds the deceleration should be kept below 0.1g with jerk as low as possible. Soft braking should be limited to around 0.2 g with low jerk. [15]

The controller must switch smoothly between the vehicle following and cruise modes and avoid sudden accelerations when the preceding vehicle exits the dedicated lanes. Fancher et al showed that abrupt accelerations by the automated vehicle made drivers feel uncomfortable and unsafe.[26] The controller must also switch smoothly between the throttle and brake without high frequency oscillations.

The controller calculates a safe minimum headway for vehicle following. This calculation uses the deceleration values of the vehicle itself and the preceding vehicle, environmental conditions measured by the vehicle and roadway, and the velocity of the vehicles.

Actuator Requirements

The brake and throttle actuators must respond quickly to commands from the controller. Faster actuators may give better control. If the delay is too long then vehicle following may be unstable if there are many vehicles in a row following one another. [50] Delays less than or equal to 0.1 seconds should be sufficient for ERSC 2. The actuators must also be accurate. The actuator delays should be taken into account in the calculation of the minimum safe headway.

Safe Headway Selection

The vehicle calculates a safe headway between vehicles. This calculation requires data on the braking capabilities of both vehicles, estimates of the road-tire friction coefficients for both vehicles and measurements of the vehicles' velocities. [101] Each vehicle can assess its own braking capabilities with built-in tests that track braking. The "check-in" procedures may also asses how well a vehicle can brake before the vehicle enters the highway with a built-in-test function that monitors the vehicle braking history. [108] The preceding vehicle can send its estimated braking capabilities to the vehicle behind it. This will help the vehicles choose a safe following distance. Without this data from the preceding vehicle or if the estimate appears incorrect, the vehicle chooses a worst case braking condition for the preceding vehicle such as A_{lm}=1 g to calculate the headway.

Table 17 gives the variables used in the minimum time headway calculations for ERSC 2. Unless noted these values are used for all the figures. Figure 43 shows the minimum time headway for different maximum deceleration values of the follower car. When the follower vehicle decelerates faster than the lead vehicle the minimum time headway decreases. When the follower vehicle decelerates slower than the lead vehicle the minimum time headway increases. This suggests that proper minimum time headways should be set as if the lead vehicle has a high maximum possible acceleration.

Table 17 Variable values used in the simulations in SHM section for ERSC 2.

Variable Name	Description	Value
V_l, V_f	Initial velocity of the lead and following vehicles	100 km/h
J_{lmax}, J_{fmax}	Maximum jerk of the lead and following vehicles	72 m/s^3
m_{lmax}, m_{fmax}	Maximum road-tire friction coefficient of the lead and following vehicles	1,1
A_{lm},A_{fm}	Maximum deceleration of the lead and following vehicles respectively	0.85 g,0.8 g
a_{fac}	Acceleration under vehicle following situation	0.05 g
a_{fauto}	Acceleration value for soft braking	0.20 g
J_{fc}	Jerk value for soft braking	20 m/s^3
t_b	Braking actuation delay	0.1 s
T(1)	Detection delay of the automated vehicle headway system	0.25s
t_{fc}	Time when vehicle begins hard or emergency braking	0.35 s

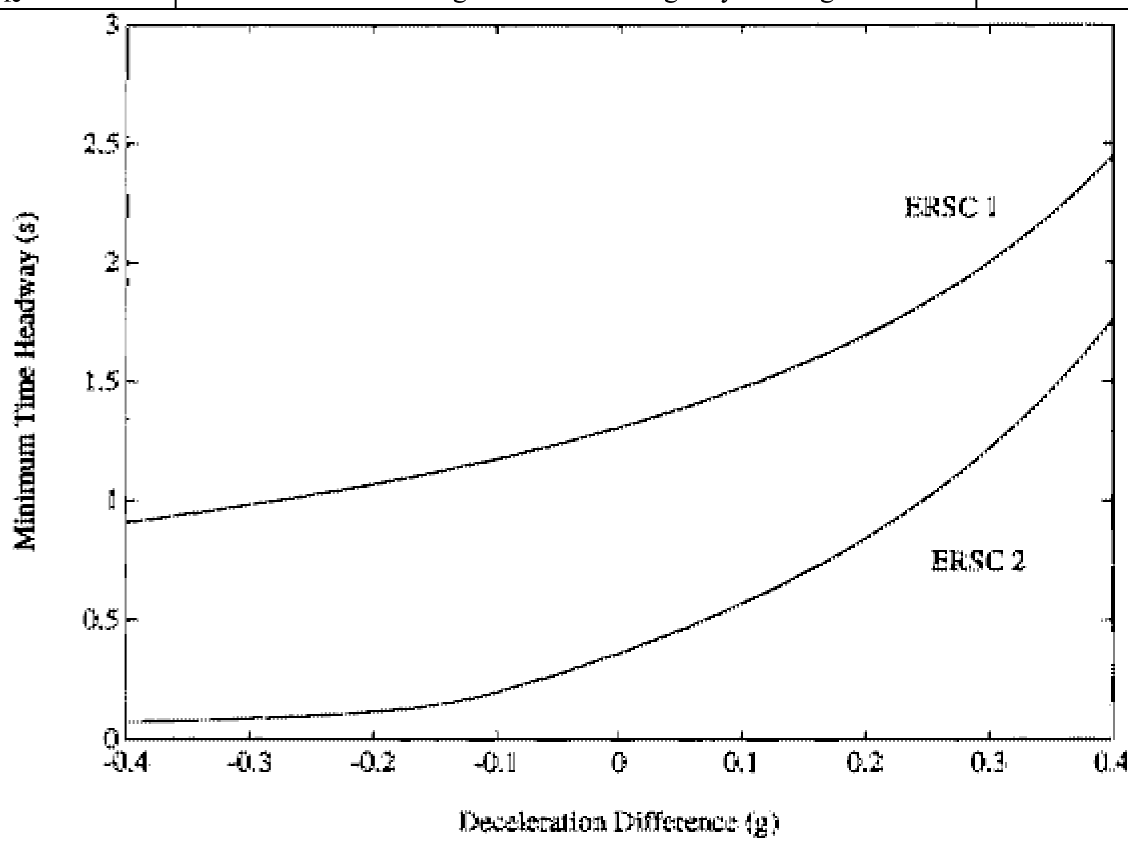


Figure 43. Minimum safe time headway with respect to differences in the maximum deceleration between vehicles ÆA_m= A_{lm}–A_{fm}. A negative acceleration value means that the follower car can brake faster than the lead car. ERSC 1 is the headway when the driver is responsible for any emergency braking situations. ERSC 2 shows the minimum headway when the vehicle has a rear-end collision avoidance function.

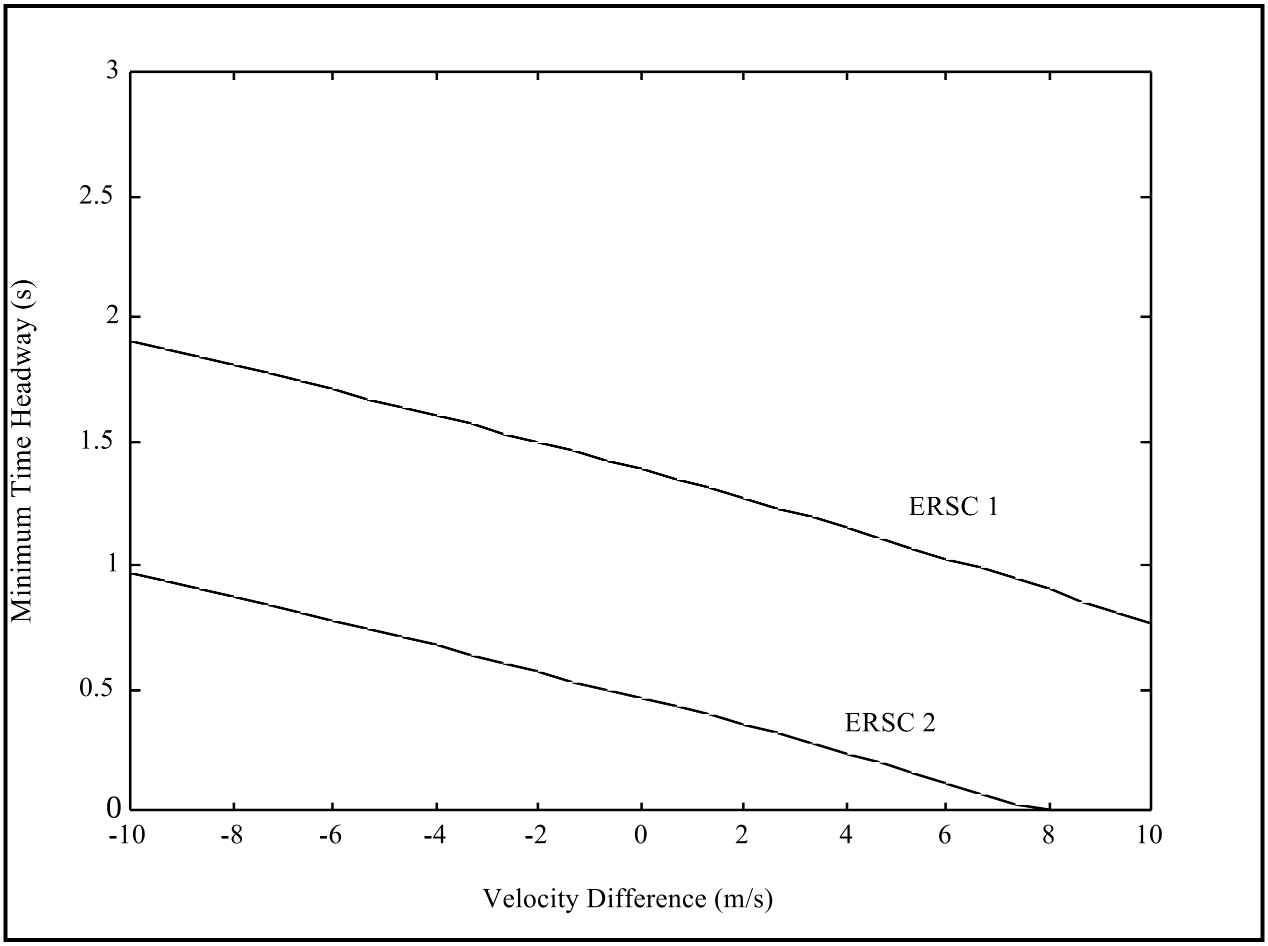


Figure 44. Minimum safe time headway with respect to differences in the initial velocity of the vehicles Æ$V_m = V_{fm} - V_{lm}$. A negative velocity difference means that the follower car is going faster than the lead car. ERSC 1 is the headway when the driver is responsible for any emergency braking situations with a 1.5 second human reaction time. ERSC 2 shows the minimum headway when the vehicle has a rear-end collision avoidance function.

Figure 44 shows the minimum time headway for different initial velocity values of the follower car. When the follower vehicle is going faster than the lead vehicle the safe time headway increases. When the follower vehicle decelerates slower than the lead vehicle the safe time headway decreases. This shows the needed gaps for cars changing lanes in and out of the dedicated lane from the manual lanes. If there is a large speed difference between lanes, vehicles will need to find large gaps to merge into the automated lane.

The condition of the roadway surface also affects the safe headway in between vehicles. Figure 45 shows the time headway for different road-tire friction coefficients. Weather conditions and roadway surface can affect the friction coefficient. [5,41] The antilock braking system on board the vehicle helps achieve the maximum deceleration without sliding the tires. This maximum deceleration is limited by the tire-road friction coefficient μ_x. The road-tire friction coefficient is weather and speed dependent. This coefficient may be estimated by the vehicle over time.[41]

If the follower vehicle decelerates slower than the vehicle in front then the minimum time headway increases. This figure assumes that both vehicles are on the same surface. For example it's raining and the roadway is equally wet for both vehicles. Localized patches of ice or puddles can cause large changes in the friction coefficient. This leads to fast changes in ÆA_m and the minimum time headway.

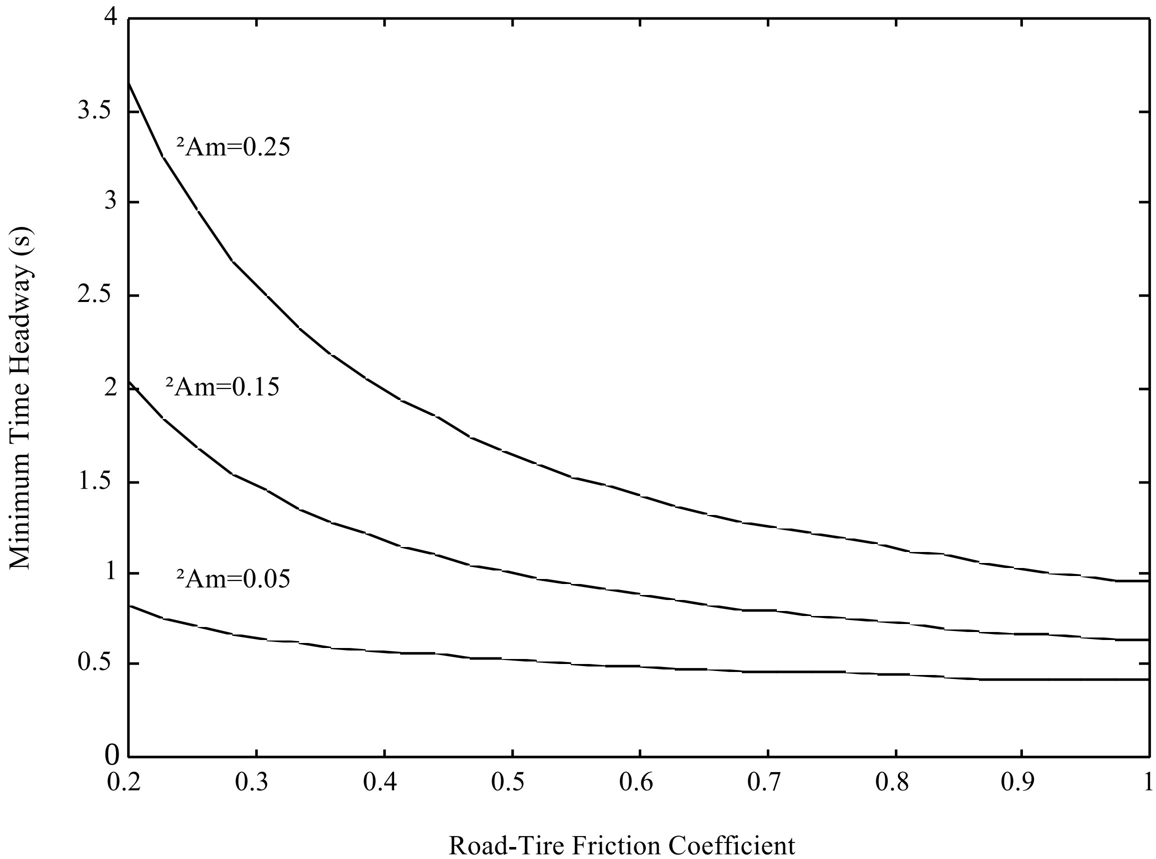


Figure 45. As the road-tire friction coefficient decreases (the road gets more slippery), the minimum safe time headway increases. ÆA_m = A_{lm} – A_{fm} is the deceleration difference between the vehicles in g. A positive value means that the lead car has a larger deceleration than the follower vehicle.

Figure 46 shows the minimum time headway for different initial velocities. Faster velocities lead to slightly larger minimum time headways. This parameter has a small effect on the final calculation of a safe headway. This implies that the velocity measurement accuracy may not be an important design requirement.

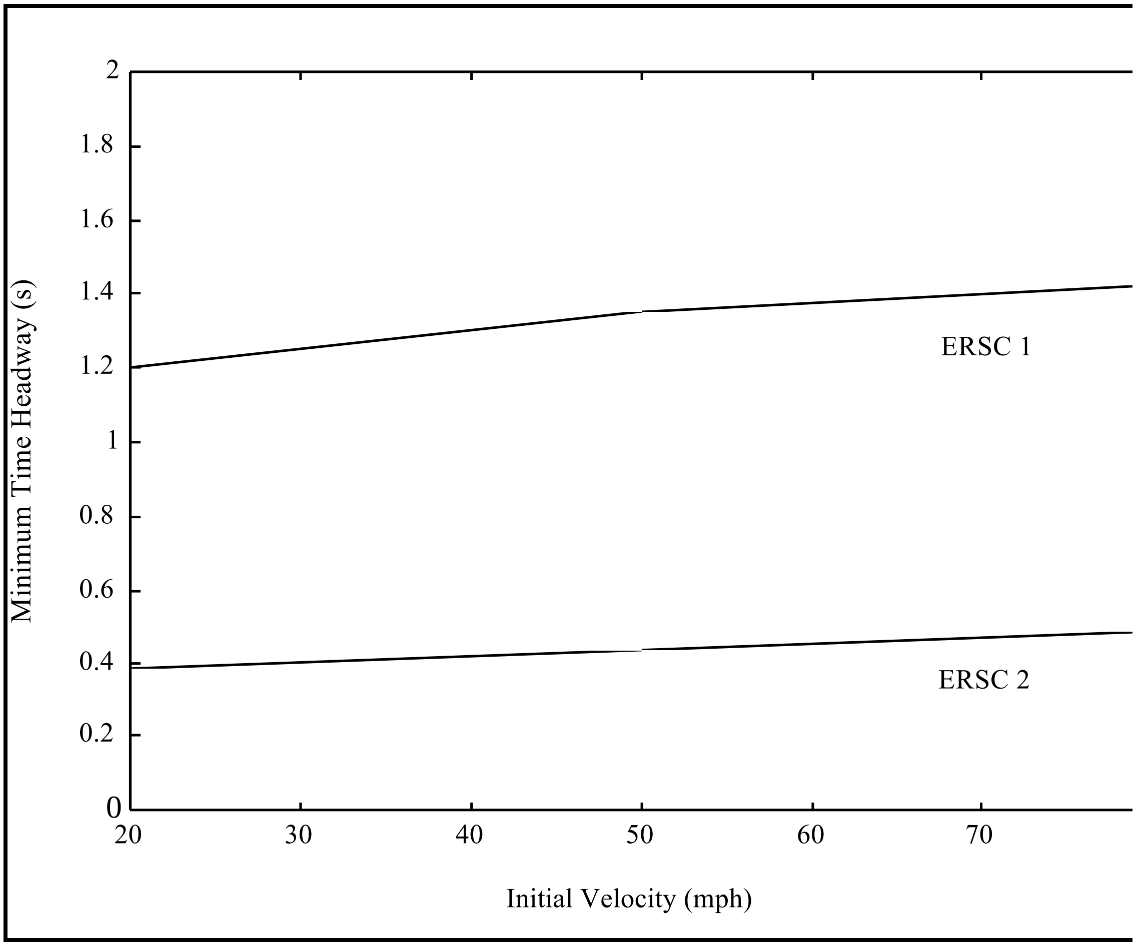


Figure 46. Minimum safe distance between vehicles for different velocities. ERSC 1 is the headway when the driver is responsible for any emergency braking situations. ERSC 2 shows the minimum headway when the vehicle has a rear-end collision avoidance function.

Driver/Roadway Interface

The vehicle responds to driver commands for switching the SHM function on and off, selecting the minimum headway, and overriding the SHM function. It also responds to roadway speed commands, headway recommendations, and displays traffic status information received from the roadway to the driver.

The driver turns the SHM function on and off. The SHM function may be turned on before the driver enters the dedicated lane or once the driver has successfully merged into the lane. Tests on a vehicle with one experimental SHM system show that most drivers do not feel safe using this automated system while merging. [26] This switch needs to be standardized and clearly marked so that the driver can begin automated operations quickly and easily. If the driver turns off the SHM function, the vehicle first increases the headway between itself and the vehicle in front since the human driver has a slower reaction time than the automated rear-end collision avoidance system. Then it transfers brake and throttle control to the driver. The check-out function regulates this transition. [108]

The vehicle responds smoothly to target speed commands from the roadway when the vehicle is in cruise mode and it is safe. The vehicle uses the time headway recommendations from the roadway and driver as lower bounds for safe headway selection.

The SHM function must clearly inform the driver of its goals and intentions so that the driver knows that it is working properly. This means that driver needs to know whether the vehicle is in following or cruise mode. The driver also needs to know the target speed and headway. This will help the driver monitor the vehicle's performance and status.

Issues and Risks

1 Function Accuracy

The SHM function has to be very accurate in this ERSC. The components for a more accurate SHM function need to be designed with AHS requirements in mind instead of taking commercial technology off the shelf.

2 Controller Algorithms

The controller algorithms need to smoothly adjust the brake and throttle to avoid sudden accelerations when the vehicle ahead leaves the lane. Driver tests indicate that drivers feel unsafe when the controller suddenly accelerates.(26) The controller needs to use algorithms that limit accelerations.(51,25)

3 Electromagnetic Interference

Full deployment of these ERSCs means that most vehicles will have active sensors such as radar. When multiple radar operate in a small area at similar frequencies the radar may interfere with one another. This interference could lead to shorter sensor ranges and poor performance.

4 Driver Interface

Research needs to be done on the driver interface to the SHM function. This device may have separate controls for enable/disable and minimum time headway. It may be too much of a burden on the driver to expect him or her to change lanes and start the SHM immediately. This function may require the driver to preset the target speed and minimum headways when he/she starts the vehicle. Human factors studies with pilots show that touch pads and buttons distract the pilot and may cause accidents.(8)

Rear End Collision Avoidance

The rear-end collision avoidance function should avoid rear-end collisions due to moving or stationary obstacles in the lane ahead under all road and environmental conditions. The rear-end collision avoidance (RECA) function needs to analyze threats fast enough to take action and override the SHM function when emergency braking is needed. The RECA also needs a low rate of false or nuisance alarms. Vehicle-to-vehicle communication of braking capabilities, decelerations, and intentions are useful in reducing false alarms. Figure 47 shows the block diagram of the rear-end collision avoidance system.

Figure 48 shows some different rear-end collision avoidance scenarios for this function. Rear end collision can be avoided by emergency braking and/or lateral maneuvers. In this ERSC, we consider rear end collision avoidance achieved by automatic emergency braking only. Lateral maneuvers are performed only by the driver in this ERSC.

The system detects the headway and the preceding vehicle's velocity/acceleration and uses these data to determine the required deceleration. If the vehicle decides that the soft braking of the SHM function can not provide enough brake force, then the rear end collision avoidance system will brake more to stop the vehicle. The driver's comfort will be affected and driver's steering control will be crucial for keeping the vehicle in the lane when harder braking is needed. The vehicle needs to warn the driver of the braking action to be taken.

The setting of the headway threshold for emergency braking should be such that the vehicle can brake safely without collision. The headway threshold is a function of the road-tire friction coefficients, the vehicle speed, and the vehicle braking capabilities. A conservative threshold setting will improve longitudinal control safety. It will also reduce the highway capacity.

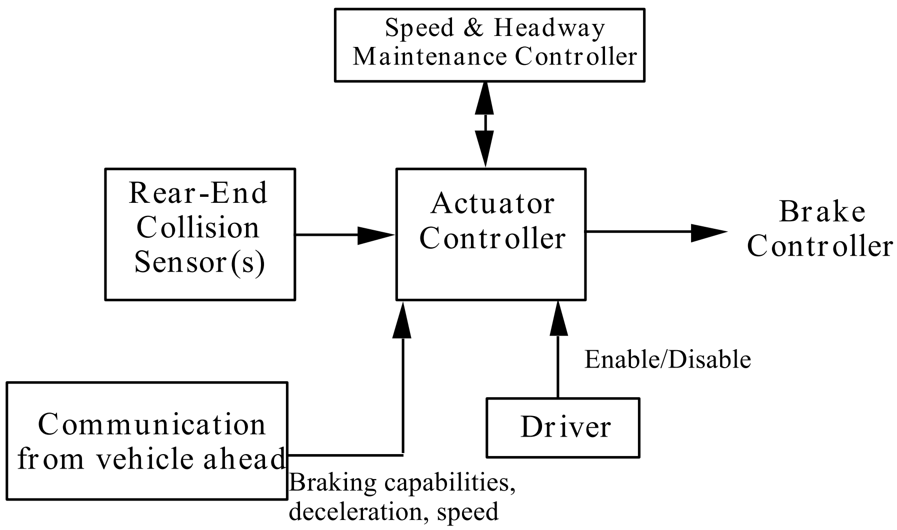


Figure 47. Block diagram of the rear-end collision avoidance system. The sensor measures the distance to obstacles. The controller assesses collision potential. This controller overrides the SHM function if an emergency stop is required.

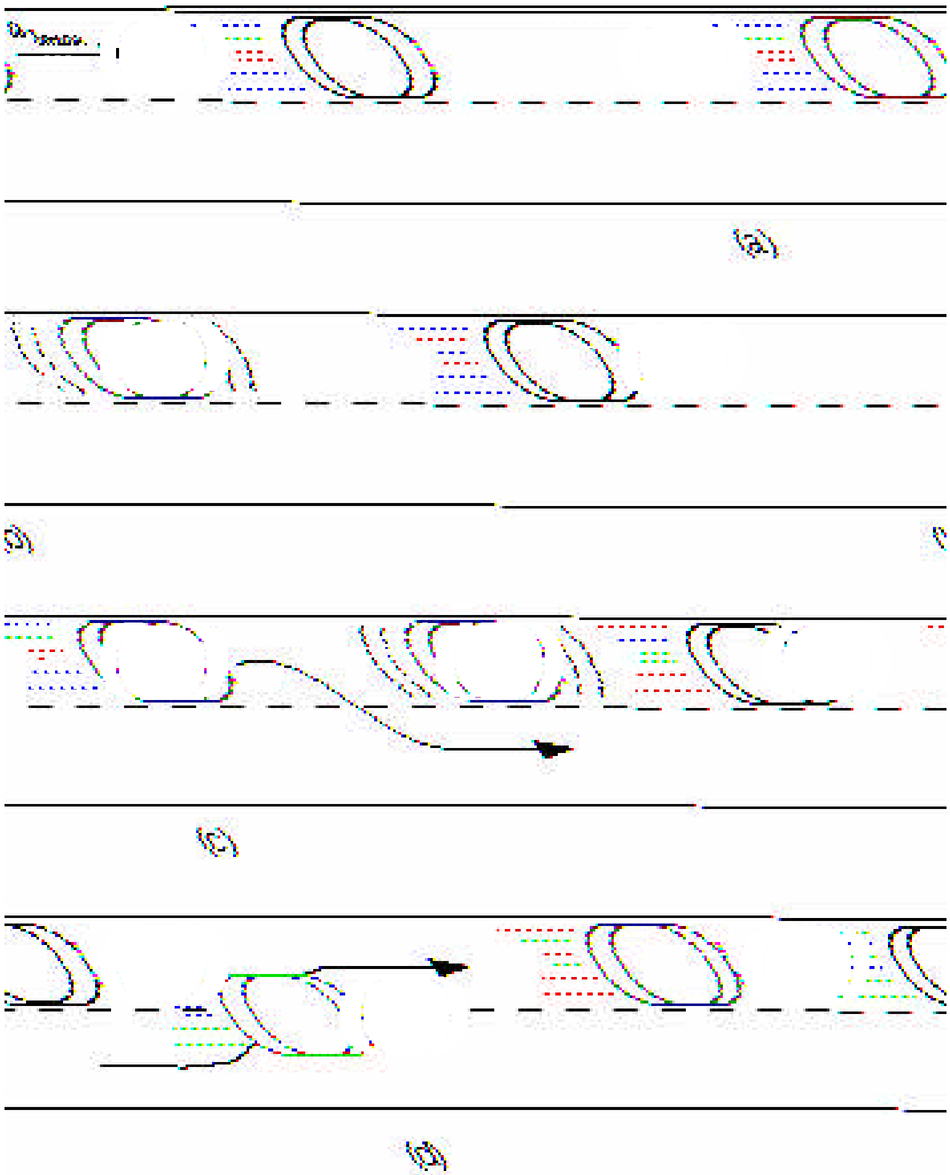


Figure 48. Different collision avoidance scenarios for the rear-end collision avoidance function. (a) The vehicle ahead begins an emergency stopping maneuver. (b) Another vehicle is stopped in the lane ahead. (c) The preceding vehicle performs an evasive maneuver by steering out of the lane to avoid a vehicle or debris ahead. (d) Another vehicle cuts-in ahead.

Sensor

The rear-end collision avoidance system uses a velocity sensor, a ranging sensor and a closing rate sensor to recognize potential collisions. These inputs allow the vehicle to estimate the time to collision that is the gap distance over the closing rate, the time headway, and the safe stopping distance. Sensors that estimate the roadway coefficient of friction may also improve the performance of a RECA system. (41)

The second requirement is that the system be able to stop when there is debris or another vehicle stopped in the roadway ahead. This scenario is known as the “brick wall” scenario. Rear-end collisions with a stationary vehicle outnumber rear-end collisions where the lead vehicle is moving by 2:1.[60] Figure 42 shows some range curves for the brick wall scenario for different velocities and a detection time of 0.5 seconds for the rear-end collision avoidance system. For example, at 100 km/h we get a range of 80 m for a vehicle with a maximum braking capability of -0.55 g. Table 17 gives the parameters used in this calculation. Figure 49 compares the stopping distances for ERSC 1 and ERSC 2 for the brick wall scenario. Since the driver’s reaction time is eliminated in ERSC 2 maximum sensor range for safe stops is smaller.

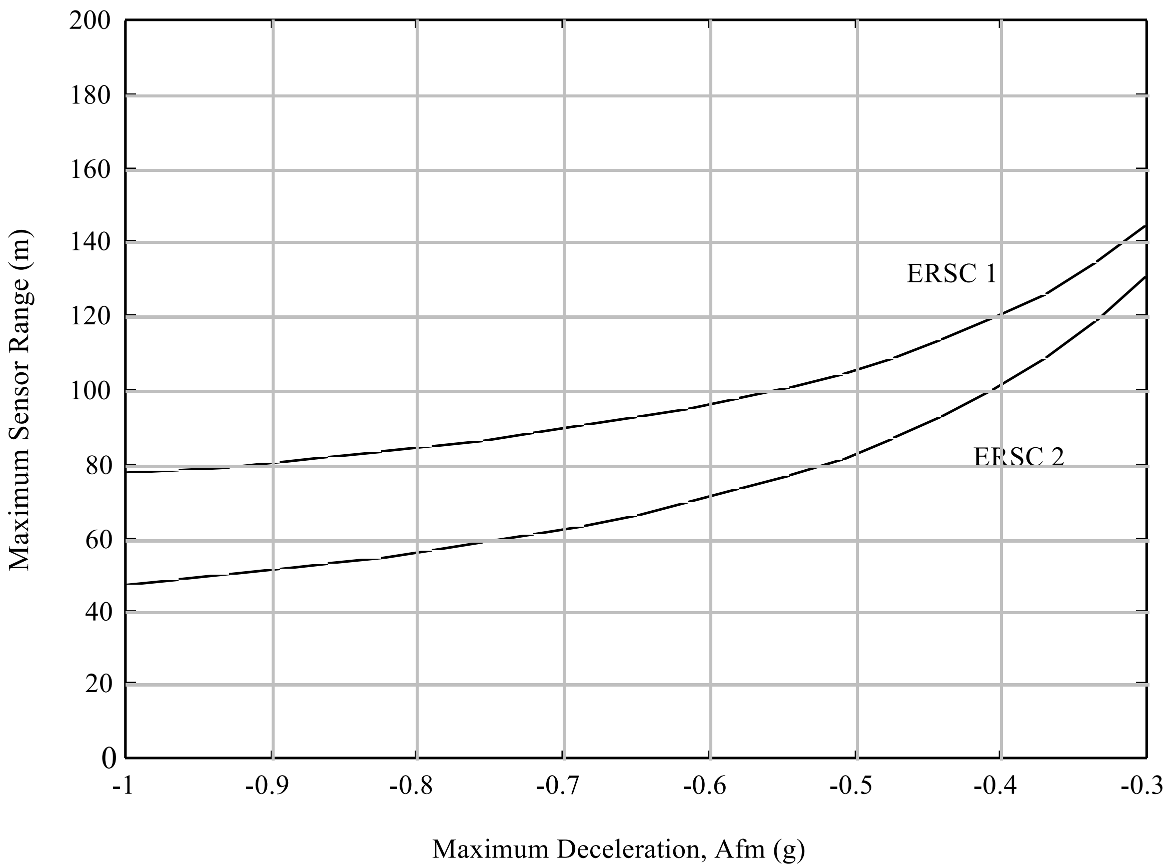


Figure 49. The maximum sensor range with respect to the maximum deceleration of the vehicle at 60 mph for ERSCs 1 and 2 (SHM without and with rear-end collision avoidance) These values come from the “brick wall” scenario when the lead vehicle is stationary or there is debris on the highway.

The sensor must also detect vehicles that cut-in in front of the automated vehicle. A single beam sensor does not see the cut-in until it enters the beam as shown in figure 11. The speed of detection depends on the area covered by the sensor, the lateral velocity of the vehicle that is cutting-in, and the distance of the cut-in from the vehicle. Most lane changes can take about 2-6 seconds.[21]

Since this system may not allow the driver to override the brake and throttle controllers, the sensors must detect all dangerous situations that the driver can see. Human factors studies on function allocation recommend that drivers should be able to override automated functions since a human driver may detect danger that the sensor does not see. (70) This implies that the vehicle must use a vision-based sensor to see what the driver sees. The problem lies in scene interpretation. Humans are superb at interpreting general scenes and identifying objects such as cardboard boxes or a dog loose on the highway. Computers require large databases to perform the same task. Most vision-based sensors track road lane lines or look for simple structures in the scene. (76,68) Other systems use "optical flow" to track objects.

There are no computer vision systems available today that can interpret a general scene as well as human driver. Current systems look for expected objects such as other vehicles, signs, and lane lines. Humans can see animals and debris.

Control Algorithm

The warning algorithm for rear-end collision avoidance is based on the time-to-collision (TTC) or minimum headway between the lead and following vehicles.

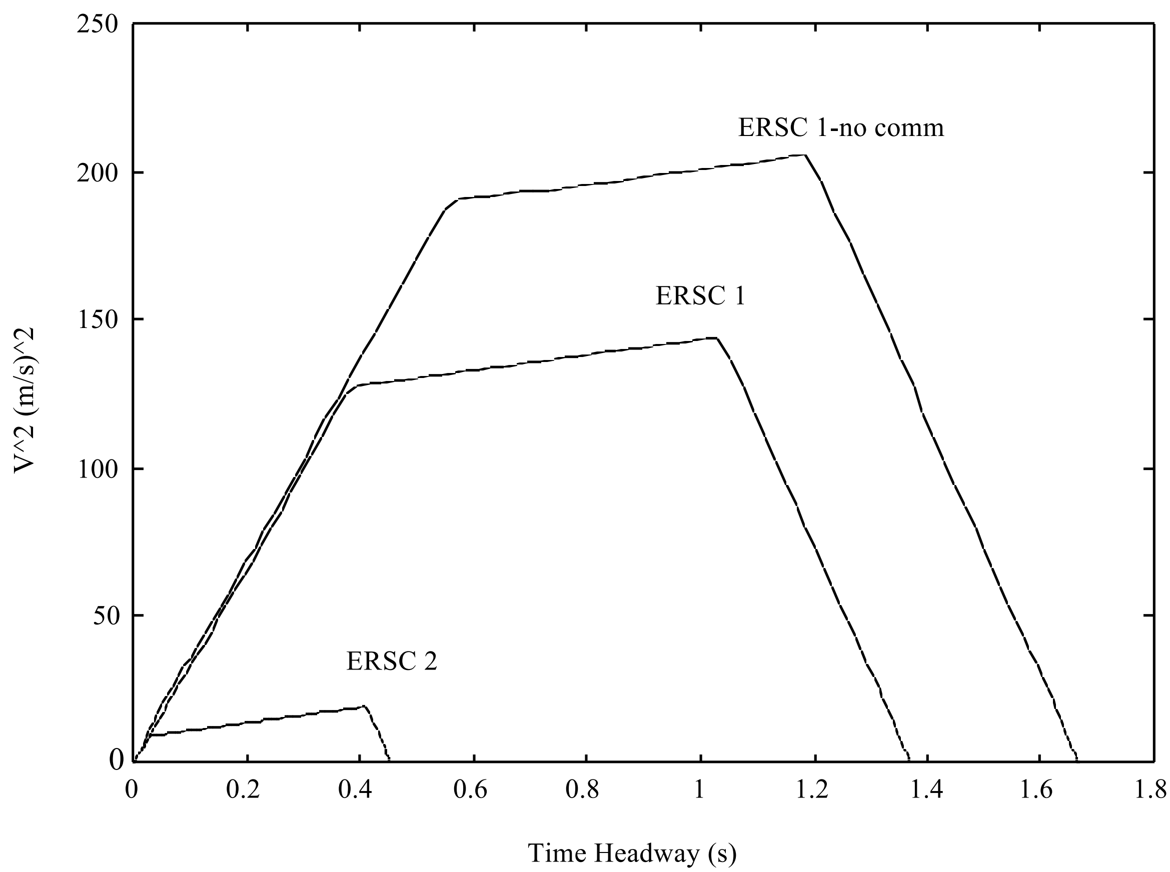


Figure 50. Changes in the detection time for lane change/merge collisions have a large effect on the potential accident severity.

The collision avoidance system must warn the driver when the vehicle ahead is braking without false alarms. High rates of false alarms may cause the driver to ignore the warnings, second guess the system, or turn off the system. This problem has been observed in the Traffic alert and Collision Avoidance System (TCAS) for airplanes. [96] This system recommends and coordinates actions for aircraft. False alarms cause hesitation and second-guessing by the pilots.

The follower vehicle must detect that the lead vehicle is starting to brake hard. This can be done either with the detection of a change in the relative velocity or acceleration between the vehicles or with the reception of an emergency transmission from the leading vehicle (a sort of electronic brake light). A deployed system may require both measurements for an emergency warning to the driver.

Vehicle to Vehicle Communications

The vehicle needs to estimate the time-to-collision (TTC) or minimum headway as described above. When the car ahead begins to brake with a deceleration, a_{bmax}, the TTC decreases. However the measurements for the distance and closing rate between the vehicle itself and the target vehicle can be quite noisy and inaccurate. The RECA function must distinguish between measurement noise in the controller and a true braking maneuver. A communications system lets the vehicle know the intentions of the preceding vehicle. The lack of this information may cause unsafe maneuvers or excessive braking. Appendix A gives the derivation of this relationship between detection time, false alarms, and detections.

Figure 51 shows the relationship for P_D and P_{FA} with respect to d. These parameters are explained in more detail in the appendix to the lateral and longitudinal control section. The curves change with . $= \infty$ corresponds to the case where the receiver always decides no acceleration. $= 0$ corresponds to the case where the receiver always decides that acceleration is present. In this case the cost for a missed detection is very high since the driver may not have an immediate override capability. The cost of a false alarm is lower since a false alarm only results in excess braking and lowered capacity. This gives a < 1. This shows that as the time available to detect a deceleration ahead increases for constant noise and accelerations, the performance of the detector improves. This may require a d on the order of 4 or higher. For example if the maximum deceleration of the lead vehicle is 8 m/s^2 and the noise deviation is 1-2 m/s for the sensor and controller noise then $t > 0.4$ s gives d=5. This means that we require at least a half second after the vehicle ahead has started braking to make a good decision. Note that the brake actuator delay (0.1 s) increases the total time delay to around 0.5 seconds before the RECA begins braking.

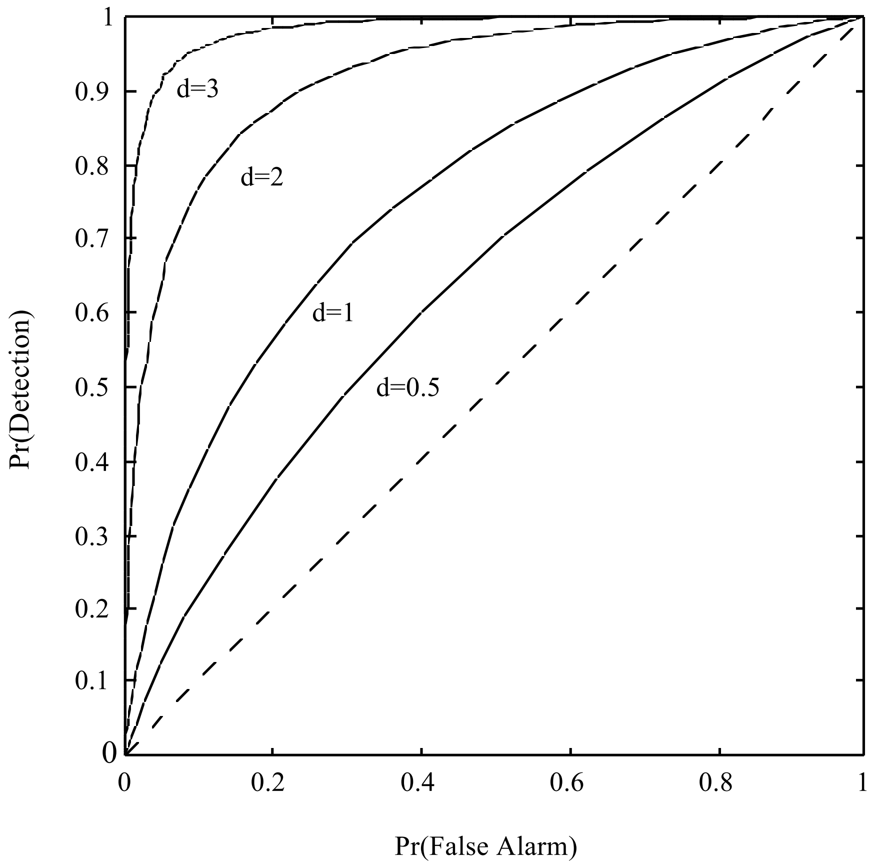


Figure 51. The probability of correctly deciding that the vehicle ahead is decelerating depends on the space between the two signals d. As d increases the detection-false alarm trade-off improves.

Vehicle-to-vehicle communications sends braking capabilities, velocity and acceleration data directly between vehicles. The probability of false alarm is low. As the lead vehicle brakes it sends its brake data directly to the vehicle behind. This braking data only needs to say that the vehicle in front is braking hard to communicate intent. This communications system can have a very short delay on the order of 0.05 to 0.1 seconds.

Each vehicle sends its deceleration to the car behind it. This lets the car behind anticipate any braking before changes in the distance or velocity can be measured. This data may be in the form of brake line pressure or an accelerometer measurement. Figure 52 shows how accident severity is affected by the deceleration capabilities of the vehicles.

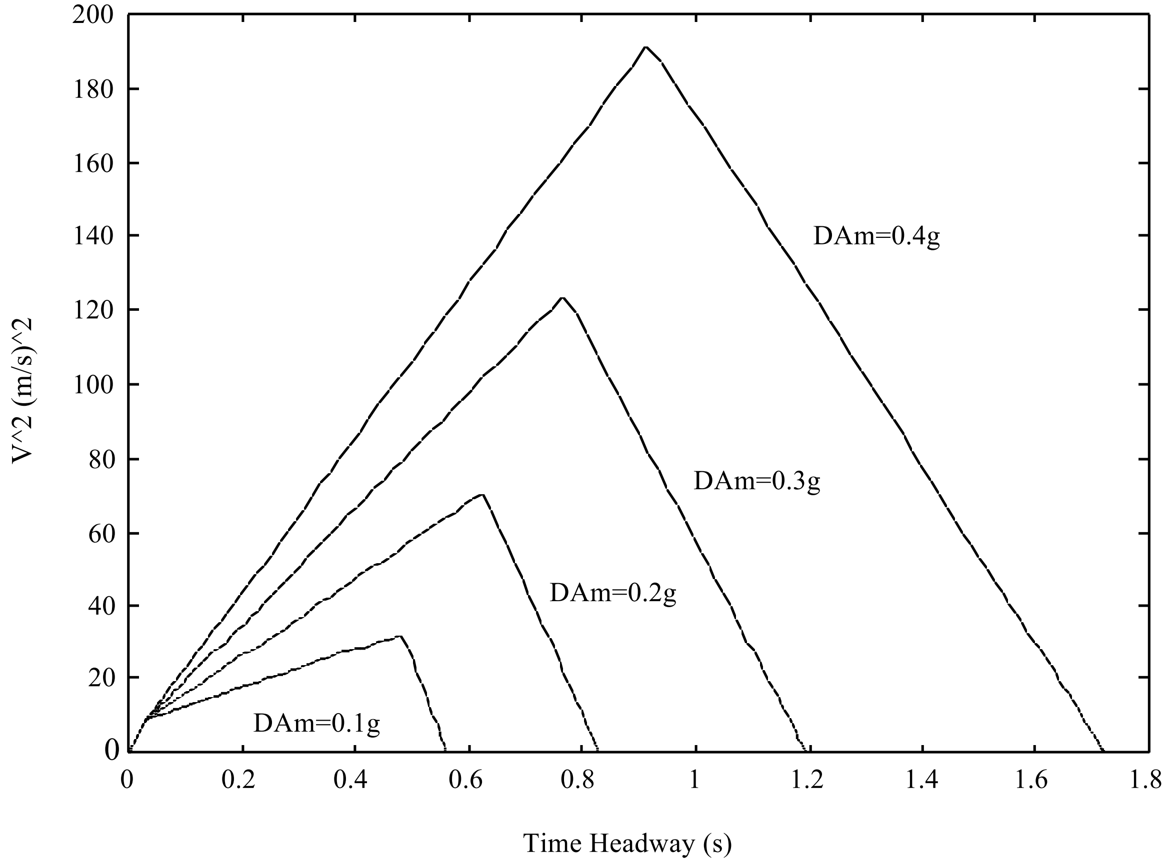


Figure 52. The deceleration difference between the vehicles ÆA_m=A_{fm}-A_{lm} has a large effect on accident severity. As ÆA_m increases the potential accident severity increases.

Other forces that decelerate a vehicle are the aerodynamic drag coefficient, the friction between the car and the roadway, and the slope of the roadway. The aerodynamic drag stays constant over the life of the vehicle. It may be compensated for by calibrating each car model. The frictional force between the car and the road depends on the roadway, the tire condition, and the mass of the vehicle and passengers. The road-tire friction coefficient may be estimated by measurements from an anti-lock braking system sensors. (40) This measurement coupled with an on-line estimate of the vehicle's maximum deceleration can give the vehicle's estimated braking capability.

Table 18. Data used in the message for vehicle to vehicle communications.

Data Contents	Source	Number of Bits
Road-tire friction coefficient	Estimated by vehicle	4-6
Maximum deceleration capability	Set by manufacturer or estimated by vehicle	4
Braking Intentions (Brake line pressure)	Measurement of brake line pressure or RECA intent	4
Velocity	Measured by vehicle	8
Acceleration	Measured by vehicle	4
	Total bits	22

Table 18 shows the fields needed in message passed between vehicles. This data may require on-line calibration to ensure that false braking signals are not sent out. The message between vehicles needs a length of around 65 bits in the worst case. This gives 16 bits for synchronization.[100] 8 bits each for the source and destination IDs if local addressing is used. The data field is 22 bits. 16 bits of error correction can help detect transmission errors.[100] If directional systems such as infrared (IR) or radio are used then the source and destination fields may not be necessary. [6]

The communications system must transmit over a range of at least 40 meters in a single lane. The signal delay is 0.05 seconds. The transmission rate is 20* M bits per second with a message length of M bits. The worst case transmission rate is 1100 bits per second. The transmission delays should be less than 20 ms since the brake data is time-critical. If the decision time is 0.1 seconds, the RECA receives at least two messages before beginning an emergency stop. The probability of message error (P_m) should be very low. Research at California PATH has produced IR systems that meet this data rate and accuracy requirement.[31] The tested system can transmit at 19.2 Kbits/second over a range of 30-40 meters.[31] As the distance between vehicles decreases the allowable data rate increases.

Driver Interface

The rear-end collision avoidance function needs to warn the driver that the vehicle is braking. This assures the driver that the system is working correctly. The warnings end when the vehicle takes action to end the threat.

The warning should be visual and located within 15-30 ° above the driver's line-of-sight for ordinary driving.[64] Visual signals are more detectable if they are near the center of the line-of-sight. The warning needs to give the driver informational feedback for headway maintenance and vehicle performance. [37] A headway display could provide this type of feedback with a heads-up display. [116,83] This type of display could also assist the driver in selecting a safe headway.

Issues and Risks

1 Sensor Capabilities

The RECA system may increase safety and reduce certain types of rear-end collisions by decreasing driver reaction time. But there are sensor and human factor issues that still must be resolved. The sensors must detect all vehicles or debris that a human can see with few nuisance alarms. A video system may be able to see small vehicles better during daylight. The video system sees what the driver sees so it may be more natural for human drivers to use. The performance of vision based systems may degrade at night and in rainy weather plus they are more expensive and complicated than radars or ultrasonic systems.

2 Collision avoidance system design

First the designers need to decide when the RECA function should be turned on: always on, only when the SHM function is on, or on only at higher speeds. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to get consistent and fast driver responses.

3 Multiple Warnings

ERSC 2 introduces multiple types of driver warnings for blind spot, lane departures, and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

4 Driver Override

This system may not allow the driver to override the brake controller immediately, without first going through check-out. This design may keep the driver safer by keeping the RECA active. On the other hand, it may interfere with the driver's ability to perform lateral collision avoidance. This area needs research to determine the best configuration.

Lane Departure Warning

The lane departure warning helps the driver safely follow the lane. When the system senses a lane departure danger, it sends a signal to warn the driver. This system consists of a lane edge detector, a warning algorithm, and a warning signal generator. Figure 53 shows the structure of lane departure warning system. The lane departure warning helps prevent single-vehicle roadway departure crashes. These crashes cause 37.4% of all fatalities, more than any

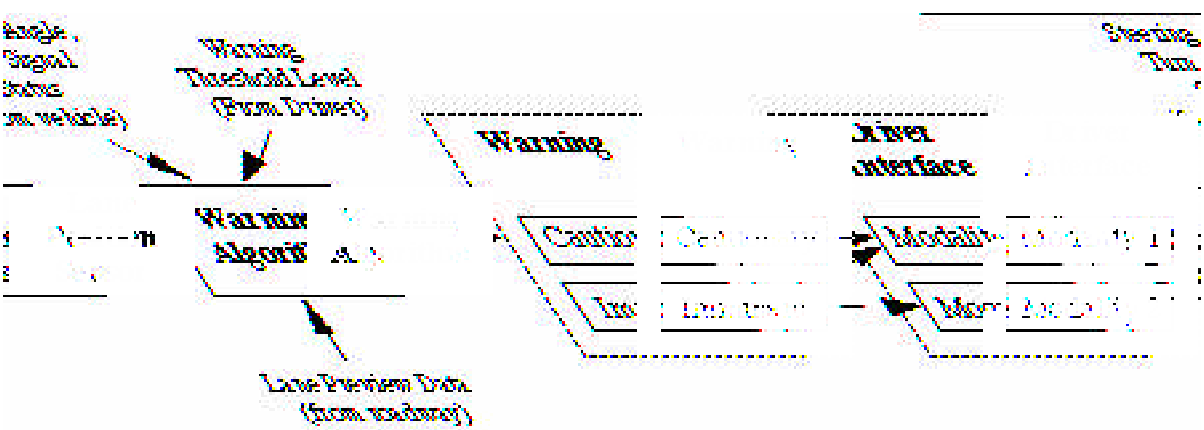


Figure 53. Block diagram of the lane departure warning system. The lane position sensors give the vehicle's position in the lane. The warning system calculates the time-to-lane-crossing and warns the driver if necessary.

other type of crash.[114] SVRD crashes are 20.8% of all police-reported crashes.[114] The lane departure warning may help prevent the crashes that occur when the driver loses control and drives off the road. But many of these crashes occur when the driver is trying to avoid a rear-end collision. Kinematics analyses of single vehicle roadway departure crashes indicate that for most crashes, the warning would come too late and the driver would not have time to respond.[72]

Sensor Requirements

The sensor needs to detect the vehicle's position and heading. The lane edge detector will require some form of lane reference aid provided by the roadway. This aid may be as simple as today's lane lines and "Bott's dots" or it could mean magnetic markers or wires embedded in the roadway. The sensing technologies can be vision-based [4,49,68], magnetic-based[95,43], or radar.[23] For accurate prediction of lane departures the vehicle may need roadway preview information that gives data on changes in roadway curvature. The system must also sense vehicle's turning angle and its turn signal status.

Vehicles with vision-based sensing will need an on-board forward looking camera or an infrared laser scanning system to sense the lane lines. An on-board real-time image processing unit then processes the sensed data and determines the lateral position. The lane reference aid can be as simple as stripes that show the lane edges. This sensing technique requires more instrumentation on the vehicle. Also, the lane reference aids can be easily maintained with existing systems. This sensing system suffers from the same limitations as human drivers at night or in bad weather .

Magnetic sensing techniques use sensors that sense magnets in the roadway. The induced voltage from the coils indicates the direction and lateral displacement from the lane center. The installation and maintenance of such lane reference aids on the roadway may be costly. Magnetic sensors may work better in snowy or rainy conditions. These sensors can encode preview data by changing the polarization of the magnetic field. The vehicle receives a binary code that can give data on the course of the roadway.

Radar-based sensing tracks a vehicle's lateral position with respect to reflectors mounted along the edge or center of the lane. The on-board transceivers emits laser beams to the reflectors mounted on the lane reference aid and receives the reflected signals. The on-board data processing unit computes the lateral deviation based on the sensed data. These systems may use reflective particles in the paint of the lane lines on the roadway. The main disadvantage in the radar sensing is that it provides little preview information. Without adequate preview information, the vehicle can not improve its tracking performance especially when it travels at high speeds.

The roadway may also send preview information to the vehicle with a vehicle to roadway communication system.[10,53] This data tells the vehicle what to expect ahead. This information may be easily updated to reflect variable road conditions such as detours.

Warning

The warning threshold should take into account the lane width, driver reaction time and, if possible, the rate of vehicle lateral deviation. The threshold should be designed to minimize the nuisance alarms while allowing the driver as much time as needed to correct his steering. Since reaction times vary among drivers, it might be necessary to let the driver select the warning threshold within some pre-specified range.

This system must estimate the time-to-lane-crossing (TLC). The TLC is the time necessary for the vehicle to reach either edge of the lane. This quantity may be based on a predictor model that assumes a fixed steering strategy during the time span of the prediction. [36] The estimate takes into account the initial lateral lane position y_o, the heading angle ψ_o, the vehicle speed V, the steering angle, and the roadway width. Figure 54 shows these parameters. Preview information can improve the estimate of lane departure time. Studies show that drivers need curvature information for distances proportional to the radius of curvature.

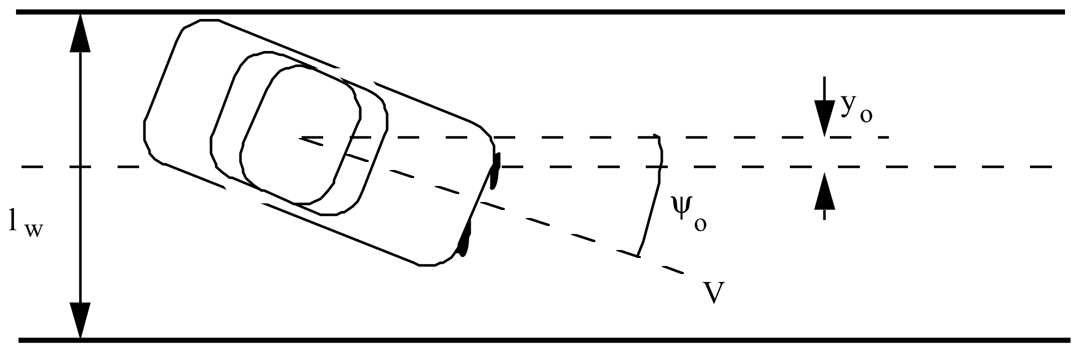


Figure 54. Variables used in the calculation of the time to lane crossing.

The lane departure warning system may be active whenever the vehicle ignition is on and the vehicle is going forward. [64] The system could also be active only if the driver is in the dedicated lane with the steering assist function turned on. The turn signal or turning on the blind spot warning would cancel the lane departure warning. The lane departure warnings may also be triggered by a change in the vehicle's steering angle that signals a lane change. This warning would probably occur too late to avoid an accident.

The lane departure warning system should have at least two levels of warning: an imminent crash avoidance warning and a cautionary warning. [98,64] A cautionary warning tells the driver that the vehicle has a short time until it leaves the lane. This warning may operate when the vehicle is moving forward or only whenever the automated systems have been turned on by the driver. An imminent crash warning alerts the driver to an imminent lane departure situation that exists when the vehicle will soon leave the lane or has already left it. A turn signal or large changes in the vehicle's steering angle can indicate a course change for the vehicle and may cancel the warning. The imminent lane departure warnings should turn off when the driver responds to the warning by correcting the steering angle.

The warning should give information on which side of the lane the vehicle is departing. Directional audio systems or a haptic warning can tell the driver which side of the lane the vehicle is approaching. Three-dimensional audio systems can help a driver recognize the angle of a threat faster.[9]

Driver Interface

The lane departure warning system provides levels of warning to the driver and provides a detector sensitivity adjustment for the driver. The different warning levels allow the vehicle to warn the driver without intrusive nuisance alarms. The detector sensitivity adjustment lets the driver adjust the range of the sensor to reduce sensitivity and false alarm rates. [64]

The cautionary warning should be visual and located within 15 ° above the line-of-sight of the driver.[64] Visual signals are more detectable if they are near the center of the line-of-sight. The warning needs to give the direction and degree of threat without startling or annoying the driver. The imminent lane departure warning should use two modalities of warnings. Lerner et al suggests a combination of auditory and visual warnings. [64] An auditory warning can help the driver determine the direction of the imminent collision with a directional signal. [9] This system could also use tactile warnings that use the steering wheel to give cues to the driver. Haptic warnings should only be used when they directly relate to the driver's needed action.[64] The system provides artificial feel feedback to the driver through the steering wheel. If necessary, the driver could override the lane departure warning and steering assist system by turning the wheel with extra force.

The lane departure warning system may have an adjustable threshold. This lets the driver reduce the sensor range to avoid excessive false alarms in which the driver perceives frequent hazards. For example, on curvy highways the sensors may be triggered as the vehicle drives safely around curves.

Issues and Risks

1 Sensor Capabilities

The lane departure sensor system may increase safety and reduce certain types of lane change/merge crashes. But there are sensor and human factor issues that still must be resolved. The amount of preview data needed for this system needs to be studied.

2 Warning system design

First the designers need to decide when the system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to be directional to get fast driver response.

3 Multiple Warnings

ERSC 2 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

Stability Augmentation System

Flight control systems have used stability augmentation systems for decades to help improve flight quality. A vehicle's steering control system may also contain a steering assist system to improve the driver's performance in lane keeping. (61) The driver uses the steering wheel to keep the vehicle in the lane and the steering assist system helps reject high frequency disturbances. The driver-vehicle system with steering assist thus improves its safety and performance when cruising at high speed.

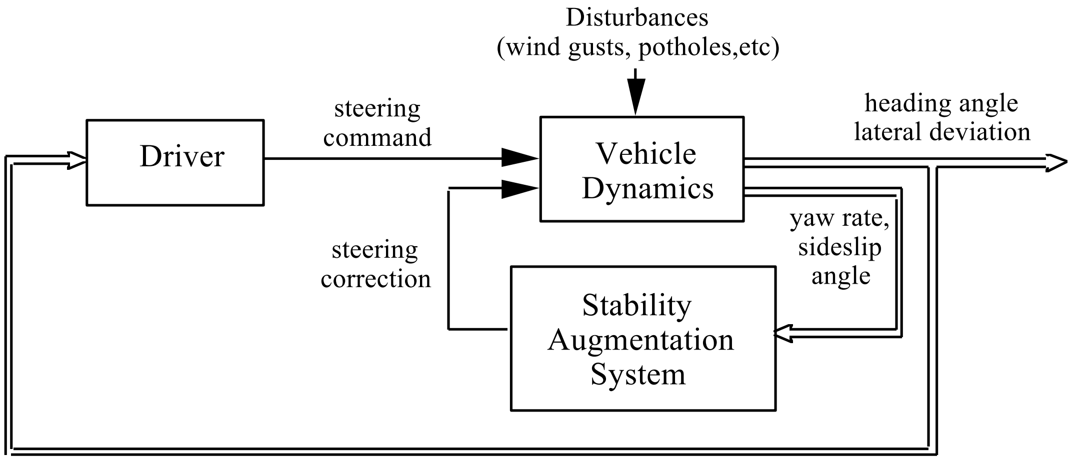


Figure 55. Block diagram of the steering assist system. The steering assist system acts as an inner loop to correct vehicle steering in the presence of disturbances such as wind gusts.

For a driver-vehicle system without a steering assist system the driver generates steering corrections based on his/her perceived heading and lane position errors. When the vehicle is traveling at high speed, the lateral control system has a high bandwidth and it is sensitive to external disturbances. The steering assist system serves as an inner loop to the human-controlled (outer) loop of the driver/vehicle system as shown in figure 55. The steering assist system consists of sensors, a computer with control algorithms, and a steering actuator. The computer generates steering correction commands to the actuator based on the data provided by the sensors. The actuator then carries out the high frequency steering actions to compensate the effects of the undesired external disturbances.

<u>Sensors</u>
The sensors collect the data on the vehicle's lateral dynamics (yaw rate, lateral acceleration and sideslip angle, etc.) A gyro built into the steering assist system can measure the yaw rate and lateral acceleration. (2,32) However, there are currently no sensors that measure sideslip angle and yaw angle accurately. Figure 56 shows the parameters that need to be measured for a steering assist system.

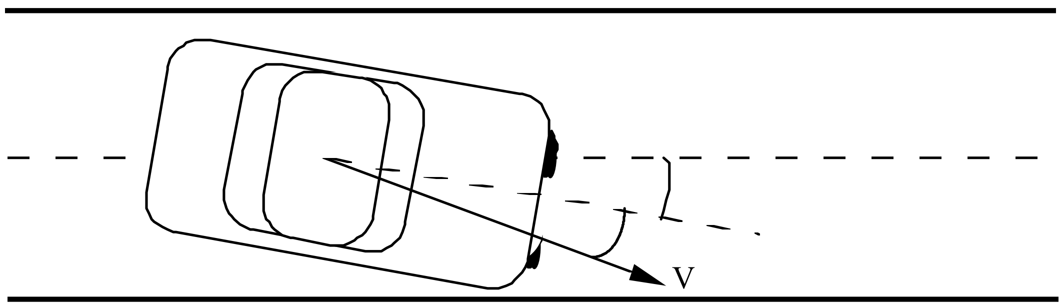


Figure 56. The sensors for the steering assist system measure the heading deviation ψ and the side slip angle β.

Control Algorithms

In the driver-vehicle system, the driver closes the steering control loop. [14] The driver's steering action contains a high frequency random response mode to keep the steering system in a dynamic mode, and a low frequency response mode that is related to the perceived lateral dynamic information. The driver's high frequency random response does not help lane keeping. There is a driver delay or lag between the time that a steering error occurs and the time that a low frequency steering correction is taken. The lag is made up of the time needed to decide what corrective action should be taken and the time necessary to initiate that action. The lag time varies as driving continues and is different for each driver. A value of 0.5 second[14] approximates the driver's average time delay. The average driver reaction time to strong wind gusts ranges from 0.3 seconds to 0.6 seconds. [115] This reaction time depends on the rise time and amplitude of the wind gust.

The steering assist system can reduce the driver's lagging effect on vehicle steering. The steering assist system senses lateral dynamics faster than the driver. If the sensors measure this data quickly enough, the steering assist system's control actions can compensate for high frequency lateral disturbances. This gives a stability augmented vehicle with higher stability margin, lower bandwidth, and better ride quality. Studies have shown that pilots prefer planes with natural frequencies of $\omega \leq 1$ radians/second and a damping ratio > 0.5. Aircraft that violate these guidelines are generally considered fatiguing to fly and are undesirable. [32] During high speed lane keeping, the driver may be subject to constant lateral and vertical vibrations. The average lateral acceleration should be less than 0.06 g for steady cruising comfort. Other studies indicate that the dominant natural frequency of the lateral motion should not exceed 1.2 Hertz (7.5 radian/sec) for buses. [2] In addition, for ride comfort, the maximum instantaneous lateral acceleration should be within the limit of 0.4 g.[3]

Actuators

An important factor that affects the steering performance of the driver-vehicle system is how fast the steering assist system generates the required steering correction. A steering assist system can improve the performance with a small delay relative to driver response. Studies show that driver reaction time to sudden wind gusts ranges from 0.3 to 0.6 seconds. [115]

The control effort generated by the steering assist system actuators needs to limited to small changes so that a system malfunction will not endanger the driver's steering control. This can be done by limiting the actuator output within certain range. Since the driver still controls the steering wheel, the driver's lateral control degradation will be minimal.

Driver Interface

The driver interface for this system should be transparent to the driver. This system should turn on automatically when the driver is at cruising speed or when the driver turns on the SHM function. The driver can override the steering assist function at any time by changing the steering angle of the vehicle and saturating the actuator.

Issues and Risks

1 Driver Override

The driver needs to be able to easily override this function to get the vehicle back into the center of the lane or to avoid a collision.

2 Interactions with Lane Departure Warnings

This function could work with the lane departure warning by providing inputs such as tactile steering “hints” that encourage the driver to return to the middle of the lane. This system requires different types of steering actuators that work in parallel with the driver to provide independent control inputs.

3. Faster Speeds

The steering assist function may allow drivers to comfortably go faster in a dedicated lane. This may cause unsafe conditions if this function fails.

Driver Interface

The driver should be able to override the speed & headway maintenance function and adjust the headway as described in the section describing the SHM function. The driver should also be able to adjust the warning thresholds on the lane departure warning and the blind spot warning. The driver also receives highway traffic information through the vehicle and may use it for speed/headway selection or route planning. The driver may also receive preview information from the roadway. This data may tell the driver about sharp curves up ahead or other roadway conditions. The driver also monitors the vehicle’s operational status and backs up failed vehicle functions. If the SHM system fails the driver takes over manual control of the vehicle in the fall-back mode.

The driver interface must show the driver that the automated functions are operating correctly or that a function has failed. This interface should be simple to understand and use. No adjustments should be required that take the driver’s attention away from the driving task. Input systems like touch pads or buttons may be distracting and may require too much driver attention.(8) The driver must be able to tell what the vehicle is doing at all times and why it is doing it. Studies show that drivers cooperate more when they know the reasons for an action.(10)

Head-up displays may be particularly useful for visual indicators of the system operation. For example a heads-up display could show the measured distance to the vehicle ahead as well as the minimum time headway and target speed. Other technologies include liquid crystal displays (LCDs), light-emitting diodes (LEDs), computer generated voice messages, sudden vehicle accelerations/decelerations (jerk), tactile feedback, and directional audio displays.[64,8,9,116]

The interface may be continuous or only active when a driver action is needed. The best design of the driver interface for human factors is an open issue and involves selecting a display technology, type and duration of warnings, user control types and locations, etc. User acceptance is crucial to user interface design. [54,67] The systems in each ERSC must be easy to use and understand and easy to adjust without the driver taking his/her eyes off the roadway for more than 1-2 seconds. [73]

Roadway/Vehicle Speed & Headway Commands

The roadway measures the average speed and traffic density, assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways. The vehicles follow the target speeds set by the roadway using the speed and headway maintenance function. The vehicles should respond to headway recommendations for longer headways due to changes in environmental conditions such as slick roads. The vehicles use the environmental data from the roadway to adjust their time headways. The vehicles check-in with the roadway by sending their identification, automated function status, and location. [108] The vehicles may also display relevant traffic information from the roadway to the driver for route planning purposes. This section covers roadway sensing systems and roadway-vehicle communications.

Roadway Sensing Systems

The roadway needs to sense the average traffic density over sections of the roadway. [58] This data can be measured by sensors that are part of the infrastructure or the vehicles can transmit their measured speed and headway to the roadway with a vehicle-roadway communication system. The vehicle may also transmit its operational status and identification to the roadway for check-in or incident management. The roadway also needs to measure roadway weather data to select a safe target speed for the environmental conditions. [57]

Vehicle to Roadway Communications (VRC)

The roadway sends speed data to the cars to smooth traffic densities and manages incidents. The vehicles may also send their measured velocity and headway to the roadway. This system may also be used for check-in. This allows the roadway to monitor the operational status of the vehicles and ensure that they are correctly operating in the automatic mode. These messages only need to be sent once per section. The vehicles will also check-in with the roadway to ensure that they are working correctly. Each vehicle sends status data on all of its automated functions to the roadway. In ERSC 2 these functions are: speed and headway maintenance, rear-end collision avoidance, blind spot warning, lane departure warning, steering assist, VRC systems, and critical engine functions. [108]

VRC systems can be mounted on the side of the roadway, on overpasses, or embedded in the roadway.[85] These systems may use automated toll collection technology with variable registers or a system that covers a wider range. [22,53] Appendix A covers the operation of these systems.

Target speed messages from the roadway to the vehicles do not need a high data rate since it will not change very often. Each field will need 6-8 bits to give a resolution of 1 meter for the gap limit and 1 mile per hour for the velocity limit. Since the message goes to all cars a destination ID code is not needed. The source ID code indicates that the message is from the roadway. Error detection coding looks for bit errors in the message. Retransmission requests are unnecessary since we can rely on repeating the message. This message should be repeated at most one time per second. The bit error rate can also be high since the message changes slowly and rarely. Repetition of messages can compensate for the high error rate. If the roadway sends preview data to the vehicles, the messages may need to be longer in curvy regions of the roadway.

The VRC may also send messages from the vehicles to the roadway. Each vehicle sends its speed and the distance to the preceding vehicle (6-8 bits each). The vehicles may also send a unique identifying code (28 bits) to the roadway for check-in. The operational status of the automated system can be sent as well, this could take 8-16 bits depending on the amount of detail required by the roadway. Other variables such as estimates of the road-tire friction coefficient can take 4 or more bits. Table 19 shows the possible variables to be sent to the roadway for check-in.[108] This gives a data length of around 90 bits.

Table 19. Potential status variables to be sent to the roadway by the vehicles for check-in.

Function	Components	Number of Bi
Speed & Headway Maintenance	Sensors, Actuators, Controller	1-6
Rear-end Collision Avoidance	Sensors, Actuators, Controller, Vehicle-Vehicle Communications System	1-8
Blind Spot Warning	Sensor, warning	1-2
Vehicle-Roadway Communication System	Transmitter, receiver, variable register	1-2
Lane Departure Warning	Sensor, warning	1-2
Steering Assist	Sensors, Actuators, Controller	1-4
Vehicle Identification Code		28
Other Vehicle Functions	Critical fluids level and pressures, brake conditions, tire pressure, engine temperature, headlights	12-16

A broadcast system with a range of 100 meters for a single automated lane must communicate with 0.3 to 0.75 vehicles per second. Analysis by Polydoros et al shows that the current Hughes VRC system and automatic toll collection systems can meet the data transmission requirements for VRC in ERSC 2. [85]

Issues and Risks

1 Dedicated Lane

An issue for AHS is how to get a separate lane for automated vehicles. The driving public rebels when a lane is taken away from active use. [99] The solution for most highway departments has been to add a new lane on the shoulder or median strip, but most urban highways do not have any more space to spare for the sole use of automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

2 Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short. The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

3 Sensors

Roadway weather sensors only cover small regions of roadway. These sensors could easily miss patches of ice or puddles on the roadway. The roadway may then choose an unsafe headway. Research needs to continue into these sensors to improve their capabilities.

4 Privacy

The vehicles “Check-in” with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

5 Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

Fall-back Mode

The system needs to degrade gracefully if a failure occurs. Many failures such as blind spot warnings may not cause the vehicle to be non-operational. Vehicles with different capabilities can coexist in the dedicated lane without incident.

In case of failure in a single control channel of the rear-end collision avoidance system, the vehicle can operate in ERSC 1 control mode with the SHM and rear-end collision warning functions since these systems do not require parallel paths for reliability. The vehicle increases the following distance or headway to a safe headway for ERSC 1 and the driver resumes control of the emergency or hard-braking function with the help of the rear-end collision warning. However, according to Riley decoupling warning and avoidance modes can cause “role confusion” for the driver. [90] The driver may also be uncomfortable dealing with a sudden change in responsibility. The driver may also be uncomfortable taking over control at higher speeds or if there is reduced visibility. [90] System design may require that the driver can force the vehicle not to transfer control to the driver until the vehicle is ready to leave the dedicated lane. [90] Meisner et al believe that such transfers between automated and manual functions need to be handled jointly by the driver and the vehicle. [70]

If the lane departure warning or the steering assist functions fail the vehicle informs the driver. Failure of these functions does not require a transfer of control to the driver so they do not require the vehicle to return to ERSC 1 control. Loss of the steering assist function may make the driver more uncomfortable at higher speeds and increase driver fatigue, but it does not require a return to ERSC 1.

Issues and Risks

1 Control Transfer

Any control transfers between the vehicle and the driver need to show which one is in charge at any given time. Abrupt changes need to be avoided unless they are initiated by the driver.

2 Mixed Modes

Vehicles with different capabilities require diverse headways and different speeds.

Reliability Requirement Analysis

In ERSC 2, the vehicle longitudinal control is fully automated with the introduction of the vehicle rear-end collision avoidance function. The on-board speed/headway maintenance (SHM) and rear-end collision avoidance (RECA) system allows the driver complete feet-off driving. The SHM and RECA system takes into account the roadway target speed commands and headway recommendations, and the braking data from the preceding vehicle to determine the desired cruising speed and safe headway for collision free vehicle following.

The driver is not part of the longitudinal control loop and is not allowed to override the SHM and RECA system directly. The driver’s reliability has no contribution to the overall reliability of the vehicle longitudinal control. The reliability of the SHM and RECA system is crucial for safe longitudinal control. It needs to be highly reliable if it is to accepted by the general public.

The driver is still responsible for all lateral control functions but receives more assistance from the vehicle and the roadway. The driver’s lane changing and merging maneuvers are assisted by the blind spot warning (BSW) system. While in the dedicated lane, the driver’s lane keeping control is helped by the steering assist (SA) system and the lane departure warning (LDW) system. The SA system compensates for high frequency lateral disturbances while the vehicle is cruising in the lane. I helps the vehicle follow a straight line. The driver can override the SA system by simply turning the steering wheel hard. The LDW system gives warnings to the driver if it detects the vehicle is departing from the lane. The LDW system may require roadway lane reference aids to help measure lateral deviation from the lane center.

In ERSC 2, all the automation technologies related to lateral control are only to assist the driver. All lateral maneuvers are initiated and performed by the driver. The driver's reliability dictates the reliability of lateral control. The on-board BSW, SA, and LDW systems are to improve the driver's lateral control reliability.

Speed/Headway Maintenance and Rear-End Collision Avoidance

In ERSC 2, the speed and headway maintenance (SHM) system together with rear-end collision avoidance (RECA) system allows the driver complete feet-off driving. The SHM system controls throttle and soft braking to maintain a desired speed and/or headway during cruising and normal vehicle following. The RECA system uses hard braking to avoid rear-end collisions during emergencies, such as sudden hard braking by the preceding vehicle.

Due to the close interaction and coupling between the SHM and RECA systems in vehicle longitudinal control, it is desirable to analyze the reliability requirements of these two systems together. We will consider the SHM and RECA as one combined system. Since the SHM system has all the major components (headway/speed sensor, controller, brake actuator, etc.) that are needed to implement the RECA system, it is reasonable that the RECA system is embedded into the SHM system in the design .

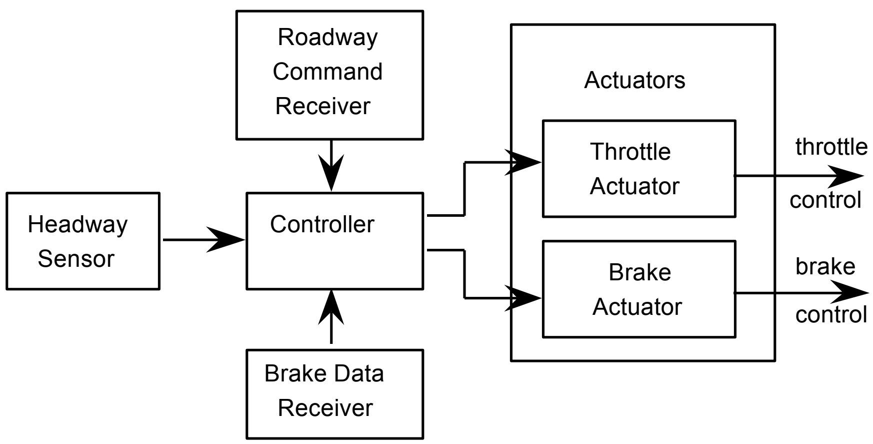


Figure 57. The functional block diagram of the SHM and RECA system.

The major components required to implement the SHM and RECA system are a headway/speed sensor, a controller, a brake actuator, and a throttle actuator, as shown in figure 57. The headway/speed sensor measures the headway and the preceding vehicle's speed. The brake data receiver receives the preceding vehicle's braking capabilities and acceleration/deceleration intentions. The roadway command receiver receives the target speed and minimum time headway commands, road surface conditions, etc. The controller uses the vehicle's braking capabilities, those of the preceding vehicle, and speed command and headway recommendation provided by the roadway to determine a desired speed for cruising and a safe headway for vehicle longitudinal control. The controller generates throttle/brake commands to the throttle/brake actuators for collision free vehicle following.

The received preceding vehicle's braking intention can be used to predict the necessity of hard braking more accurately.

Required Reliability Estimation

The headway used by the controller does not take into account the driver reaction time since the vehicle handles the rear-end collision avoidance. The driver is not expected to take over longitudinal control safely if the SHM and RECA system fails. The driver can not be considered as a back-up to the SHM and RECA system. The SHM and RECA system has to be so reliable that an internal system malfunction will not lead to a rear-end collision. Drivers in the U.S. average one rear-end collision about every 50 years. [27] This suggests that the SHM and RECA system will not be accepted by the general public if its mean time to failure is not much greater than 50 years.

Reliability Functional Requirement

Since the driver is not considered to be a back-up to the SHM and RECA system, a rear-end collision may happen if the SHM and RECA system fails. A single component/point failure can lead to a rear-end collision unless the SHM and RECA system is designed to be fail-safe. The reliability functional requirement for the SHM and RECA system is thus proposed as:

> "Under no circumstances should a single component/point failure let the vehicle crash into any moving or stationary object in the lane, and there should be no common failure mode."

To fulfill this requirement, the SHM and RECA system needs to be able to detect potential internal failures. If an internal failure occurs, the system must be able to continue its function until the driver takes over control safely.

Required Redundancy

Safe longitudinal control relies on the accurate output from the subsystems of headway/speed sensor, controller, and throttle/brake actuators. The fact that these subsystems are connected in series implies that the whole system will fail if any one of these subsystems fails. To achieve the proposed reliability functional requirement, component redundancy will be needed to improve the reliability of these subsystems. Figure 58 shows a design framework that can potentially fulfill the reliability functional requirement.

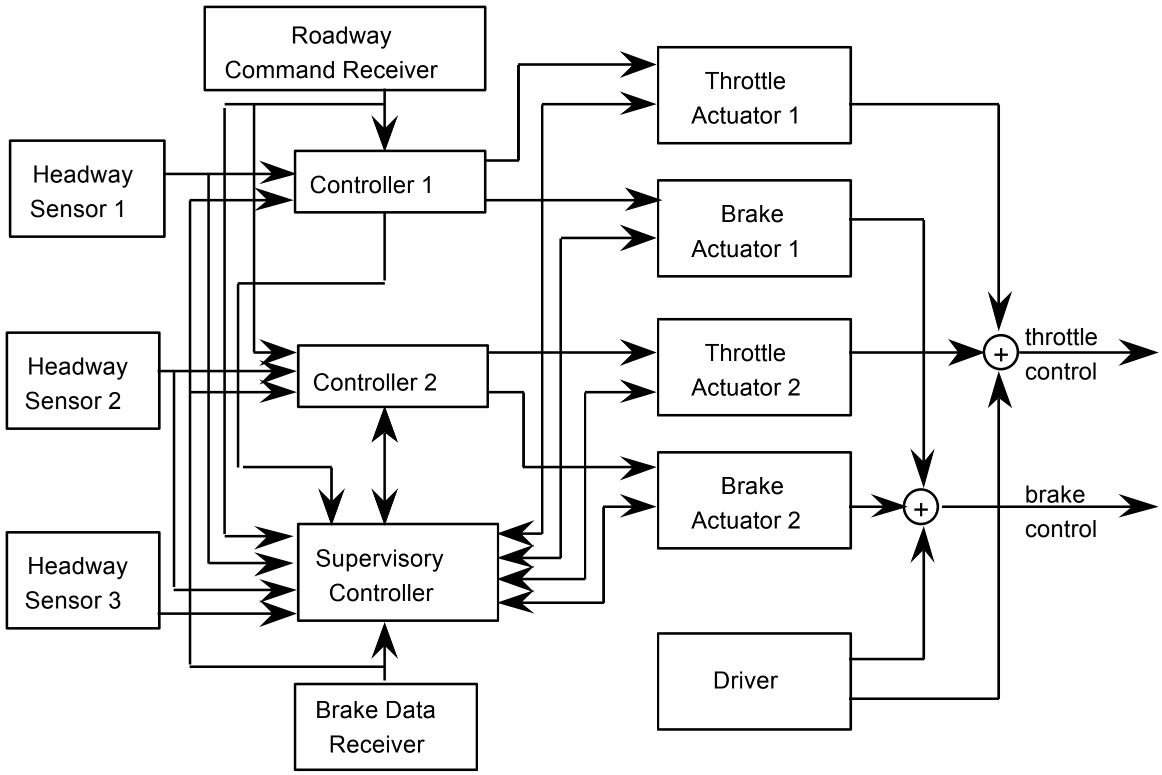


Figure 58. The SHM and RECA system framework for reliability design.

The proposed design framework has two active control channels. Each control channel has a headway/speed sensor, a controller, a throttle actuator, and a brake actuator. The controller of each channel receives roadway target speed commands and minimum time headway recommendations, and receives braking data from the preceding vehicle. Each control channel is capable of performing the SHM and RECA functions alone. If a component/point failure causes one control channel to fail, the other channel continues its operation. This gives the driver enough time to successfully take over control from the non-fail-safe system. A third headway/speed sensor may be used to improve the accuracy of headway sensing and to help identify any failed headway/speed sensor. A supervisory controller is used to help detect any failed component and to deactivate the failed control channel.

If a potential internal failure causes one control channel to be deactivated, the SHM and RECA system is not in the fail-safe condition. Any additional component/point failure may cause a rear-end collision. For safety reasons, the SHM and RECA system should warn the driver of the detected potential failure and ask him/her to back up the rear-end collision avoidance function. The system framework as in figure 58 allows the vehicle longitudinal control to fall back to ERSC 1.

When one control channel is deactivated due to a potential component/point failure, the SHM and RECA system may need a period of transition time to have the other channel operate effectively. Since the vehicle may be traveling at high speeds, a performance degradation such as this may have safety implications. To reduce the transition time required for fully activating or deactivating a control channel, it is desirable that the two redundant control channels be kept active all the time as long as the SHM and RECA system is in operation. In this case, one can activate or deactivate a control channel by quickly adjusting its control gain. Feedback design can be used to efficiently adapt the control gains based on the operational status.

The “no common failure modes” requirement avoids the situation when redundant components fail simultaneously due to the same failure cause. This implies that the redundancies in the proposed framework need to be independent, i.e., redundant components have to operate with different technologies and/or be supported by independent hardware/software. For example, the three redundant headway/speed sensors are one radar based[75,109], one laser based[103,118,92], and one vision based.[91,109,78] Furthermore, the three headway/speed sensors have to be powered independently so that a power source failure will not cause two of them to failed simultaneously.

System Level Design Requirements
Without doing the complete FMEA, one can still identify the following major system failure modes based on the system design framework proposed in figure 58.

1. Headway/speed sensor failure
2. Controller failure
3. Actuator failure
4. Incorrect speed/headway commands received from roadway
5. Incorrect braking data received from the preceding vehicle

These potential failure modes impose important system level design requirements that are presented in the following.

Potential Failure Mode 1: Headway/Speed Sensor failure

1.1 Headway/Speed Sensor 1 or 2 computes incorrect headway or closing rate data.
Design requirements:

1.1.1 Headway/Speed Sensor 1 and 2 need to have an internal independent check of the reasonableness of the computed headway and closing rate data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should then be executed. The System Failure Response disables the control channel that connects the failed component, warns the driver of the failure, and asks driver to take over longitudinal control.

1.1.2 Controller 1 and 2 and Supervisory Controller should verify that each headway/speed sensor is operating in a timely manner by verifying that new data is received from each headway/speed sensor every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

1.2 The data values generated by Headway/Speed Sensor 1 and 2 are substantially different.
Design requirements:

1.2.1 Supervisory Controller should sense the discrepancy and use the data from Headway/Speed Sensor 3 to determine the failed headway/speed sensor. The System Failure Response should then be executed.

1.3 Headway/Speed Sensor 3 computes incorrect headway or closing rate data.
Design requirements:

1.3.1 Headway/Speed Sensor 3 needs to have an internal independent check of the reasonableness of the computed headway and closing rate data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.3.2 Supervisory Controller should compare the data computed by Headway/Speed Sensor 3 with those computed by Headway/Speed Sensor 1 and 2 to check if Headway/Speed Sensor 3 is working properly. If an error is detected, the System Failure Response should be executed.

1.3.3 Supervisory Controller should verify that Headway/Speed Sensor 3 is operating in a timely manner by verifying that new data is received from Headway/Speed Sensor 3 every tbd time interval. If an error is detected, the System Failure Response should be executed.

1.4 Data from Headway/Speed Sensor 1 or 2 is not communicated to the controllers, or is corrupted in transmission through interface.
Design requirements:

1.4.1 Each controller should incorporate an independent check of the reasonableness of the computed headway and closing rate data from Headway/Speed Sensor 1 and 2, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.4.2 Same as for 1.1.2.

1.5 Data from Headway/Speed Sensor 3 is not communicated to Supervisory Controller, or is corrupted in transmission through interface.
Design requirements:

1.5.1 Supervisory Controller should incorporate an independent check of the reasonableness of the computed headway and closing rate data from Headway/Speed Sensor 3, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.5.2 Same as for 1.3.2.

Potential Failure Mode 2: Controller failure

2.1 Controller 1 or 2 computes incorrect throttle or brake command.

Design requirements:

2.1.1 Each of Controller 1 and 2 should incorporate an independent check of the reasonableness of the computed throttle or brake command before it is sent to the throttle or brake actuator, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.2 Each of Throttle Actuator 1 and 2 should incorporate an independent check of the reasonableness of the throttle command computed by the associated controller, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.3 Each of Brake Actuator 1 and 2 sh ould incorporate an independent check of the reasonableness of the brake command computed by the associated controller after it is received, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.2 Throttle (or brake) commands computed by Controller 1 and 2 are substantially different.
Design requirements:

2.2.1 Supervisory Controller should sense the discrepancy in the throttle (or brake) commands computed by Controller 1 and 2, and determine the controller that fails. The System Failure Response should then be executed.

2.3 Supervisory Controller fails.
Design requirements:

2.3.1 Supervisory Controller should incorporate circuitry, such as a watchdog timer, to detect failure and to ensure that the processor functions in a timely manner. If a failure is detected, the circuitry should deactivate Supervisory Controller, and the System Failure Response should be executed.

2.4 Supervisory Controller computes incorrect throttle or brake command.
Design requirements:

2.4.1 Supervisory Controller should compare the computed throttle and brake commands with those computed by Controller 1 and 2 to determine if Supervisory Controller is working properly. If an error is detected, the System Failure Response should be executed.

2.5 Throttle/brake commands from Controller 1 or 2 is not communicated to Throttle/Brake Actuator 1 or 2 at appropriate time, or is corrupted in transmission through interface.
Design requirements:

2.5.1 Each of Throttle/Brake Actuator 1 and 2 should verify that it is receiving updated throttle/brake commands from the associated controller in a timely manner. If an error is detected, the System Failure Response should be executed.

2.6 Supervisory Controller's command data is not communicated to controllers and throttle/brake actuators at appropriate time, or is corrupted in transmission through interface.
Design requirements:

2.6.1 Each of the two controllers and th rottle/brake actuators should verify that it is receiving updated commands from Supervisory Controller in a timely manner. If an error is detected, the System Failure Response should be executed.

Potential Failure Mode 3: Actuator failure

3.1 Throttle Actuator 1 or 2 produces incorrect throttle angle for a given throttle command.
Design requirements:

3.1.1 Each throttle actuator should incorporate built in tests to be performed on the vehicle startup and during speed/headway maintenance operation to verify that proper throttle angle can be produced and is within the allowable range. If an error is detected, the System Failure Response should be executed.

3.2 Throttle Actuator 1 or 2 can not be deactivated when the associated control channel is determined to be deactivated.
Design requirements:

3.2.1 The SHM and RECA system should provide for two independent, redundant means of deactivating the throttle actuators.

3.3 Brake Actuator 1 or 2 generates incorrect brake force for a given brake command.
Design Requirements:

3.3.1 Brake Actuator 1 and 2 should incorporate built in tests to be performed on the vehicle startup and during speed/headway maintenance operation to verify that proper brake force can be produced. If an error is detected, System Failure Response should be executed.

3.4 Brake Actuator 1 or 2 can not be deactivated when the associated control channel is determined to be deactivated.
Design Requirements:

3.4.1 The SHM and RECA system should provide for two independent, redund ant means of deactivating the brake actuators.

Potential Failure Mode 4: Incorrect target speed commands or minimum time headway recommendations received from the roadway

4.1 The roadway target speed commands or minimum time headway recommendations are not communicated to Roadway Command Receiver, or are corrupted during transmission.

4.1.1 The data/commands sent from the roadway should contain error detection and error correction codes to improve the accuracy of the data received by Roadway Command Receiver.

4.1.2 Supervisory Controller should verify that target speed commands and minimum time headway recommendations are received in a timely manner. If updated data is not received for tbd consecutive times, Supervisory Controller should re-evaluate a new lower target speed and/or a more conservative safe time headway for speed and headway maintenance and rear-end collision avoidance, based on the known roadway surface characteristics and traffic conditions. Supervisory Controller should notify the driver the speed and headway adjustment actions taken by the controllers, and may have to ask the driver to take over the rear-end collision avoidance function.

4.1.3 Supervisory Controller should incorporate an independent check of the reasonableness of the received target speed commands and minimum time headway recommendations from the roadway, based on the physical attainability and known ranges of the system variables. If unreasonable data is received over tbd consecutive times, the SHM and RECA system should respond as described in 4.1.2.

Potential Failure Mode 5: Incorrect braking data received from the preceding vehicle

5.1 The braking data from the preceding vehicle is not communicated to Brake Data Receiver or is corrupted during transmission.
Design Requirements:

5.1.1 The communicated braking data should contain error detection and correction codes to improve the accuracy of the data received by Brake Data Receiver.

5.1.2 Supervisory Controller should verify that, during headway maintenance operation, braking data from the preceding vehicle is received in a timely manner. If updated braking data is not received for tbd consecutive times, controllers should evaluate a new safe time headway for headway maintenance and rear-end collision avoidance, based on the known braking characteristics of the preceding vehicle. Supervisory Controller should notify the driver of the headway adjustment action taken by the controllers, and may have to ask the driver to take over rear-end collision avoidance.

5.1.3 Supervisory Controller should incorporate an independent check of the reasonableness of the received braking data from the preceding vehicle, based on the physical attainability and known ranges of the system variables. If unreasonable braking data is received over tbd consecutive times, the SHM and RECA system should respond as described in 5.1.2.

Key Findings

1. The driver can not be considered as a back-up to the SHM and RECA system. A fail-safe SHM and RECA system design will have considerable structure complexity and component redundancies.

2. The reliability functional requirement for the SHM and RECA system is: "A single component or point failure is not allowed to cause a rear-end collision, and there should be no common failure modes."

3. The redundant control channels in the proposed design framework need to be always kept active to ensure safe and smooth deactivation of a control channel.

Issues and Risks

1. There could be rear-end collisions that can not be avoided by the SHM and REC A system. For example, if the preceding vehicle abruptly change lanes to avoid crashing into a close, stationary obstacle in the lane, the SHM and RECA system may not have enough distance for safe braking. In this case, lateral control will be required for evasive maneuver. The driver in this case is positioned in a situation that he/she may not be able to handle since he/she may not have enough time to avoid collision by using lateral control. This suggests that the RECA function probably should be presented in ERSC 4 together with the vehicle's lateral collision avoidance function, instead of in ERSC 2.

2. The redundancy requirement in the design of the SHM and RECA system will substantially increase the cost for deployment. Potential system failures raise serious liability concerns.

3. Complete feet-off driving may further relax the driver and affect his/her performance in lateral collision avoidance.

Blind Spot Warning

The analysis of the reliability requirement is the same as in ERSC 1.

Steering Assist

The steering assist (SA) system smoothes the driver's steering control by compensating the high frequency lateral disturbances. When the vehicle is traveling at high speeds in the dedicated lane, the vehicle lateral dynamics has high bandwidth and is sensitive to external disturbances such as wind gust or uneven road surface. The SA system generates high frequency but small scale steering commands to compensate the disturbances and to reduce the bandwidth of the vehicle lateral dynamics. The SA system thus improves the safety and ride comfort by augmenting the steering control stability and smoothing the driver's steering.

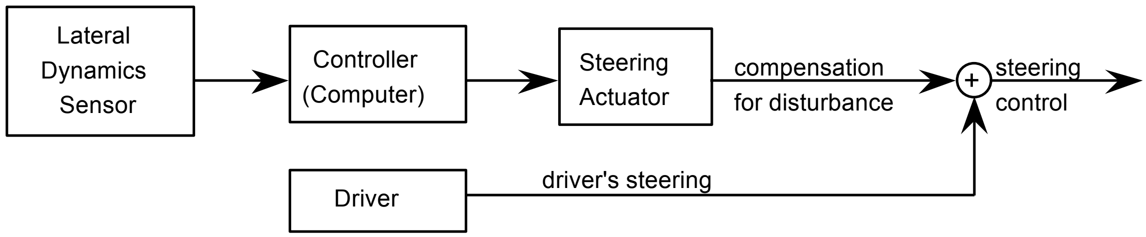


Figure 59. The block diagram of the steering assist system interfacing with the driver.

The SA system consists of a lateral dynamics sensor, controller (computer with control algorithms), and a steering actuator. The sensor collect the vehicle's lateral dynamics information, such as yaw rate, lateral acceleration and sideslip angle [61], etc. The computer generates steering correction commands to the actuator based on the data provided by the lateral dynamics sensor. The actuator then carries out the high frequency steering actions to compensate the effects of the external disturbances. Figure 59 shows a block diagram for the SA system interfacing with the driver.

The SA system is similar to the stability augmentation system (SAS) that has been used in the flight control for decades. The steering actuator is connected to the steering shaft in series so that the driver's high frequency random steering actions do not cause the vehicle to wiggle in the lane. The steering actuator should be saturated if it receives large steering commands from the controller or large counteracting steering force from the driver. This allows the driver to steer the vehicle to following a curve or to change lanes by applying extra force at the steering wheel.

Reliability Functional Requirement

The SA system only assist the driver in lateral control. The driver is hands on the steering wheel and steers the vehicle. A sudden loss of the steering assist is not likely to endanger of the driver's lateral control. However, if the SA system generate large steering force when it fails, the vehicle may depart from the lane before the driver can react to the danger. The reliability functional requirement for the SA system is thus proposed as:

> "The SA system should provide for independent, redundant means to constrain the automatically generated steering force within safe bounds."

The independent, redundant means of constraining steering force are required to protect the system from any common failure mode. This requirement does not impose redundancy requirement for major components in the design. However, extra hardware/software will be needed to detect internal malfunction, to constrain or saturate the steering force, and to warn the driver of the potential failures.

System Level Design Requirements

Based on the above discussion, one can identify the following major system failure modes:

1. Lateral dynamics sensor failure
2. Controller failure
3. Steering actuator failure

These potential failure modes impose important system level design requirements that are presented in the following.

Potential Failure Mode 1: Lateral Dynamics Sensor failure

1.1 Sensor computes incorrect lateral dynamics data.
Design requirements:

1.1.1 Lateral Dynamics Sensor needs to hav e an internal independent check of the reasonableness of the computed lateral dynamics data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the driver should be warned and the SA system should be deactivated.

1.1.2 Controller should verify that Lateral Dynamics Sensor is operating in a timely manner by verifying that new data is received every tbd time interval. If an error is detected, the driver should be warned and the SA system should be deactivated.

1.2 Data from Lateral Dynamics Sensor is not communicated to Controllers, or is corrupted in transmission through interface.
Design requirements:

1.2.1 Controller should incorporate an independent check of the reasonableness of the received data from Lateral Dynamics Sensor, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the driver should be warned and the SA system should be deactivated.

1.2.2 Same as for 1.1.2.

Potential Failure Mode 2: Controller failure

2.1 Controller computes incorrect steering command.
Design requirements:

2.1.1 Controller should incorporate an independent check of the reasonableness of the computed steering correction command before it is sent to Steering Actuator, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the driver should be warned and the SA system should be deactivated.

2.1.2 Steering Actuator should incorporate an independent c heck of the reasonableness of the steering command computed by Controller after it is received, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the driver should be warned and the SA system should be deactivated.

2.2 Steering command from Controller is not communicated to Steering Actuator at appropriate time, or is corrupted in transmission through interface.
Design requirements:

2.2.1 Steering Actuator should verify that it is receiving upda ted steering commands from Controller in a timely manner. If an error is detected, the driver should be warned and the SA system should be deactivated.

Potential Failure Mode 3: Incorrect steering force generated from Steering Actuator.

3.1 Steering Actuator produces incorrect steering force for a given steering command. Design requirements:

3.1.1 Steering Actuator should incorporate built in tests to be performed on the vehicle startup and during steering assist operation to verify that proper steering force can be produced and is within the allowable range. If an error is detected, the driver should be warned and the SA system should be deactivated.

3.2 Excessive steering force generated from Steering Actuator. Design requirements:

3.2.1 The SA system should provide for independent, redundant means to constrain the steering force from the Steering Actuator within safe ranges.

Key Findings

1. Loss of steering assist will not impose immediate danger to the driver's lane keeping control since the driver is hands on the steering wheel.

2. The proposed reliability functional requirement of the SA system is to provide independent and redundant means to constrain the steering force generated by the SA system.

Issues and Risks

1. The SA system may need the information from lane reference aid provided by the roadway to improve the accuracy of the measured lateral dynamics.

2. The driver needs to apply extra steering force to override the SA system. This may degrade the driver's performance in lateral collision avoidance.

Lane Departure Warning

The lane departure warning (LDW) system improves the safety of the driver's lane keeping control. The LDW system warns the driver of lane departure danger if it detects that the vehicle lateral displacement exceeds a certain threshold. The roadway provides lane reference aid to assist the LDW system in measuring the lateral deviation. The driver has to respond to the warning by applying steering correction to avoid lane departure. Figure 60 shows the interaction between the LDW system and the driver.

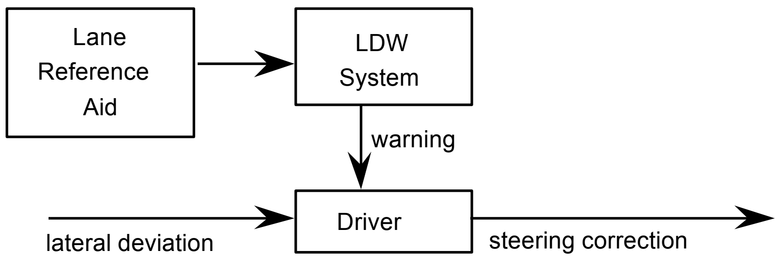


Figure 60. The LDW system interfaces with the driver and roadway.

The on-board LDW system is composed of a lateral deviation sensor, a processor and a warning interface. The lateral deviation sensor measures the vehicle's lateral displacement with the help from the lane reference aid. The processor uses the data from the sensor to compute time-to-line crossing (TLC).[36] The processor compares the TLC with the driver reaction time to determine if a warning should be issued. The warning interface takes the command from the processor and sends the warning signal to the driver.

Reliability Functional Requirement

Since the driver is hands on the steering wheel for steering control, lane keeping depends on the man-machine interactions between the driver and the LDW system. The LDW system fails if it does not detect a lane departing danger or if it generates a false alarm. A LDW system with low detection rates will not benefit driver safety/reliability in lane keeping. Frequent false alarms may irritate the driver or cause the driver to turn off the LDW system. To improve the driver's reliability in lane keeping, the reliability functional requirement for the LDW system is proposed as:

"The LDW system should have high detection rates and low false alarm rates. ”

To reduce false alarms and nuisance alarms, it may be necessary to allow the driver to adjust the sensitivity of warning. The driver set the warning threshold based on his/her driving skill and environmental conditions. Two levels of warning, cautionary warning and imminent warning[64], may be required for effective interface with the driver. To ensure that the driver can perceive imminent warnings, imminent warnings should contain signals with redundant, independent modalities, such as auditory and visual.

System Level Design Requirements

To achieve fail-safe design, the LDW system will need to have reliable hardware/software with self-diagnosis element to detect internal failures. The lane reference aid needs to be able to effectively support the lane position detection technology used by the LDW system. Further system level design requirements can be identified by analyzing major potential failure modes and causes, based on the system framework in figure 61.

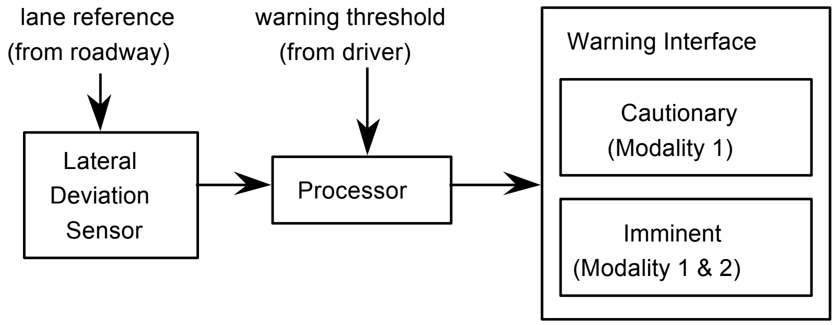


Figure 61. The LDW system framework for reliability design.

Potential Failure Mode 1: Lateral Deviation Sensor failure

1.1 Lateral Deviation Sensor measures incorrect lateral displacement data.
Design requirements:

1.1.1 Lateral Deviation Sensor needs to have an internal independent check of the reasonableness of the computed lateral displacement data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response warns the driver of the potential failure and asks him/her to turn off the LDW system.

1.1.2 Processor should incorporate an independent check of the reasonableness of the measured data from Lateral Deviation Sensor, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.2 Data from Lateral Deviation Sensor is not communicated to Processor, or is corrupted in transmission through interface.
Design requirements:

1.2.1 Processor should verify that Lateral Deviation Sensor is operating in a timely manner by verifying that new data is received from Lateral Deviation Sensor every tbd time interval. If an error is detected, the System Failure Response should be executed.

1.2.2 Same as for 1.1.2.

1.3 The roadway provides incorrect lane reference data.
Design requirements:

1.3.1 The roadway should provide for reliable lane reference aid to support the LDW function. The roadway should have an internal check on the accuracy of the lane reference data. If correct lane reference data can not be provided, drivers on the dedicated lane should be notified to deactivate the LDW system.

1.3.2 Processor should incorporate technologies that can detect potential failures in the lane reference aid. If an error is detected, the System Failure Response should be executed.

1.3.3 Same as for 1.1.2.

Potential Failure Mode 2: Processor failure

2.1 Processor computes incorrect time-to-line crossing.
Design requirements:

2.1.1 Processor should incorporate an independent check of reasonableness of the computed time-to-line crossing, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.2 Processor command is not communicated to Warning Interface at appropriate time or is corrupted in transmission through interface.
Design requirements:

2.2.1 Warning Interface should verify that it is receiving updated command from Processor in a timely manner. If an error is detected, the System Failure Response should then be executed.

Potential Failure Mode 3: Warning Interface failure

3.1 Warning Interface fails to give warnings or generate incorrect level/modality of warnings, after receiving a warning command from Processor.
Design requirements:

3.1.1 Warning Interface should incorporate built in tests to be performed on the vehicle startup and during driver's lane keeping operation to verify that proper warning signals can be generated. If an error is detected, the System Failure Response should be executed.

Key findings

1. Two levels of warning may be required. Imminent collision warning may require redundancy with different warning modalities.

2. The reliability functional requirements for the LDW system are high detection rates and low false alarm rates.

Issues and Risks

1. The driver may become over-reliant on the LDW system and degrade his/her reliability/performance in lateral collision avoidance.

2. The driver may experience warning overload and warning confusion problems while interfacing with other vehicle and roadway functions.

Roadway to Vehicle Speed and Headway Commands

The analysis of the reliability requirement is the same as in ERSC 1.

ERSC 2 Driver Tasks and Workload

This section discusses the drivers' tasks in this ERSC. It covers normal driving in the dedicated lane when all of the automated functions work perfectly. Then it covers the fall-back mode in which the vehicle switches into ERSC 1 with speed and headway maintenance and rear-end collision warning if the rear-end collision avoidance system fails or degrades. Finally we discuss the lane departure warnings and the steering assist function and their interactions with the drivers.

The driver drives the car to the automated lane. The driver turns on the vehicle's turn signal and blind spot warning system. The driver enters the lane when a safe gap appears in the traffic flow. The driver steers the car into the lane and turns on the SHM function and rear-end collision avoidance system. The vehicle takes over the throttle and brake when the car is in the lane or as the vehicle enters the lane. The driver steers the vehicle while in the automated lane with the help of the steering assist function and the lane departure warning. The driver workload in ERSC 2 is very similar to that of today's driving except that the vehicle has full longitudinal control while the vehicle is in the dedicated lane.

The driver turns on the turn signal and blind spot warning system to leave the automated lane. This initiates check-out procedures. Check-out returns the throttle and brake control to the driver and turns off the lane departure warning and the steering assist function. The vehicle increases the headway before transferring throttle control to the driver since human drivers have slower reaction times that the automated rear-end collision avoidance system. The driver then resumes control of the throttle and changes lanes out of the automated lane. The driver turns off the communications links when he leaves the automated lane.

Task Analysis–Normal Driving

In normal operations, the vehicle controls the throttle and brake. The driver steers the vehicle in the lane with the aid of the steering assist function. The roadway sends target speed commands and minimum headway information electronically to the vehicle. This data helps the vehicle compute a safe headway. The task analysis table below shows the driver cues for this task.

Table 20. Driver task description for ERSC 2 driving

Task	Monitor Vehicle Operation and Steer Vehicle in Normal Driving
General	Task similar to manual driving
Initiating Cue	Enter Dedicated Lane and turn on speed and headway maintenance and the rear-end collision avoidance function–The driver sets time headway and initial speed
Feedback	Visual, auditory, and kinesthetic cues of accelerating, braking, slowing, and steering
Task Standards	Duration the same as manual driving for steering
Task Conditions	Weather, road conditions, or traffic
Skills Required	Reaction times appropriate to speed and roadway conditions. Perceptional judgment of vehicle kinematics
Potential Errors	Driver inattention causes vehicle to leave road Turn off speed and headway maintenance system accidentally Vehicle fails to maintain speed or proper headway Vehicle selects unsafe headway Roadway sends incomplete or wrong speed command
Causes of Error	Fails to perceive or misinterprets system feedback Poor judgment of speed and road curvature Hit wrong button or brake pedal Sensor or actuator failure on vehicle
Consequences of Error	Disrupt traffic flow and lower capacity Rear-end collision with preceding vehicle Rear-end collision by vehicle in back Lane departure collision
Recovery Points	Minimum safe headway setting on vehicle to avoid collisions Rear-end collision warning Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off; prevent easy override of SHM and RECA functions Blind spot or lane departure warning
Individual Differences	Education Age Driving Skill
Criticality	Essential

<u>Task Analysis–Fall-back Mode</u>

In the fall-back mode, the rear-end collision avoidance system suffers a partial failure when one control channel fails, but the other one remains intact. If the failure is such that the speed and headway maintenance system can still function then the vehicle switches to ERSC 1 operations in which the driver is responsible for emergency or hard braking. The vehicle warns the driver that he is now responsible for rear-end collision avoidance and increases the headway to a safe distance for manual collision avoidance.

If the warnings fail, the vehicle notifies the driver and the driver performs the task without the aid of warnings.

Table 21 Driver resumes control of rear-end collision avoidance function.

Task	Fall-back mode to ERSC 1
General	Task may be similar to manual driving
Initiating Cue	Vehicle warns driver to resume responsibility for braking Driver receives warning signal for braking from vehicle Vehicle increases headway for to allow for manual braking
Feedback	Visual, auditory, and kinesthetic cues of accelerating, braking, slowing, and steering
Task Standards	Duration the same as manual driving, transition to manual driving must be gradual, vehicle keeps deceleration low while increasing time headway
Task Conditions	Weather, road conditions, suggestions from traffic control center
Skills Required	Reaction times appropriate to speed, following distance and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Driver inattention causes vehicle to have a rear-end collision Driver overrides speed and headway maintenance system accidentally Driver does not respond in time to rear-end collision warning Vehicle fails to maintain speed or proper headway Vehicle selects wrong speed or unsafe headway Vehicle does not warn driver adequately of a control transfer
Causes of Error	Fails to perceive or misinterprets system feedback Poor judgment of speed and following distance Hit wrong button or brake pedal Sensor or actuator failure on vehicle Role confusion
Consequences of Error	Disrupt traffic flow and lower capacity Rear-end collision Rear-end collision by vehicle in back
Recovery Points	Minimum safe headway setting on vehicle to avoid tail-gating Rear-end collision warning Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off Vehicle requires active response from driver before a control transfer Driver interface shows headway and driver control status clearly
Individual Differences	Older or less experienced drivers may be uncomfortable taking over braking control at high speeds or in reduced visibility
Criticality	Essential

Task Analysis–Rear-End Collision Avoidance

Drivers avoid collisions by using both the brake and the throttle. [66] In most cases the driver only uses the brake. The driver may not be able to override the rear-end collision avoidance system for braking. This may limit the driver's options for lateral and rear-end collision avoidance if they can only control the steering.

Human factors studies suggest that collision avoidance systems need multiple levels of warning.[64] In the first level the collision warning system shows the driver that it is operating with a head up display or other indicator that shows the distance to the car ahead. In the second level the collision warning system warns of a possible collision with a visual warning such as changing the color or intensity of the display. In the third level the collision warning tells the driver to brake with combined auditory and visual warnings. These levels could correspond to no threat, a distance warning and a conservative time to collision based warning set by the driver. The driver needs to control the vehicle's steering during hard braking. This requires the vehicle to warn the driver. Table 22 shows the driver task description for this task. Rear-end collision avoidance systems may also help decrease the number of single vehicle roadway departure crashes since many of these crashes occur when the driver tries to avoid a rear-end collision. (114)

Table 22 Driver task description for hard or emergency braking.

Task	Steer while vehicle brakes to avoid a collision
General	Task similar to manual driving
Initiating Cue	Warning from vehicle that emergency braking occurs
Feedback	Visual, auditory, and kinesthetic cues of braking and slowing
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking, driver needs to control steering
Task Standards	Driver must maintain control of vehicle with steering alone
Task Conditions	Weather, traffic conditions, position of following vehicle
Skills Required	Reaction times appropriate to speed, following distance, and roadway conditions. Perceptional judgment of vehicle kinematics
Potential Errors	Respond too slowly to emergency Vehicle does not brake smoothly Driver loses control of vehicle steering Driver ignores vehicle's braking warning
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Poor judgment of steering Rear-end collision system does not detect emergency braking situation Rear-end collision system has a high false alarm rate Driver cannot avoid collision due to no override of RECA
Consequences of Error	Lateral collision with potentially severe results for the system Lose control of the vehicle Disrupt of traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it
Recovery Points	Check-in of brakes and tires Improve vehicle braking capabilities Redundant sensors to improve detection Lane departure warning and steering assist help stabilize vehicle Vehicle to vehicle communications
Individual Differences	PRTs for older drivers have not shown them to be less alert or significantly slower in responding to unexpected hazards.
Criticality	Very Critical

Task Analysis–Lane Departure Warning

The lane departure warning watches for possible lane departures. If the sensor detects a lane departure then it warns the driver. This sensor backs up the driver when he steers. Table 23 shows driver-lane departure warning system operation. The lane departure warning system should ideally warn the driver before the lane departure begins to avoid a strong swerve to avoid an accident. This could cause an accident if the driver does not respond quickly enough.

The lane departure warning helps prevent single-vehicle roadway departure crashes. These crashes cause 37.4% of all fatalities, more than any other type of crash. (114) SVRD crashes are 20.8% of all police-reported crashes. (114) The lane departure warning may help prevent the crashes that occur when the driver loses control and drives off the road. But many of these crashes occur when the driver is trying to avoid a rear-end collision. The combination of a rear-end collision avoidance system and the lane departure warning may reduce the number and severity of these crashes. (114)

Table 23 Driver task description for lane departure warning.

Task	Respond to Lane Departure Warning
General	Task similar to that in manual driving
Initiating Cue	Warning from vehicle that vehicle may leave lane Vehicle detects change in steering angle
Feedback	Visual, auditory, and kinesthetic cues of steering
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking
Task Standards	Steer back into lane center when warned
Task Conditions	Weather, traffic, roadway condition, position of vehicle in the lane
Skills Required	Reaction times appropriate to speed and roadway conditions. Perceptional judgment of vehicle kinematics
Potential Errors	Overconfidence in system-driver does not look Driver does not respond to the warning or responds too late Sensor false alarms (Vehicle in center of lane, system warns driver anyway) Sensor does not detect lane departure
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Driver delay in response to warning Lane position sensor warning threshold too high or low, malfunction
Consequences of Error	Lane change/Merge collision with potentially severe results for the system Single vehicle departs roadway Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore warning
Recovery Points	Vehicle steering assist applies resistance or correction to steering wheel if la departure sensed (option) Multiple warnings from detector
Individual Differences	Accident statistics, citations and self report data indicate that older drivers h difficulty in merging, changing lanes, and exiting maneuvers (113) Younger male drivers (<25 years) are most likely to be involved in single vehicle roadway departure crashes due too drowsiness and excessive speed(114)
Criticality	Critical

Issues and Risks

1. Driver confidence in warning

If the driver has too much confidence in the collision warning systems then she may not pay enough attention during lane changes or while following another vehicle. This could lead to accidents if the warning system does not detect an object or the system fails. Driver lack of confidence in the warning could cause the driver to disable or ignore the warning system. Research needs to be done on how many false alarms and detection failures are acceptable.

2. Enabling/Disabling Automatic Systems

This ERSC includes a speed and headway maintenance system, lane departure and blind spot warnings, and communication systems. Research needs to be done on the instrumentation needed to control these different systems. The question of whether all the automatic systems need to be controlled with one switch or many needs to be answered.

3. Multiple Warnings

The blind spot and lane departure warnings may occur simultaneously. The vehicle must prioritize the alarms so that the driver only has to work with one task at a time.

4. Driver override of braking

Even with multiple sensors the vehicle may not see and recognize everything that a human driver sees. This is especially true of unexpected objects such as animals or debris on the roadway. It may be necessary for the driver to override the rear-end collision avoidance system on the vehicle to avoid these objects. Research needs to be done on whether this driver override should be allowed to occur.

Key Results

Benefits

<u>Capacity</u>

Vehicles with rear-end collision avoidance systems can safely use shorter following distances than manually driven vehicles since an automatic system has a smaller reaction time than a human driver. Figure 62 shows the maximum steady-state highway capacity for vehicles travelling 25 m/s. Rear-end collision avoidance can increase the maximum highway capacity.

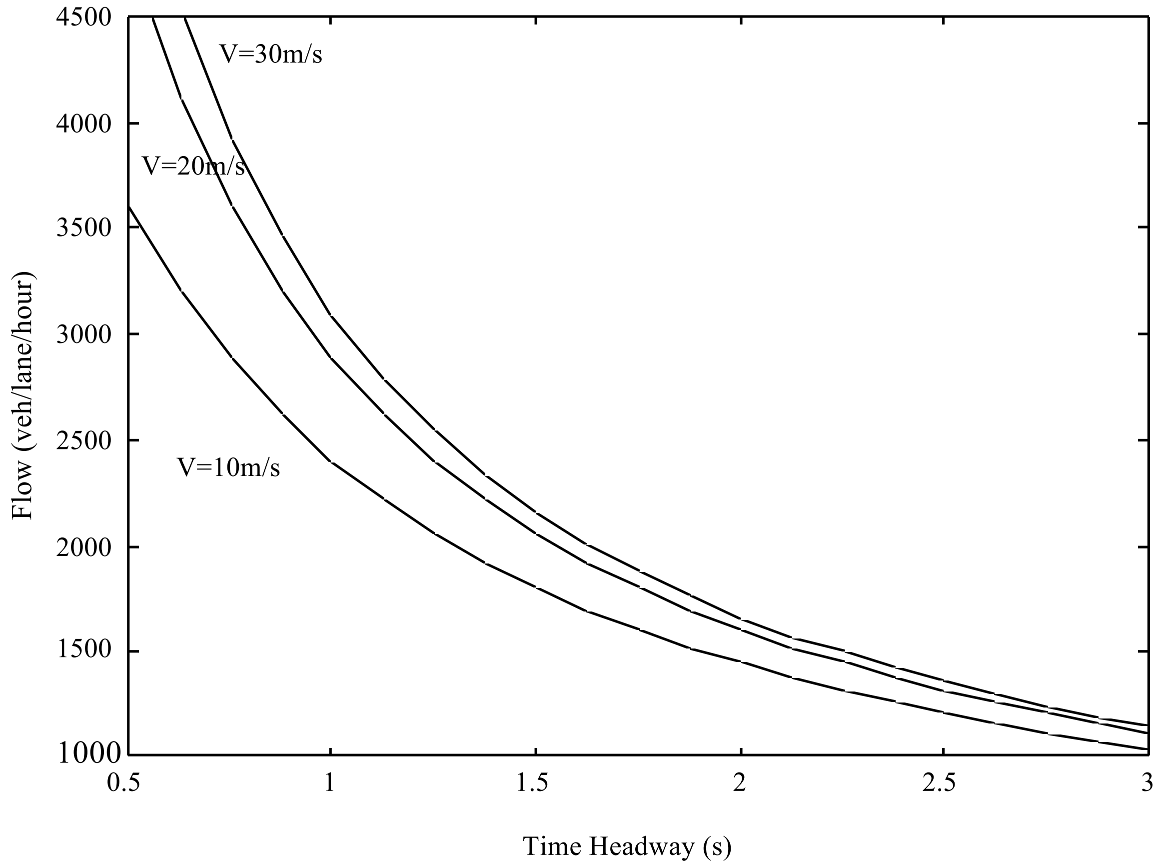


Figure 62. Maximum steady state flow rates for different velocities and time headways.

Traffic Flow Control

Consider a long segment of dedicated lane that is divided into 12 sections as shown in figure 32. The length of each section is 500 meters. Assume that an accident occurs at section 8 and interrupts traffic. In this situation, vehicles accumulate upstream of section 8. The accident is removed quickly. Due to the direct impact of the accident, the traffic density at section 8 is high after the accident has been removed. And the traffic density at section 6, 7 increases to an intermediate-high value due to the indirect impact of the accident. In addition, since section 8 is blocked by the accident, no vehicle can enter sections 9 - 12. The traffic density of these sections is very low. The initial traffic conditions after the accident are shown below.

Section	1	2	3	4	5	6	7	8	9	10	11	12
Initial Density (Veh/km/lane)	30	30	30	30	30	40	70	80	10	10	10	10
Initial Velocity (km/hour)	10	10	10	10	10	7.5	4.3	3.7	30	30	30	30

ERSC 2 increases traffic flow rate by increasing traffic density. Therefore in this case, the traffic flow entering section 1 has a high value. The traffic flow entering section 1 is shown in Figure 63. Since the accident was removed quickly, its impact on the traffic is not very

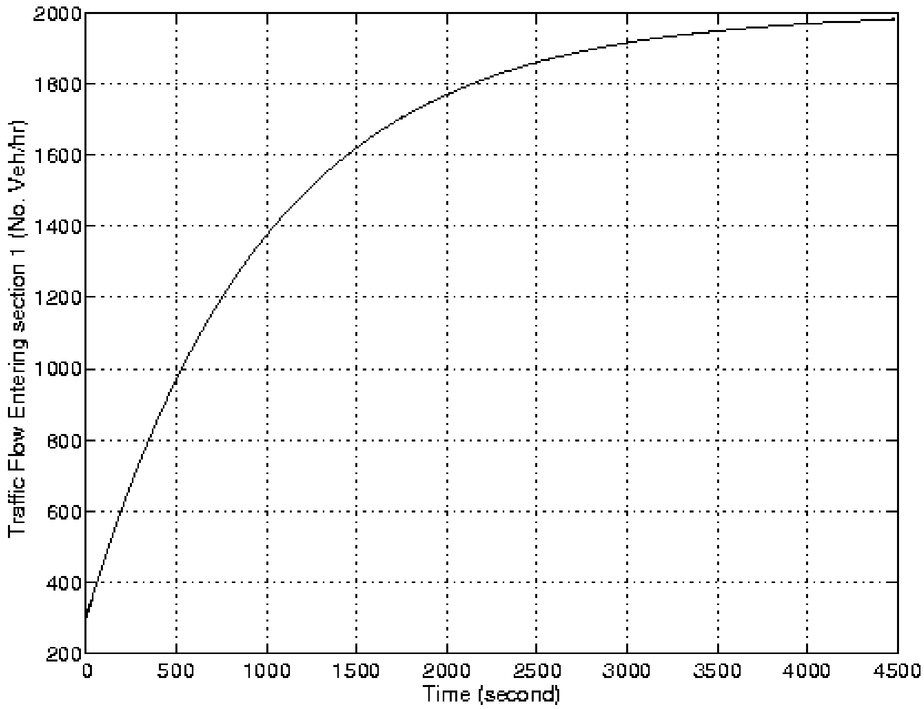


Figure 63. Traffic flow entering section 1 during the simulation.

severe.

The figures below compare the effects of control with the case of no control for high traffic flow. All the simulations use the traffic model described in section 5 and appendix C. The example shows a situation where an accident occurs in section 8 when there is a high flow rate of traffic onto the highway.

Figure 64 shows the evolution of the traffic density when there is no control. The disturbance in section 8 propagates back down the highway and causes a severe traffic jam in earlier sections. The disturbance in traffic density brings traffic to a standstill since the lane has more vehicles than it can handle. Section 8 is the section where the accident originally occurred. The traffic flow is very jerky and inhomogeneous as the accident effects propagate.

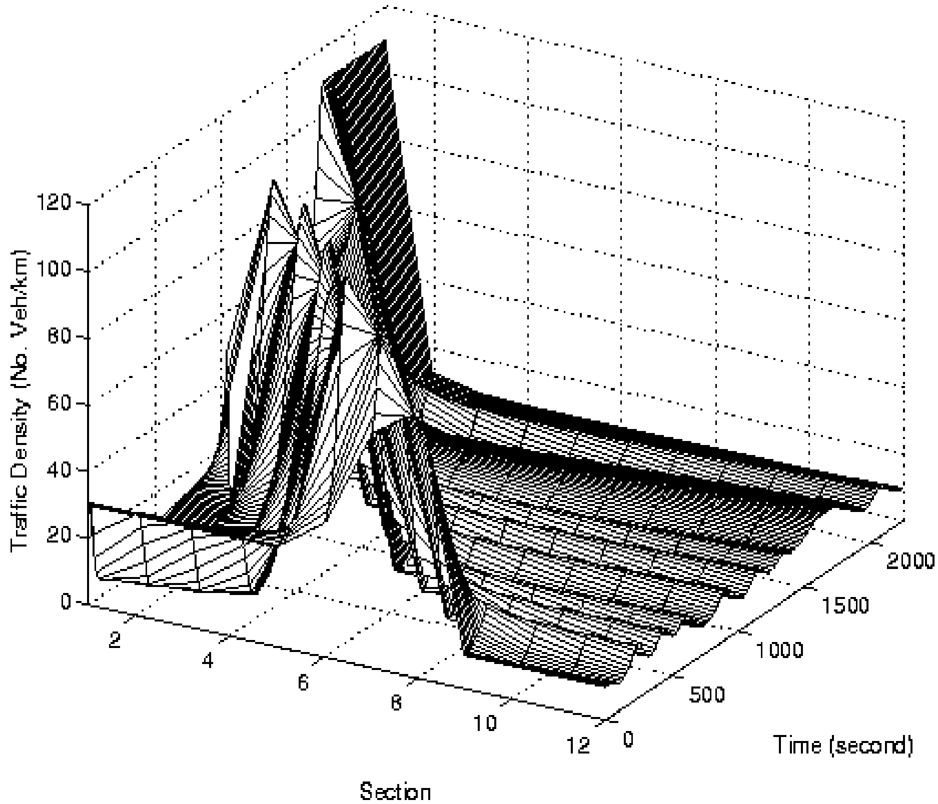


Figure 64. Evolution of traffic density when no roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8.

Figure 65 shows the evolution of the traffic density when the controller is operating. The disturbance in section 8 propagates back down the highway but dies out quickly. This lets the highway quickly return to a constant flow rate. The roadway without control stayed jammed up and it could not handle the increased traffic. Figure 66(a) shows the velocities for each section of the roadway over time when the controller is not operating. Figure 66(b) shows the velocities for each section of the roadway over time when the controller is operating. The velocity returns to a constant speed. Figure 67 shows the evolution of the traffic flow rate for sections 8 and 3. Section 8 is the section where the accident originally occurred. The traffic flow quickly returns to its original rate. Since the traffic flow rate quickly smoothes out the highway can handle more vehicles smoothly.

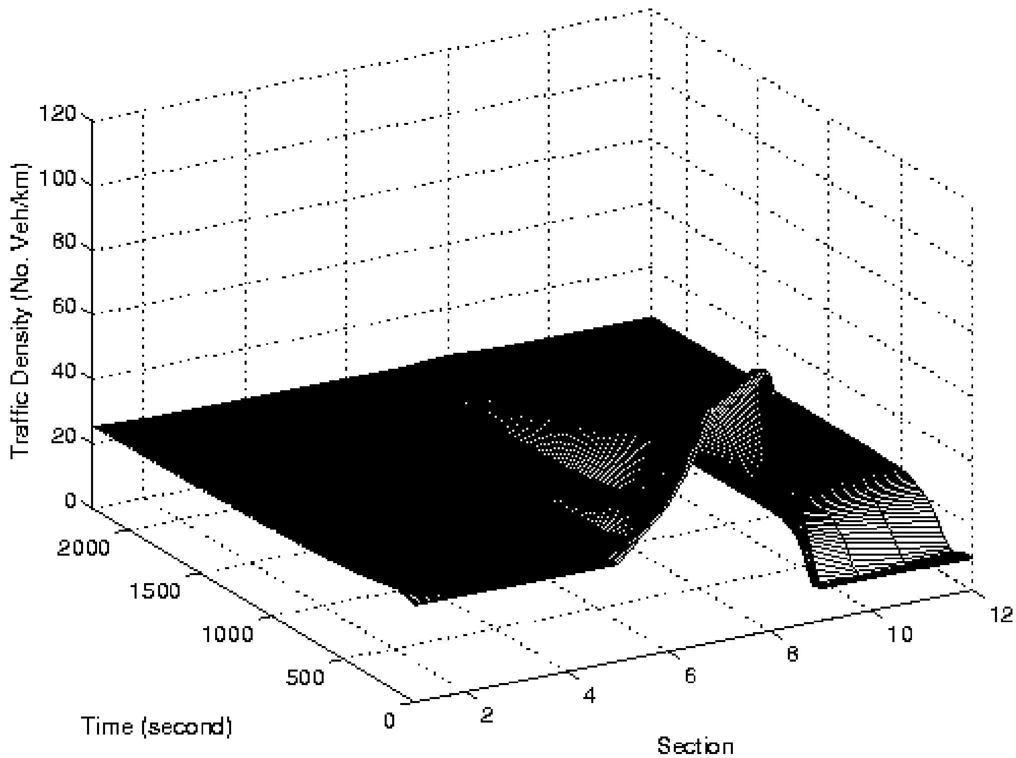
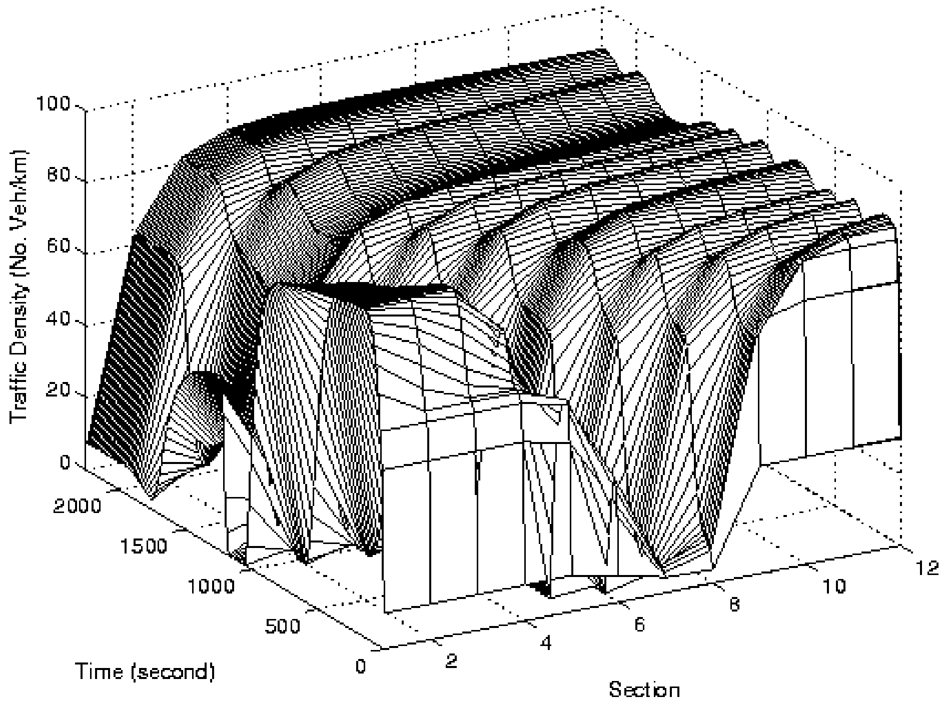


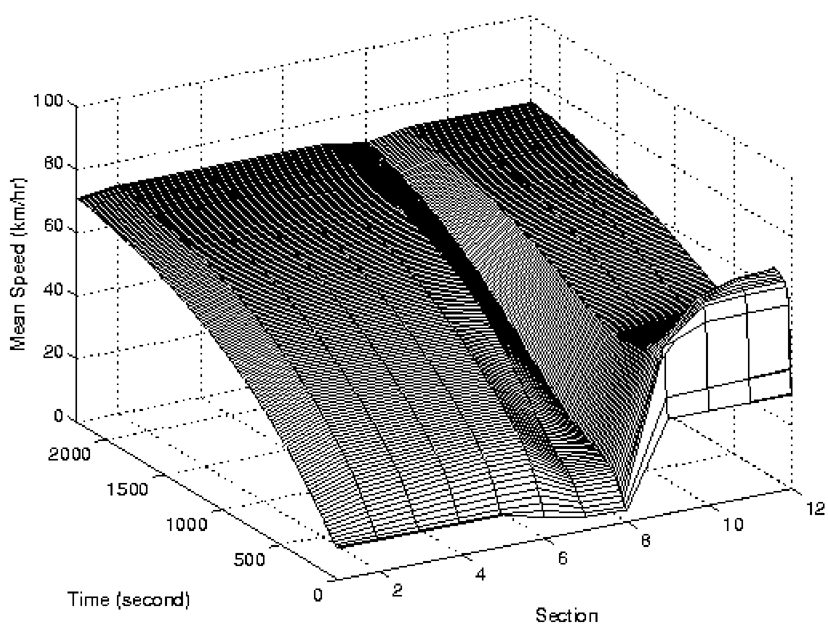
Figure 65. Evolution of traffic density when the roadway controller is present. The disturbance propagates back down the roadway after the accident is removed from section 8.

When many vehicles enter the congested area, the congestion phenomenon does not gradually disappear. Instead, the congestion is propagated upstream until a traffic jam occurs. Since the simulation model is not validated to represent the traffic evolution after a traffic jam. We stop our simulation when the traffic jam is achieved. However, based on daily freeway experience, it will take a very long time for the traffic recovering to a normal condition from a traffic jam.

The accident in the dedicated lane caused a traffic jam for highway systems without control. However, the congestion phenomenon around section 8 is damped out quickly and the steady state is quickly reached for highway system with roadway control.



(a)



(b)

Figure 66. (a) Evolution of traffic velocity when there is no roadway controller. (b) Evolution of traffic velocity when the roadway controller is present. The disturbance quickly dies out and the vehicles stay at a uniform speed.

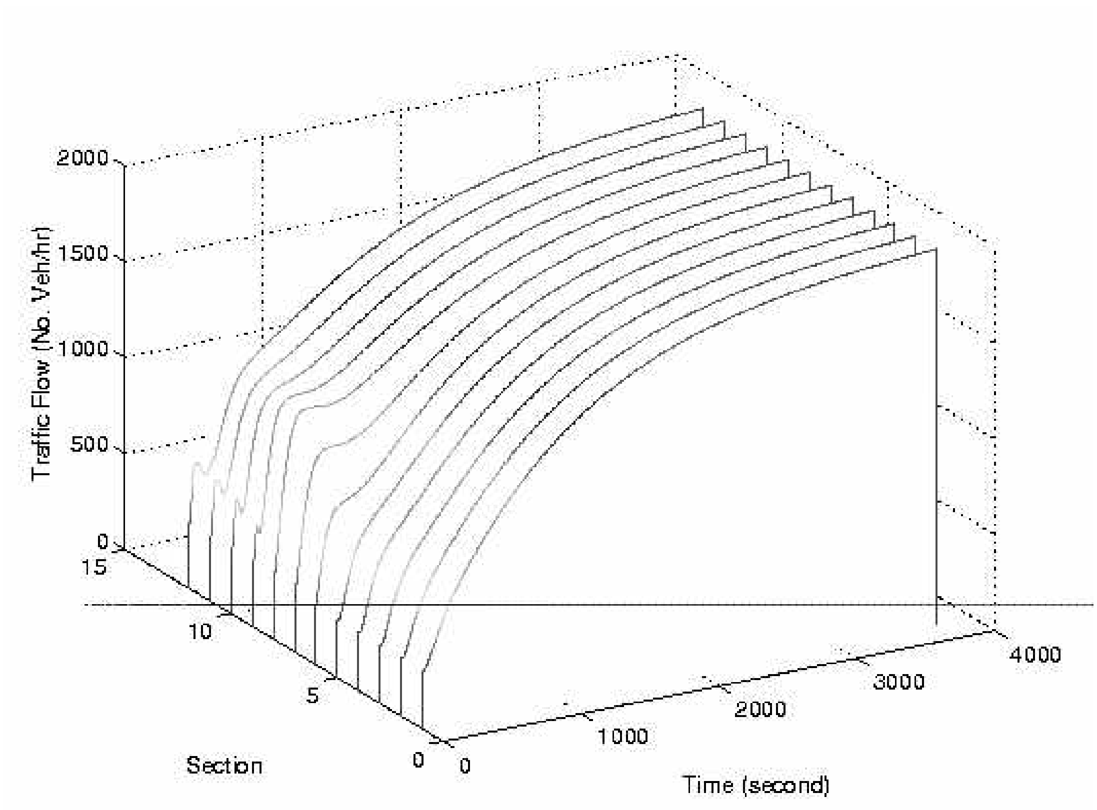


Figure 67. The traffic flow evolution with respect to time for the roadway with roadway control. The traffic flow quickly smoothes out to the steady state velocity.

Issues and Risks

1. Driver Confidence

The driver may not trust the collision avoidance system to handle emergency braking itself. This may cause the driver to choose larger headways than the automated system requires. This reduces the capacity of the automated lane. The driver is not a truly parallel system to the SHM function with rear-end collision avoidance since the driver has a much slower reaction time. Extra redundancy may be needed to make the collision avoidance system as reliable as a human driver.

2. Liability Issues

Rear end collision avoidance leads to new liability issues. If a vehicle collides with the vehicle in front, then who is at fault? The driver may set the time headway too small or the collision avoidance system may not work properly.

3 Driver Attention to Driving Task

As the vehicle assumes more of the driver tasks, the driver may pay less attention to the other vehicles or the highway. This increases driver reaction time to emergencies requiring lateral collision avoidance. The type of feedback that the driver needs from the system needs to be studied.

4 Rear-end Collision Avoidance Sensors

The sensors for rear-end collision avoidance must recognize hazardous situations quickly and accurately. More research needs to done to reduce the number of false alarms and improve the detection performance of these systems.

5 Driver Override of Braking

The driver may need to override the automated braking system if he/she sees an object that the collision avoidance sensors do not. However, this could lead to dangerous situations and a loss of vehicular control. This issue needs further study.

Key Findings

1 The driver can not act as a back-up for an automated rear-end collision avoidance system. There is not enough time for the driver to react to dangerous situations. The reliability requirement for the rear-end collision avoidance system is: “Under no circumstances should a single component/point failure let the vehicle crash into any moving or stationary object in the lane, and there should be no common failure mode.” One possible design leads to multiple control paths and sensors to ensure system reliability. This increases the cost and complexity of automated rear-end collision avoidance system.

2 Driver warnings from the lane departure warning system and the blind spot warning system must be prioritized to avoid driver confusion if multiple warnings occur. Great care must taken in ERSCs that combine automated systems with manual driving to make sure that the driver interface is simple to operate and understand.

3 Traffic control systems can smooth traffic and respond to incidents in the dedicated lane. These controllers prevent high density traffic from slowing to a stop after a minor incident. These controllers may prove to be particularly important for the high density traffic that results from automated vehicles with rear-end collision avoidance systems and automated longitudinal control.

Section 7: ERSC 3 Analysis

Description of ERSC 3

In ERSC 3 the roadway provides and maintains a dedicated lane with a similar accessibility to vehicles as in ERSC 1, 2. The roadway provides lane reference aids that support the lane keeping function of the vehicle as well as lane preview information for smooth and accurate lane following.

The vehicle has all the capabilities as in ERSC 2. The blind spot warning evolves into a lateral collision warning. The vehicle is fully responsible for vehicle-following in the longitudinal direction and rear-end collision avoidance. The vehicle tracks the center of the dedicated lane without any support from the driver. It sends its speed, headway and operational status to the roadway. It responds to target speed commands and traffic information received from the roadway in a similar manner as in ERSC 2. The vehicle notifies the driver in case of malfunctions and responds to commands for switching between the manual and automated modes. The vehicle also coordinates its maneuvers with other vehicles when entering and exiting the dedicated lane. The vehicle warns the driver of potential lateral collisions in time for the driver to respond to the warnings.

The vehicle alerts the driver when it is time to assume manual control and transfers control to the driver in a smooth way that is compatible with driver's skills and reaction times. The vehicle uses its on-board diagnostics to notify the driver of the fitness of the vehicle to operate on the dedicated lane. In case of malfunctions or failures in some of the automated vehicle functions the vehicle has a fall-back mode that allows the vehicle to operate as in ERSC 2 or ERSC 1 or the manual mode.

The driver is responsible for merging the vehicle into the dedicated lane with the aid of lateral collision warning and maneuver coordination between the vehicles and roadway. The driver switches the automated mode on and off. Since driving is hands-off and feet-off, the driver has no responsibility during normal vehicle operation in the dedicated lane apart from deciding the vehicle’s route and the end of the trip. The point at which the driver releases manual control could be on the dedicated ramp or in the dedicated lane depending on the entry configuration.

The motivations behind ERSC 3 are:

- to smooth traffic flow and increase capacity by using the roadway commands and smaller headways

- to improve safety by introducing a lateral collision warning.

ERSC 3 allows us to focus on the analysis of both the fully automated longitudinal control and lane keeping functions, i.e., feet-off/hands-off operation without the complexity of automatic lane changing. Table 24 summarizes the functions of the driver, vehicle, and roadway in this ERSC.

Table 24. ERSC 3 functions and driver/vehicle/roadway performance requirements.

Function	Requirement	Driver/Vehicle/Roadway Tasks
Automatic Lane Keeping	– Senses the position and course of the vehicle in the lane and generates the appropriate commands for the steering actuator – Keeps vehicle in the center of the lane around curves and on straight-a-ways	– Sense position of vehicle in the lane with sufficient accuracy – Sense or receive preview information about roadway geometry – Keep vehicle in the center of the roadway – High reliability required since the driver cannot serve as a back-up in case of failure – Transfer of lane keeping function to driver should be done gradually in a smooth way – Interact with rear-end collision function to avoid spinning or rollover during stopping emergencies around curves
Lateral collision warning	Warn the driver of potential lateral collisions due to moving or stationary obstacles around the vehicle	– Detect objects on both sides of vehicle – High detection rate and a low rate of false or nuisance alarms – Warn driver in time to avoid collision – Driver enables warning – Respond to driver command to adjust warning thresholds
Maneuver Coordination	Coordinate lane change/merge maneuvers for entry and exit into the dedicated lane	– Roadway sends commands to increase headway to help vehicles merge into the dedicated lane – Vehicles in dedicated lane respond to headway commands from roadway
Driver Interface	– Adjust thresholds on warnings – Enable/Disable automatic functions – Adjust headway – Show driver what functions are operable at any given time	– Driver should be able to: » adjust headway » adjust warning thresholds » enable/disable automatic functions – Interface should be simple to understand and use – No adjustments should be required that take driver's attention away from driving
Fall-back Mode to ERSC 2	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- Sense status of different vehicle control channels - Safely transfer control of steering to the driver if lane keeping function fails or degrades
Speed and Headway Maintenance (See Section 6-Performance Requirements)	- Maintain the selected cruising speed when no vehicle is ahead. - Calculate and maintain a headway for collision-free vehicle following.	Same as in ERSC 2.

Rear-end Collision Avoidance (See Section 6-Performance Requirements)	The rear-end collision avoidance function should avoid rear-end collisions due to moving or stationary obstacles in the lane under all road and environmental conditions.	Same as in ERSC 2.
Roadway/Vehicle speed & headway commands (See Section 6-Performance Requirements)	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow; Performs check-in and vehicle status monitoring	Same as in ERSC 2.

Performance Requirements

Automatic Lane Keeping

The automatic lane keeping function keeps the vehicle in the center of the lane on normal highway geometries. The vehicle should accurately follow a desired path and provide satisfactory ride comfort over a wide range of speeds, roadway conditions, and disturbing forces. The automatic lane keeping function controls the vehicle's steering smoothly and without oscillations. The automatic lane keeping function should also prevent the vehicle from rolling over or going out of control when the rear-end collision avoidance system needs to brake on curved roads.

The driver checks-in and then enters the automated lane. The point at which the driver releases manual control could be on the dedicated ramp or in the dedicated lane depending on the entry configuration. Once the vehicle has entered the lane the driver starts the automated systems for lane keeping and speed and headway maintenance. The vehicle smoothly takes over control from the driver. The lane keeping function keeps the vehicle in the center of the lane and smoothly navigates curves. The driver is responsible for merging the vehicle into the dedicated lane with the aid of lateral collision warning and maneuver coordination between the vehicles and roadway.

The automatic lane keeping system requires sensors, a computer with control algorithms, and steering actuators. The sensors measure the vehicle's dynamics and the forward roadway geometry. Lane reference aids [30] help the vehicle sensors measure roadway geometry information. The computer generates control signals for vehicle steering as shown in figure 68.

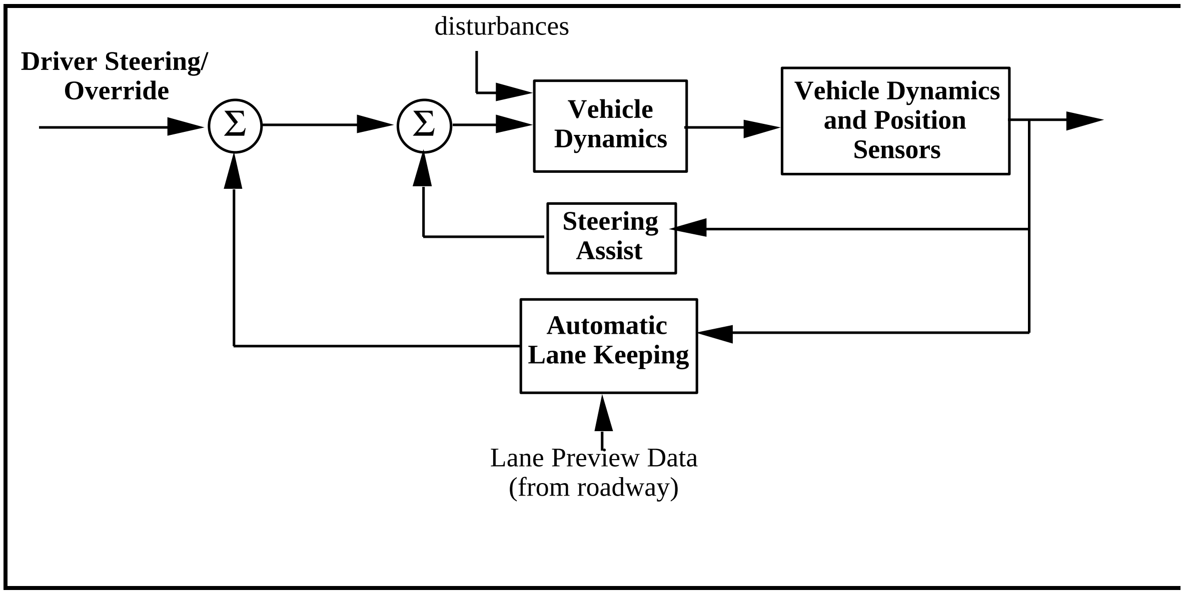


Figure 68. Block diagram for the automatic lane keeping function.

<u>Sensors</u>

The vehicle sensors must detect the vehicle's position in the lane and the curvature of the roadway. The sensors must also measure or estimated the vehicle's yaw rate and slip angle for smooth response. Section 7 on the vehicle lane departure warning discusses sensors for detecting the vehicle's position in the lane.

Drivers use preview information to track the roadway. The driver extracts the information to align the vehicle and to anticipate future actions. Several studies cited in McLean and Hoffman show that human drivers need a preview time of around 3 seconds at most highway speeds.[69] This number corresponds to the "effective" preview time. Distances beyond this limit do not improve system performance. The effective preview time depends on the control bandwidth and reaction time [62]:

$$T_p \approx -0.5 + \frac{4}{BW} \approx \frac{3}{BW}$$

T_p is the preview time. BW is the bandwidth of the controller. Automatic controllers with steering assist will need less preview information if they have larger controller bandwidths than a human driver.

Preview information is important for the performance of the hands off lane keeping control. [84,4] Automatic steering with preview information feedback can tolerate the actuators with lower bandwidth than the one designed without preview. [62] However, more preview means more complex data processing and delays for the sensors.

The required accuracy's of the lane position and preview sensors depends on the lane and vehicle width. Since the goal is to keep the vehicle within a few inches of the center of the lane at all times the sensors must at least detect the vehicle's position within a few inches.

There are several combinations of sensors that can meet these requirements: magnetic markers, vision-based sensors, radar systems, navigation data from the roadway, and global positioning data.

1. Magnetic-Marker-Based
This sensing technique requires a lane reference aid with high degree of roadway instrumentation. In such a lane reference aid, magnetic markers are installed along the center of the lane with about 1 meter spacing. Each marker is with 2.5 cm diameter and 10 cm long, and can provide a 25 cm radius magnetic field when measured at 12 cm above the road surface.[95] The road geometry information can be stored in an on-board database or in the markers as binary codes. When the vehicle is traveling in the lane, the on-board magnetic reference sensor measures the magnetic field to determine the lateral deviation and direction. The sensor can also read the lane geometry information from the markers or the on-board database.

The installation and maintenance of such a lane reference aid can be more costly than the other sensing techniques. However, the vehicle will require less hardware to accommodate the lane reference aid. Experimental results indicate that such technique allows the vehicle to track the center of line with small tracking errors (< 15 cm) [84] at slow speeds. This lane reference aid tends to be robust to the change of weather conditions.

2. Vision-Based
Vision-based sensing uses cameras to detect a vehicle's position on the road. [86,4] Vision-based sensing needs more instrumentation on the vehicle. The vehicle will be equipped with a forward looking camera to sense the vehicle's lateral deviation and roadway geometry. The image signals are sent to an on-board real-time image processing unit that processes the image data. The processor extracts roadway parameters by finding the edges of the roadway and fitting these edges to a roadway model. The camera needs to cover wide angles and large distances to provide the required preview information.

Vision based sensing requires few infrastructure changes. However, it requires more instrumentation on the vehicle. The lane reference aid can be as simple as standard lane markers (stripes) on the roadway to indicate the lane. The lane markers on the lane surface need to give clear contrast for the video camera. Experiments [4] indicate that standard white markers 9 feet long, 4 inches wide, with 15 feet spacing on two edges of the 12 feet wide freshly sealed asphalt lane can provide excellent contrast. The lane lines can be easily furnished and maintained. However, vision systems might not be effective in some weather conditions or at night.

3. Radar-Based
Radar-based sensing tracks the vehicle's lateral position with respect to reflector(s) mounted along the road lane. The reflector can be aluminum foil glued to the plywood wall surface.[23] Experiments [23] show that a vehicle can stay within ± 2.5 cm of the desired lateral position when the vehicle is traveling at 14 m/s.

The reflectors can also be corner cubes [103] installed along the road lane. The vehicle has transceiver(s) to emit and receive laser beam signals. When the vehicle passes through the corner cubes, the vehicles recognize the corner cubes by detecting the reflected laser beam. The vehicle then measures the moved distances and estimates the lateral position and heading relative to the corner cubes based on the triangulation principle. The estimated information is then used as the initial values in the iterated calculation for final position and heading determination. Experimental results [103] show that tracking errors within millimeters can be achieved at speed 20 km/h.

The main disadvantage in the radar sensing is that it provides little preview information. Without adequate preview information, the vehicle may not improve its tracking performance especially when it travels at high speeds.

4. Navigation Data from Roadway

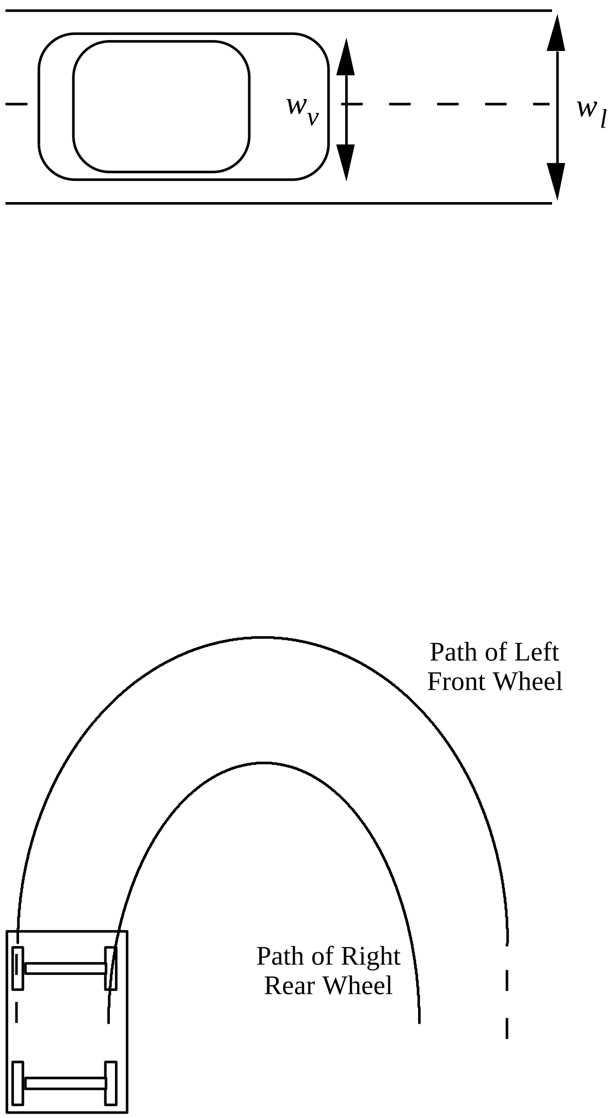
The roadway could also send data to the vehicles about roadway curvature. [33] This approach uses beacons at fixed spots to tell the vehicles about the roadway ahead. The vehicle then uses information on the location of the beacon and dead-reckoning for preview information.[55] Dead-reckoning systems use wheel odometers accelerometers to measure distance and gyroscopes to measure the vehicle's heading. This approach has already been tested in the Prometheus project. [10]

5. Global Positioning System

The global positioning system (GPS) provides absolute position data free from error accumulation.[55] However GPS accuracy is degraded by tall buildings, tunnels, and large trees that are common in large cities. The vehicle can then use on-board maps and dead-reckoning to calculate the preview data. [55] The absolute position accuracy of GPS can then provide feedback and calibration signals to correct dead-reckoning errors. These systems can be integrated with algorithms that switch between systems depending on which has better conditions for operation or a filter can combine all sensor information to get the best estimate.[55] This method suffers from time delays which may make it impractical for real-time control applications.

Control Algorithms

The control algorithms need to keep the vehicle in the center of the lane. The accuracy depends on the lane width, the vehicle length and width, and the roadway design parameters such as curvature. The controller must not oscillate in position. The controller should also restrict the amount of lateral acceleration to less than 0.08 g and the jerk to less than 0.17 g/s for driver comfort.[15] Figure 69 shows the roadway geometry and required accuracy's for an automated lane keeping system. [82]



(a) (b)

Figure 69. Roadway geometry for the lane width calculations. (a) shows these calculations for lane width on a straight section of roadway. (b) shows the turning path for a vehicle on a curve.

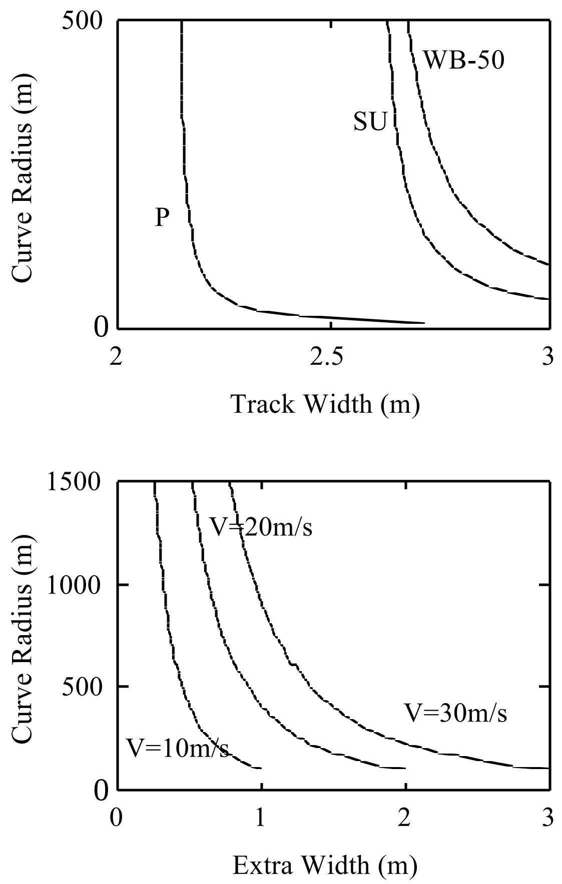
One way to increase highway capacity without building more highways is to increase the number of lanes on the same right-of-way. This will require narrower lanes. In California most freeway lanes are 12 feet (3.7 m) wide with a minimum radius of curvature of 300 meters. Automatic lane keeping is another approach to allow vehicles to cruise on narrowed lanes at freeway speeds. The lane width can be made smaller by taking advantage of the precise lane tracking performance of automated lane keeping. Table 25 gives some parameters for the design vehicles of different types.

Table 25. Design vehicle parameters for highway design.[1]

Design Vehicle Type	Height (Feet)	Width (Feet)	Length (Feet)	Front Overhang (Feet)	Rear Overhang (Feet)
Passenger Car	4.25	7	19	3	5
Single Unit Truck	13.5	8.5	30	4	6
Single Unit Bus	13.5	8.5	40	7	8
Semi-Trailer Truck	13.5	8.5	50	4	6
Large Semi-Trailer	13.5	8.5	55	3	2
Full-Trailer Truck	13.5	8.5	65	2	3
Recreational Vehicles		8	30	4	8

There is a trade-off between the lane width and safety. The vehicle may not cross the lane boundaries while in lane keeping mode. Therefore, the required minimum lane width will depend upon the width of the vehicle and the performance of the automatic lane keeping. Vehicles with wider bodies (e.g., trucks) will need wider lanes. The lane has to be wide enough to accommodate the lateral deviation error caused by the lane keeping system.

In the U.S., 12 feet (3.7 meters) wide lanes are used on more than 97% of the total length of all interstate highways and more than 82% of the total length of other principal arterial highways.[1] Drivers (of trucks and passenger vehicles) in U.S. are already used to driving on highways with standard 12 feet lane width. Most passenger vehicles have width less than 7 feet. If the automatic lane keeping can maintain tracking error within 2-3 inches (5-7.5 cm) bound, 8 feet lanes can be used for passenger vehicles. The width for most trucks is less than 8.5 feet. If the tracking error can always be kept within 6 inches (15 cm), 10 foot lanes can be used for trucks. Some preliminary research/experimental results [84], have demonstrated that such high accuracy lane tracking is possible. More reduction of the lane width is possible if we can further restrict or regulate the width of the automated vehicles. The roadway width for curves needs to be wider to allow for the track width of the outside wheels as shown in figure 70 a. The track width changes with the radius of curvature. The minimum radius of curvature for highways in California is around 300 m. Human drivers require extra width on curves. The amount of extra width depends on the design speed of the highway . [82] Even for narrowed lanes, the rules of highway geometric design still apply. Curve widening will be necessary since the vehicle's front and rear wheels do not track exactly the same trajectories on a curved roadway. This is particularly true for combination-unit trucks. The required width increment will depend on the roadway curvature. Up to a 3 foot per lane increment may be necessary for trucks on sharp freeway curves.



(a) **(b)**

Figure 70. Roadway width for different roadway curvatures. (a) The track width for different types of vehicles. P denotes passenger vehicles. SU is a single unit truck. WB-50 is a semi-trailer truck. (b) Human drivers require extra width on turns. The extra width depends on the design speed of the highway.

Reduction of lane width implies the reduction of the required real estate, construction and maintenance costs. For ERSC's with multiple dedicated lanes, capacity gains are also possible. For examples, 3 standard 12 feet lanes can be converted into 2 narrowed lanes restricted for automated passenger vehicles and 2 narrowed lanes for any automated vehicles. This leads to a potential 33% increase of traffic capacity. The benefits will be significant especially in the urban areas where the land is expensive and traffics get congested often.

The automatic lane keeping has to be so reliable that the benefits of lane width reduction will not be offset by the increase of lateral collision rates. The automated check-in procedure needs to make sure that the vehicle passes the more restrictive fitness test to operate in the narrowed lane. That will insure the vehicle's desired lateral control performance. The required infrastructure instrumentation to support the lane keeping also needs to be checked frequently to ensure proper interaction with on-board lateral control sensor(s).

<u>Actuators</u>

This system will use hydraulic or electronic steering components. Electronic steering may increase the energy efficiency, driver comfort and stability of the steering system. [94] The actuator should have a small delay and respond accurately to the commands from the driver. The steering actuator needs to be reliable and fail-safe since the driver will not be able to regain control if the steering fails suddenly. [24]

Driver Interface

The transfer of control from the driver to the automatic lane keeping system depends on the entry/exit design of the highway. If there are dedicated on and off ramps for the dedicated lane then the vehicle may take over lateral control on the on-ramp. Other entry/exit configurations require the driver to steer the vehicle into the automated lane during entry and to resume steering control before exit takes place, the automated lane should be kept at standard lane width near entry and exit points. It is desirable to gradually reduce the lane width from some point near an entry point and gradually increase the lane width from some point where the driver's resumption control begins.

The driver may not feel safe or comfortable when the vehicle is cruising at high speed in narrowed lanes. The driver's reaction to narrow lanes is a human factors issue and requires more investigation. The driver may be uncomfortable taking over control of the vehicle in the fall-back mode in narrow lanes. The potential damage caused by a lateral collision in the narrowed lanes may be more serious than in the case of standard lanes. All these concerns can only be alleviated by improving the reliability of automated control functions.

If the driver is allowed to override the system for lateral collision avoidance, the driver may have difficulties in maintaining the vehicle in the lane. In the case that the on-board lane keeping system fails, it will be difficult for the driver to take over lateral control in a narrowed lane. This implies that the driver is given less reaction time to plot and execute steering corrections in emergency.

Issues and Risks

1 Preview Data- The vehicle requires preview data for smooth steering and lateral control. The vehicle may depend on the roadway to help get this data. The system reliability requirements may require two independent sources of data for good results.

2 Weather concerns- The controller needs to safely steer the vehicle during all types of weather. Many of the lane reference aids do not work well when the weather is snowy or visibility is limited.

3 Safe driver override - The driver may need to override the automatic functions if he/she sees an obstacle that the vehicle does not. The override must not put the driver in an unsafe position.

4 Reduced lane width - Automatic control may allow smaller lane widths. However, if the vehicle needs to fallback to a manual control mode this change may not be practical.

Lateral Collision Warning

The lateral collision warning system warns the driver of lateral collisions. Most lateral collisions are of the lane change/merge variety with a smaller number of lane departure collisions. Most (95%) of lane change/merge crashes are angle or sideswipe collisions. [113] The driver of the merging car either did not see the other vehicle or misjudged the distance between the vehicles. These crashes usually happen in dry, clear, daylight conditions. [113] The driver "did not see" the other vehicles until too late. The lateral collision warning system on the vehicle detects vehicles in adjacent lanes that are traveling in the same direction. [59] Figure 71 shows the different types of lane change crashes. [21] Most collisions are of the proximity type, only around 10% of crashes are of the fast approach variety. [21]

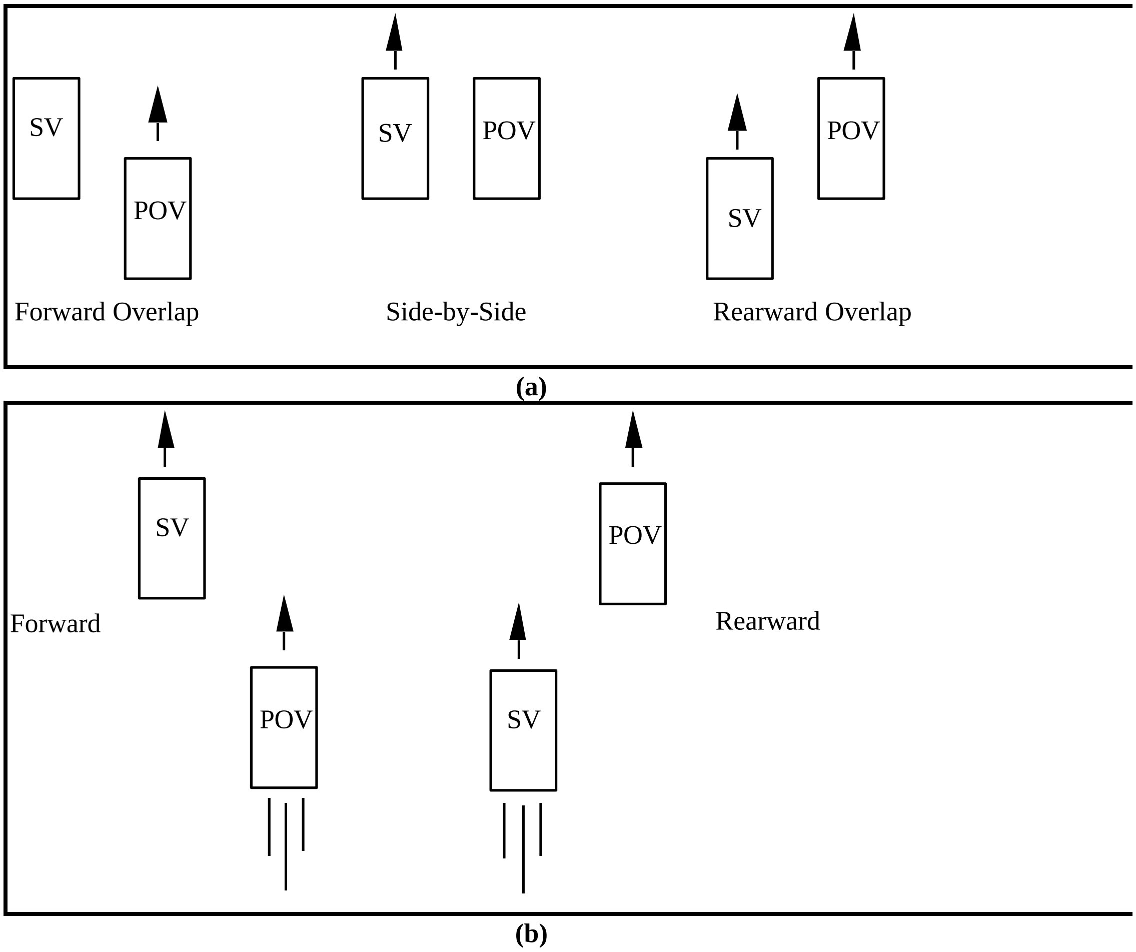


Figure 71. Lane change crash subtypes and variations.[21] SV is the subject vehicle. POV is the Principal Other Vehicle. (a) Types of proximity crashes. Both vehicles have a small velocity differential. (b) Fast approach crashes. There is a large velocity difference between the vehicles that rapidly closes the longitudinal gap between the vehicles.

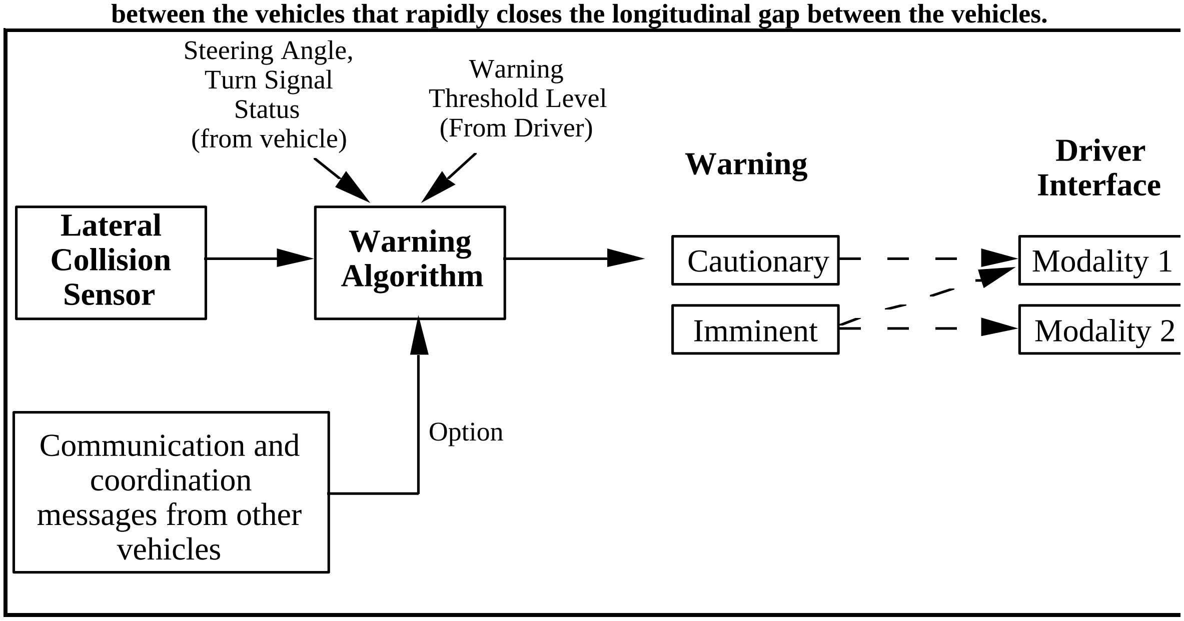


Figure 72. Block diagram of the lateral collision warning system. Sensors detect possible obstacles. Then the warning algorithm calculates the time to collision and warns the driver of potential collisions.

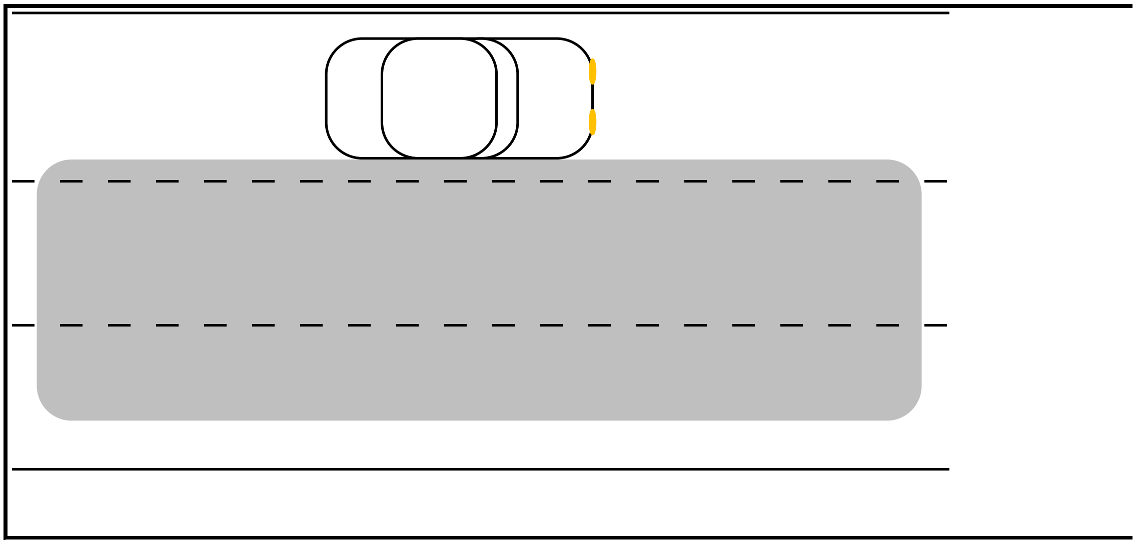


Figure 73. The shaded area shows the region of coverage for a blind spot sensor on the left side of the vehicle.

This type of lateral collision warning system helps avoid lateral crashes. [21] The lateral collision warning system has a sensor and a system that warns the driver. Figure 72 shows the block diagram of the lateral collision warning system. The communications system helps the vehicles signal intent, a sort of electronic turn signal. This type of signal can come from the turn signal or other indicators of the driver's intent to change lanes such as lane position, eye movements, or steering wheel angles.

Sensor

Since lane change/merge accidents occur with equal frequency on both sides of the vehicle there should be lateral collision detection sensors on both sides of the vehicle. [64] Figure 73 shows the left-side lateral collision sensor zone for a vehicle. These sensors should increase safety as vehicles enter and exit the automated lane. The sensor needs to detect vehicles accurately with few unnecessary warnings or false alarms. Too many warnings will cause the driver to turn off the system or ignore its warnings.

The lateral collision detector should cover the adjacent lane to the side and behind the vehicle. The detection zone should cover the full length of the vehicle on both sides. [21] The sensor should reliably detect small vehicles such as motorcycles in all likely lane positions. [64] The detection capability might also extend into adjacent lanes to avoid collisions with vehicles going out of control. However this type of collision is rare and it may happen too quickly for the driver to respond. The driver may not be able to avoid it since drivers have been found to have an average reaction time of 0.82 seconds to swerving emergencies. [21] The reaction time may be longer for automated vehicles when the driver is "hands-off and feet-off." We use 0.82 seconds as a lower bound for the collision avoidance warning.

Currently available lateral collision sensor systems use ultrasound, radar and video systems.[76] Ultrasonic systems transmit ultrasound pulses to detect objects and measure their distance. Radar systems use frequency modulation and range-gating to find the range and relative velocity of objects. Video systems can show the driver a shot of the blind spot or they may add in computer vision technology to search for objects. These systems can be improved if each vehicle signals its "intent" to leave or enter the lane.

Ultrasonic sensors detect objects and their range with pulses of ultrasound. The sensor estimates the pulse time-of-flight. Sensor accuracy depends on local air properties, such as humidity and temperature. These sensors are short range (0.3-10 m) [76] with accurate range measurements. These sensors have too short of a range to be useful for fast approach lateral collisions.

Radar sensors measure the range and relative velocity of objects. The radar estimates the pulse time-of-flight with range gates that look for return pulses at different time ranges. Pulse doppler radars measure the relative velocity between vehicles. This lets the radar tell which vehicles are approaching and which are dropping back. Radar sensors have a longer range than do ultrasound sensors (15-45 m), but they are not as accurate.

Video systems can show the driver an image of what is happening around them. This system has image processing that searches for vehicles. These systems use the continuity between image frames to track vehicles and estimate their distance. These systems have problems with one vehicle blocking or obscuring another.

The lateral collision warning system may also use a combination of these sensors to get full coverage around the vehicle and to track different types of targets. The driver may have a driver situation display that shows the driver's vehicle as well as surrounding vehicles. [21] This system could actively warn the driver or leave all judgments on maneuver safety to the vehicle. The vehicles may also use a cooperative communication system to help track other vehicles. In this system each vehicle would broadcast its position and heading to the surrounding vehicles.

<u>Warning</u>

The lateral collision warning system may be active whenever the vehicle ignition is on and the vehicle is going forward or whenever the driver turns it on. [64] This system may have many nuisance alarms caused by slow traffic or parked cars. Nuisance alarms occur when the sensor detects an object that is not there or is not a threat. The system could also be active only if the driver indicates an intent to change course, such as with a turn signal. This system relies on the driver to signal course changes. The lateral collision warnings may also be triggered by a change in the vehicle's steering angle that signals a lane change. This warning would probably occur too late to avoid an accident.

The lateral collision warning system should have at least two levels of warning: an imminent crash avoidance warning and a cautionary warning. [98,64] A cautionary warning tells the driver that there is a potential collision. This warning may operate when the vehicle is moving forward or only when the automated systems have been turned on by the driver. An imminent lateral collision warning alerts the driver to an imminent crash avoidance situation that exists when an object is sensed and there is an indication that the vehicle's path may cause a collision with that object. [64]

The imminent lateral collision warnings should turn off when the hazard disappears or the driver responds to the warning. The cautionary warning stays on until there is no vehicle in the sensor field. The warning should give information on the location and speed of the threat without causing the driver to look away from the roadway. Directional audio systems can tell the driver the location of the threat and help them recognize the threat more quickly . [9]

The lateral collision detector may turn on only when the driver turns on the turn signal to change lanes or it could be on the entire time the vehicle is in the automated lane. But if the lateral collision sensor was on continuously, it would sound warnings every time the vehicle passed another vehicle. Another option is have the warnings sound only when the turn signal is on.

Driver Interface

The lateral collision warning system provides levels of warning to the driver and provides a detector sensitivity adjustment for the driver. The different warning levels allow the vehicle to warn the driver without intrusive nuisance alarms. The detector sensitivity adjustment lets the driver adjust the range of the sensor to reduce sensitivity and false alarm rates. [64]

The cautionary warning should be visual and located within 15 ° above the line-of-sight of the side view mirror. [64] Visual signals are more detectable if they are near the center of the line-of-sight. The imminent lateral collision warning should use two types of warnings. Lerner et al suggests a combination of auditory and visual warnings. [64] The auditory warning can help the driver determine the direction of the imminent collision with a directional signal. This system has been tested on pilots in simulators. A directional audio signal helps a pilot locate a potential problem 1.5-2 seconds faster than a non-directional warning. [9]

A more sophisticated system is the driver situation display that renders the driver's own vehicle and the vehicles around it. [21] This display gives the driver information on whether it is safe to perform a lane change and where potential trouble might lurk. The sensors would provide vehicle location, velocity, and closing rate data. This display could give the driver the situation awareness data needed to guide the driver's actions.

The lateral collision warning system may have an adjustable threshold. This lets the driver reduce the sensor range to avoid excessive false alarms in which the driver perceives frequent hazards. For example, on multiple-lane highways the sensors may be triggered by objects across the adjacent lane or by vehicles two lanes away.

Issues and Risks

1 Sensor Capabilities

The lateral collision sensor system may increase safety and reduce certain types of lane change/merge crashes. But there are sensor and human factor issues that still must be resolved. The sensors must detect small vehicles, such as motorcycles with few nuisance alarms. A video system may be able to track small vehicles better during daylight. The video system sees what the driver sees so it may be more natural for human drivers to use. The performance of vision based systems may degrade at night and in rainy weather plus it is more expensive and complicated than radars of ultrasonic systems.

2 Warning system desig n

First the designers need to decide when the system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to be directional to get fast driver response.

3 Multiple Warnings

ERSC 3 introduces multiple types of driver warnings for lateral collisions. Research needs to be done on the interaction and prioritization of these warnings for the human driver. For lateral collision avoidance the driver may have very little time to react to any warnings let alone try to figure out what to do.

Maneuver Coordination

This ERSC introduces limited maneuver coordination to help the vehicles merge into the dedicated lane provided by the roadway. The roadway has sensors that monitor traffic back-up for entry onto the dedicated lane. If there are many vehicles waiting to enter the dedicated then the roadway can recommend that the vehicles increase their gaps to allow the drivers to merge onto the highway. This system is similar to today's ramp metering systems. Merge maneuvers may also be simplified by using "rules of the road" that specify which vehicle must give way when a merge occurs. Figure 74 shows how this system would work.

This maneuver coordination tries to make merging easier by increasing gaps between vehicles. However it is still the driver's responsibility to perform the lane entry maneuver. This means that the roadway control system cannot assign each vehicle a slot in traffic. The roadway may assist the driver by sending data on traffic gaps, but it is still the driver's responsibility.

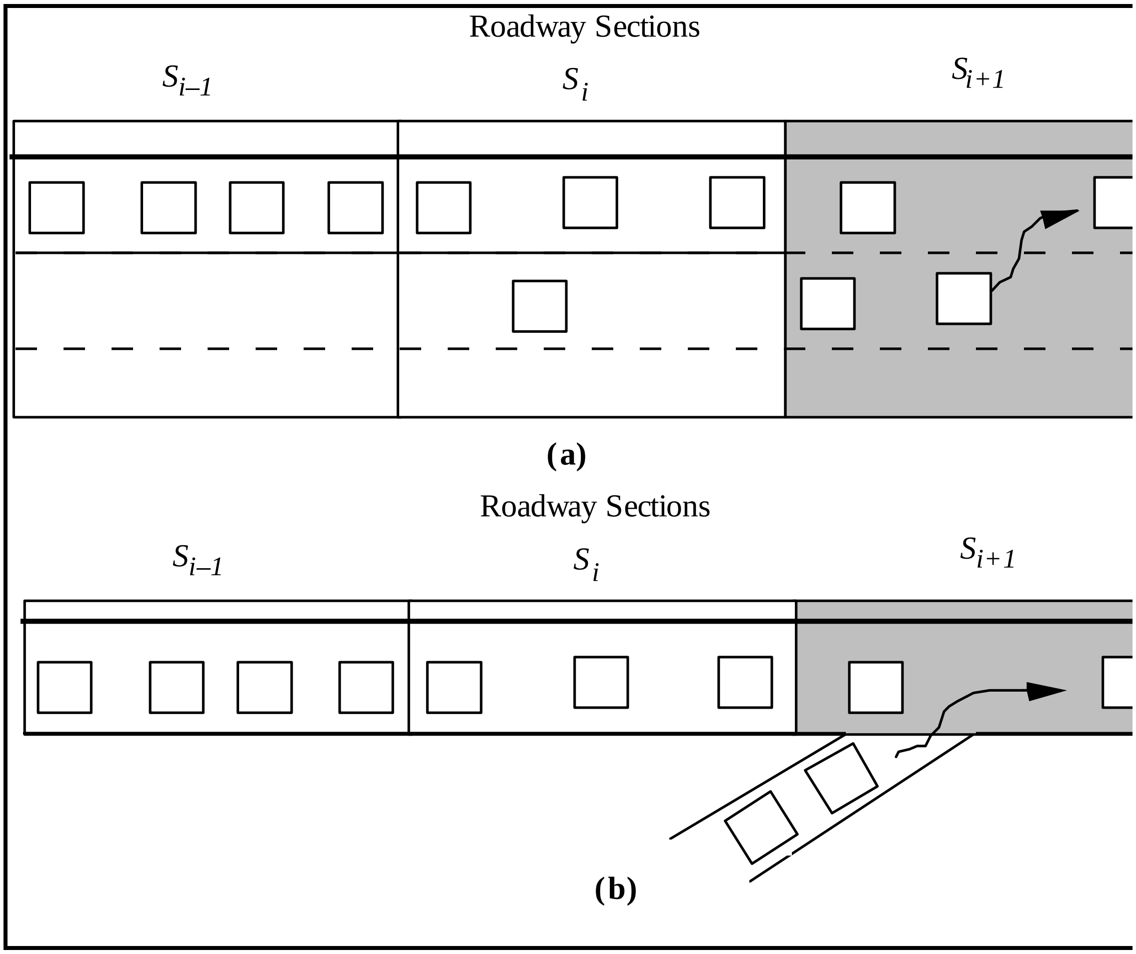


Figure 74. Geometry and operation for entry/exit maneuver coordination. The roadway adjusts the speed and headway of the vehicles to allow for easy entrance in segment S_{i+1}. (a) Geometry for designated entry/exit points. (b) Geometry for dedicated ramps.

Roadway Sensing Systems

The roadway needs to sense the average traffic density over sections of the roadway and the amount of traffic entering the dedicated lane. This data can be measured by sensors that are part of the infrastructure. Proximity sensors such as inductive loops count the number of vehicles that pass over them in a given time period. [112] The data is collected over sections of roadway to monitor traffic flow. [112] The sensors can be hardwired to a roadway traffic control center or they can transmit their data electronically to the traffic control center. These sensors may require changes in the infrastructure and roadbed. These sensors have been in use on freeways for at least a decade and many urban areas already have them in place for traffic monitoring and incident management. [112]

Overhead infrared sensors have also been tested for traffic monitoring. [80,48] These sensors can measure vehicle speed, density, and vehicle type. This sensor type may allow the roadway to choose minimum headways based on the mix of vehicle capabilities.

Communications Requirements

The vehicle needs to check-in with the roadway. The roadway needs to communicate with vehicles on different sections of roadway to adjust their gaps and speed to aid merging. This system can use a roadway-vehicle communication system similar to that described in ERSCs 1 and 2.

Driver Interface

The driver needs to know when gaps in the traffic may be approaching the merge point. The roadway could send a message to the vehicle in the form of in-vehicle signing or a ramp metering system. This would help the driver merge.

Issues and Risks

1 Driver compliance- Maneuver coordination depends on driver coordin ation with the commands from the roadway. If the drivers ignore the inputs from the roadway the vehicle could crash.

2 Entry/Exit Configurations - This type of maneuver coordination with probably require a dedicated ramp so that entering vehicles can match speeds with the vehicles on the roadway.

Driver/Vehicle/Roadway Interface

The driver should be able to override the speed & headway maintenance function and adjust the headway as described in Section 7 on the SHM function. The driver should also be able adjust the warning thresholds on the lane departure warning and the lateral collision warning as described in sections 6 and 7 on the lane departure warning and lateral collision warning functions. The driver also receives highway traffic information through the vehicle and may use it for route planning. The driver may also receive preview information from the roadway. This data may tell the driver about sharp curves up ahead or other roadway conditions. The driver also monitors the vehicle's operational status and backs up failed vehicle functions if possible. If the automated lane keeping system fails the driver takes over manual steering of the vehicle in the fall-back mode.

The driver interface must show the driver that the automated functions are operating correctly or that a function has failed. This interface should be simple to understand and use. No adjustments should be required that take the driver's attention away from the driving task. Input systems like touch pads or buttons may be distracting and may require too much driver attention.(8) The driver must be able to tell what the vehicle is doing at all times and why it is doing it. This shows the driver that the vehicle is operating correctly. Studies show that drivers cooperate more when they know the reasons for an action. (10)

Head-up displays may be particularly useful for visual indicators of the system operation. For example a heads-up display could show the measured distance to the vehicle ahead as well as the minimum time headway and target speed. Other technologies include liquid crystal displays (LCDs), light-emitting diodes (LEDs), computer generated voice messages, sudden vehicle accelerations/decelerations (jerk), tactile feedback, and directional audio displays.(64,8,9)

The interface may be continuous or only active when a driver action is needed. The best design of the driver interface for human factors is an open issue and involves selecting a display technology, type and duration of warnings, user control types and locations, etc. User acceptance is crucial to user interface design. The systems in each ERSC must be easy to use and understand and easy to adjust without the driver taking his eyes off the roadway for more than 1-2 seconds .(73)

Issues and Risks

1 Role Confusion

The driver always needs to know what he/she is responsible for. It may not be a good idea to allow a vehicle to have different modes of operation.

2 Driver Training

3 Complexity

The system must be easy to use and understand.

Fall-back Mode

The system needs to degrade gracefully if a failure occurs. Many failures such as lateral collision warnings may not cause the vehicle to be non-operational. Vehicles with different capabilities may coexist in the dedicated lane without incident.

In case of failure in a single control channel of the automatic lane-keeping system, the vehicle can operate in ERSC 2 control mode with the SHM and rear-end collision avoidance functions. The vehicle may decrease its speed to a safe value for ERSC 2 and the driver resumes control of the steering function with the help of the steering assist system and the lane departure warning. However, according to Riley decoupling warning and avoidance modes can cause “role confusion” for the driver. (90) The driver may also be uncomfortable dealing with a sudden change in responsibility especially during hands-off, feet-off driving. The driver may also be uncomfortable taking over steering control at higher speeds or if there is reduced visibility.(90) Safe system design may require that the driver can force the vehicle not to transfer control until the vehicle is ready to leave the dedicated lane. (90) Meisner et al believe that such transfers between automated and manual functions need to be handled jointly by the driver and the vehicle. [70] The vehicle should not transfer control to the driver in dangerous situations. The driver should not be forced into an uncomfortable situation.

If the lateral collision warning or the maneuver coordination functions fail the vehicle informs the driver. Failure of these functions does not require a transfer of control to the driver so they do not require the vehicle to return to ERSC 2 control.

Vehicle to Roadway Communications

The roadway measures the average speed and traffic density, assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways. The vehicles follow the target speeds set by the roadway using the speed and headway maintenance function. The vehicles should respond to headway recommendations for longer headways due to changes in environmental conditions such as slick roads. The vehicles use the environmental data from the roadway to adjust their time headways. The vehicles check-in with the roadway by sending their identification, automated function status, and location. [108] The vehicles may also display relevant traffic information from the roadway to the driver for route planning purposes. This section covers roadway-vehicle communications for check-in in ERSC 3.

<u>Vehicle to Roadway Communications (VRC)</u>
The roadway sends speed data to the cars to smooth traffic densities, manage incidents, and aid in maneuver coordination. The vehicles may also send their measured velocity and headway to the roadway. The VRC system will be used for check-in. This allows the roadway to monitor the operational status of the vehicles and ensure that they are correctly operating in the automatic mode. These messages only need to be sent once per section. Each vehicle sends status data on all of its automated functions to the roadway. In ERSC 3 these functions are: speed and headway maintenance, rear-end collision avoidance, lateral collision warning, automated lane keeping, VRC systems, and critical engine functions. [108]

VRC systems can be mounted on the side of the roadway, on overpasses, or embedded in the roadway.[85] These systems may use automated toll collection technology with variable registers or a system that covers a wider range. [22,53] Appendix A covers the operation of these systems.

The VRC will send messages from the vehicles to the roadway. Each vehicle sends its speed and the distance to the preceding vehicle (6-8 bits each). The vehicles also send a unique identifying code (at least 28 bits) to the roadway for check-in. The operational status of the automated system can be sent as well, this could take 8-16 bits depending on the amount of detail required by the roadway. Other variables such as estimates of the road-tire friction coefficient can take 4 or more bits. Table 26 shows the possible variables to be sent to the roadway for check-in.[108, page 25] This gives a data length of around 90 bits. The overhead for synchronization and error detection and correction gives a message length of around 200 bits.

Table 26. Potential status variables to be sent to the roadway by the vehicles for check-in.

Function	Components	Number of Bits
Speed & Headway Maintenance	Sensors, Actuators, Controller	1-6
Rear-end Collision Avoidance	Sensors, Actuators, Controller, Vehicle-Vehicle Communications System	1-8
Lateral Collision Warning	Sensor, warning	1-2
Vehicle-Roadway Communication System	Transmitter, receiver, variable register	1-2
Automatic lane keeping	Sensors, Actuators, Controller	1-6
Vehicle Identification Code	Communication code	28
Other Vehicle Functions	Critical fluids level and pressures, brake conditions, tire pressure, engine temperature, headlights	12-16

A broadcast system with a range of 100 meters for a single automated lane must communicate with 0.3 to 0.75 vehicles per second. Analysis by Polydoros et al shows that the current Hughes VRC system and automatic toll collection systems can meet the data transmission requirements for VRC in ERSC 3. (85)

Issues and Risks

1 Dedicated Lane

An issue for AHS is how to get a separate lane for automated vehicles. The driving public rebels when a lane is taken away from active use.(99) The solution for most highway departments has been to add a new lane on the shoulder or median strip, but most urban highways do not have any more space to spare for the sole use of automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

2 Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short. The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

3 Sensors

Roadway weather sensors only cover small regions of roadway. These sensors could easily miss patches of ice or puddles on the roadway. The roadway may then choose an unsafe headway. Research needs to continue into these sensors to improve their capabilities.

4 Privacy

The vehicles "Check-in" with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

5 Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

Reliability Requirement Analysis

In additions to the vehicle functions in ERSC 2, the vehicle can perform automatic lane keeping (ALK) and lateral collision warning (LCW) in ERSC 3. The on-board ALK system together with the speed/headway maintenance and rear-end collision avoidance (SHM/RECA) system allows the driver feet-off and hands-off when the vehicle is in the dedicated lane. The driver is assisted by the LCW system to carry out lateral collision avoidance. To improve the safety during the entry/exit of the dedicated lane, the roadway may assist the maneuver coordination near the entry/exit points.

The ALK system is designed in such a way that it can be overridden by the driver for lateral collision avoidance maneuvers. However, while the vehicle is following the lane and cruising at high speed, it is not guaranteed that the driver can safely take over a failed ALK system. The driver can not be regarded as a back-up to the ALK system. This observation leads to serious reliability requirements for a fail-safe ALK system design. The structure complexity and component redundancy required to implement a fail-safe design will be enormous.

The operation of automatic lane keeping requires lane reference aids from the roadway. The lane reference aids help the ALK system to obtain the necessary lateral dynamics information for lane keeping control. The lane reference aids need to be implemented based on the sensing technologies that are used by the ALK system. The reliability of lane reference aids affects the safety and availability of the ALK operation in the dedicated lane.

The LCW system warns the driver of the potential lateral collision threats. It assists the driver in performing lateral collision avoidance. A no-detections failure is likely to lead to a lateral collision especially when the driver becomes too relaxed in hands-off and feet-off driving. False alarms may affect the effectiveness of the LCW system. Improving detection rates and reducing false alarm rates are the LCW system's major reliability concern.

The roadway can help the entry/exit maneuver coordination by sending slower speed and/or larger headway commands to the vehicles near the entry/exit points. The roadway has to detect the vehicles that intend to enter and get off the lane, and broadcast the speed/headway commands. Reliable communication between the roadway and vehicles is essential for safe maneuver coordination.

Speed/Headway Maintenance and Rear-End Collision Avoidance

The reliability analysis is mainly the same as in ERSC 2 with additional reliability requirements discussed below.

In ERSC 3, the SHM and RECA system may take advantage of the automatic lane keeping and adopt a higher desired cruising speed and/or a smaller headway. If the vehicle can not perform lane keeping, the speed and headway commands from the roadway may be too extreme for the driver to keep the vehicle in the dedicated lane. In this case, the operation of the SHM and RECA system falls back to ERSC 2, i.e., the driver has to steer the vehicle. The speed and headway used by the SHM and RECA systems may be too extreme and have to be re-evaluated. Since the SHM and RECA system determines the safe cruising speed and vehicle following headway, the controller of the SHM and RECA system needs to know the operation status of the automatic lane keeping (ALK) system. Figure 75 shows the functional block diagram of the SHM and RECA system in ERSC 3 that detects the operational status of the ALK system.

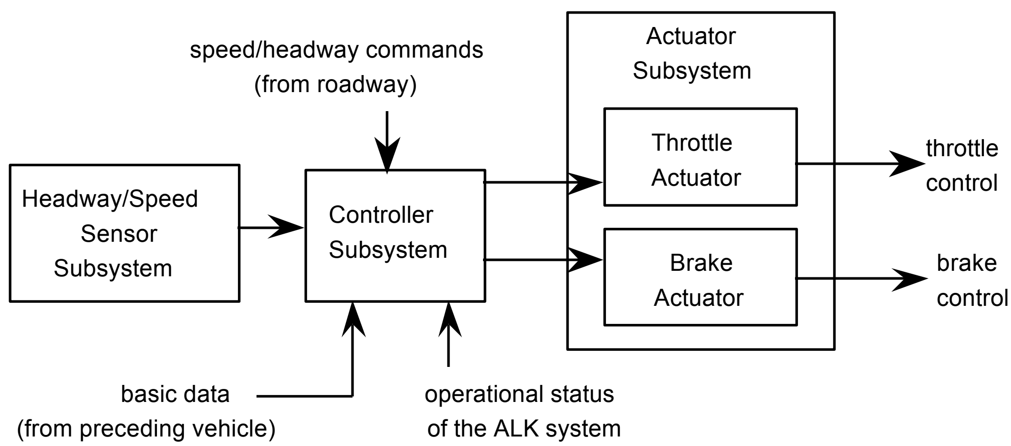


Figure 75. The functional block diagram of the SHM and RECA system in ERSC 3.

Since the impacts of losing automatic lane keeping while the vehicle is at high speed may be severe, the SHM and RECA system may require redundant, independent methods for monitoring the deactivation of the ALK system.

Automatic Lane Keeping

The automatic lane keeping (ALK) system keeps the vehicle in the lane without the driver's steering control. The ALK system is designed in such way that it can be overridden by the driver. The driver overrides the ALK system by turning the steering wheel hard in case of emergencies.

The major components required to implement an ALK system are a lateral dynamics sensor, a controller (a computer with control algorithms), and a steering actuator. The lateral dynamics sensor collects data, such as lateral deviation, lateral speed/acceleration, yaw rate, preview information, etc. The lateral dynamic sensor is supported by the lane reference aids provided by the roadway for data collection. The controller uses the data provided by the lateral dynamics sensor to compute steering commands. The steering actuator takes the steering commands and generates steering force to keep the vehicle in the lane. Figure 76 shows a block diagram of the ALK system.

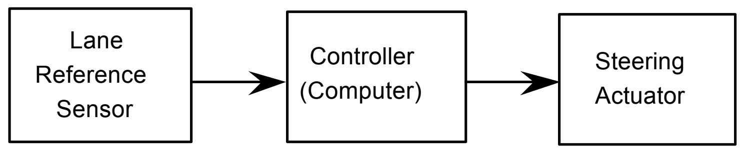


Figure 76. The reliability block diagram of the automatic lane keeping system.

Reliability Requirement Estimation

The ALK system together with SHM and RECA system allows the driver complete hands-off and feet-off driving in the dedicated lane. Since the vehicle is cruising at high speed, the driver will have difficulties in recovering the lateral control if the ALK system fails. The vehicle can depart from the lane before the driver can successfully apply steering correction. Consequently, the driver can not be regarded as an emergency back up when the ALK system fails.

The ALK system is acceptable only if it is much more reliable than manual lane keeping control. The lane departure accident rates in today's manual driving can be used to estimate the required ALK system reliability. The expected number of lane departure collisions during the average vehicle life is 0.0865. [114] The average vehicle life is about 13 years. That gives us an estimate that a vehicle experiences one lane departure collision about every 150 years. The ALK system should have mean time to failure much more than 150 years if it is to be accepted by the general public.

Reliability Functional Requirement

The driver can not be regarded as a back-up to the ALK system since he/she can be hands off the steering wheel. The ALK system has to be fail-safe enough so that an internal component failure or malfunction will not affect the safety in lane keeping. Since the driver is not expected to recover the ALK system failures, any failure that can potentially cause vehicle lane departure is not allowed. The reliability functional requirement for the ALK system is thus proposed as

> “Under no circumstances, should a single component/point failure let the vehicle drift or depart from the lane, and there should be no common failure mode.”

Required Redundancy

Safe lane keeping control depends on the reliability of sensor, controller and steering actuator. The fact that these major components are connected in series, as shown in figure 76, indicates that a single component/point failure may lead to break down of the ALK system. Since the driver is not expected to help recover lane keeping control in emergency and a single component failure is not allowed to cause catastrophe, redundancy will be required in designing the ALK system. A proposed ALK system design framework that has the potential of satisfying the proposed reliability functional requirement is shown in figure 77.

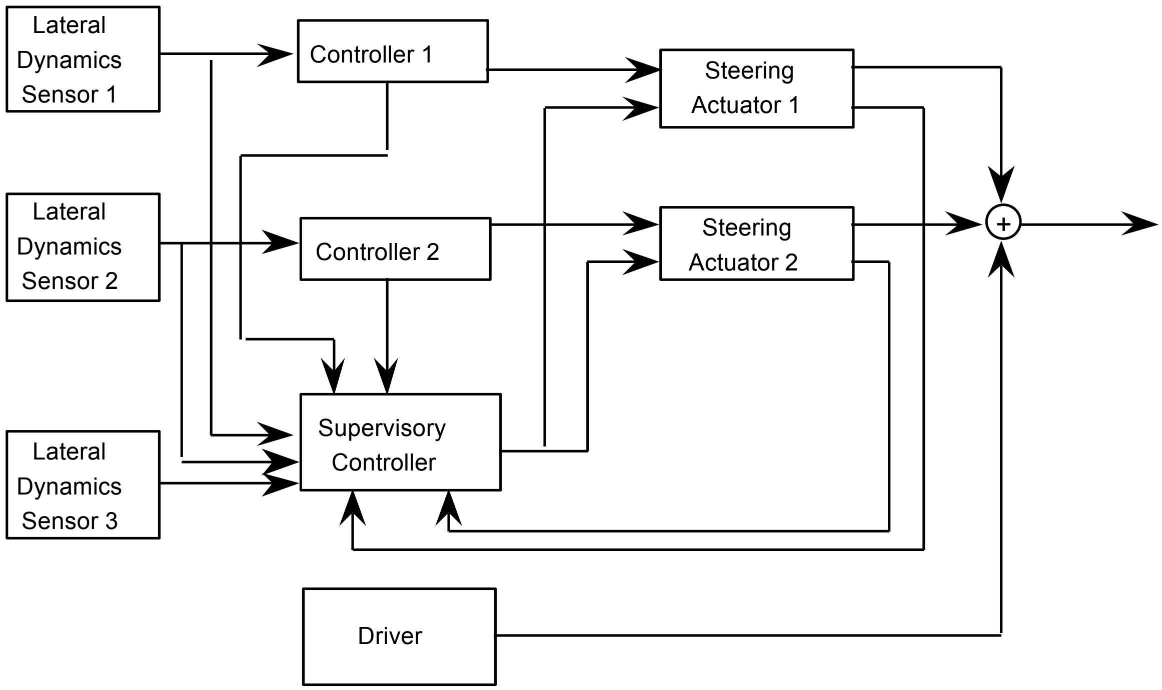


Figure 77. The block diagram of the proposed automated lane keeping design.

The proposed system framework has two redundant active control channels. Each control channel contains a lateral dynamics sensor, a controller and a steering actuator. Each control channel is capable of keeping the vehicle in the dedicated lane. If a component/point failure causes one control channel to fail, the other channel can still operate until the driver safely back up the less reliable ALK system. A third lateral dynamics sensor is used to improve the accuracy of the sensing and to help identify any failed sensor. A supervisory controller is used to help detect any failed component and to deactivate the failed control channel. The probability that any additional component/point fails while the driver is taking over lateral control is negligible. Safe lateral control transition from the ALK system to the driver thus can be obtained.

When one control channel is deactivated due to a potential component/point failure, the ALK system may need a period of transition time to have the other channel operate effectively. Since the vehicle may be traveling at high speeds, a lateral control degradation like this may have safety implications. To reduce the transition time required for fully activating or deactivating a control channel, it is desirable that the two redundant control channels be kept active all the time as long as the ALK system is in operation. In this case, one can activate or deactivate a control channel by quickly adjusting its control gain. Feedback design can be used to efficiently adapt the control gains based on the operational status.

When one control channel is deactivated due to a potential component/point failure, the ALK system is not in the fail-safe condition. Any additional component/point failure may cause the vehicle depart from the lane. In this case, the ALK system should warn the driver of the detected potential failure and ask him/her to take over lateral control. The ALK system should also notify the SHM and RECA system of the action taken so that the SHM and RECA system can re-calculate a safe desired cruising speed and headway. The above system design framework allows the vehicle lane keeping control to fall back to steering assist and lane departure warning in ERSC 2.

It is unsafe that the driver takes over rear-end collision avoidance and/or speed/headway maintenance while the vehicle is performing lane keeping. The ALK system should detect the deactivation of the SHM or RECA system operation. If the SHM or RECA system is deactivated, the ALK system should ask the driver to take over lane keeping control.

The reliability functional requirement does not allow the existence of any common failure mode. A common failure mode can cause simultaneous failures in redundant components and destroy the merits of redundancy. This requirement demands that the redundancies in the proposed framework be independent. The redundant sensors, controllers and actuators have to operate with different technologies, and be supported by independent hardware/software. For example, the three redundant lateral dynamic sensors use three different technologies such as laser scanning of lane markers, vision based sensing, and magnetic marker based sensing. Furthermore, they are powered independently so that a power down will not cause two of them to fail simultaneously.

System Level Design Requirements
In addition to the redundancy discussed above, more detailed design requirements can be obtained by analyzing ,major potential system failure modes. Simply using the system framework in figure 77, one can easily identify the following major potential failure modes:

1. Lateral dynamics sensor failure

2. Controller failure

3. Steering actuator failure

4. Incorrect lane reference data received from the roadway lane reference aids

The ALK system design should minimize the probability of the above major potential failure modes to improve its fail-safe operation. The following important system level design requirements are to counteract the major failure modes.

Potential Failure Mode 1: Lateral Dynamics Sensor failure

1.1 Lateral Dynamics Sensor 1 or 2 computes incorrect lateral dynamics or lane reference data.
Design requirements:

1.1.1 Lateral Dynamics Sensor 1 and 2 need to have an internal independent check of the reasonableness of the computed data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response disables the channel that connects the failed component, warns the driver of the potential failure, and asks him/her to take over lane keeping control.

1.1.2 Controller 1 and 2 and Supervisory Controller should verify that the lateral dynamics sensors are operating in a timely manner by verifying that new data is received from the lane sensor every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

1.2 The data values provided by Lateral Dynamics Sensor 1 and 2 are substantially different.
Design requirements:

1.2.1 Supervisory Controller should sense the discrepancy and use the data from Lateral Dynamics Sensor 3 to determine the sensor that fails. The System Failure Response should then be executed.

1.3 Lateral Dynamics Sensor 3 computes incorrect lateral dynamics or lane reference data.
Design requirements:

1.3.1 Lateral Dynamics Sensor 3 needs to have an internal independent check of the reasonableness of the computed data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, Supervisory Controller should be notified, and the driver should be warned of the failure and be asked to take over steering control.

1.3.2 Supervisory Controller should compare the data computed by Lateral Dynamics Sensor 3 with that computed by Sensor 1 and 2 to check if Lateral Dynamics Sensor 3 is working properly. If an error is detected, Supervisory Controller should be notified, and the driver should be warned of the failure and be asked to take over steering control.

1.3.3 Supervisory Controller should verify that the processor of Lateral Dynamics Sensor 3 is operating in a timely manner by verifying that new data is received from the lane sensor every tbd time interval. If an error is detected, Supervisory Controller should be notified, and the driver should be warned of the failure and be asked to take over steering control.

1.4 Data from Lateral Dynamics Sensor 1 or 2 is not communicated to the controllers, or is corrupted in transmission through interface.
Design requirements:

1.4.1 Each controller should incorporate an independent check of the reasonableness of the computed data from Lateral Dynamics Sensor 1 and 2, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.4.2 Same as for 1.1.2.

1.5 Data from Lateral Dynamics Sensor 3 is not communicated to Supervisory Controller, or is corrupted in transmission through interface.
Design requirements:

1.5.1 Supervisory Controller should incorporate an independent check of the reasonableness of the computed data from Lateral Dynamics Sensor 3, based on the physical attainability and valid known ranges of the system variables. If an error is detected, Supervisory Controller should be notified, and the driver should be warned of the failure and be asked to take over steering control.

1.5.2 Same as for 1.3.2.

Potential Failure Mode 2: Controller failure

2.1 Controller 1 or 2 computes incorrect steering commands.
Design requirements:

2.1.1 Each of Controller 1 and 2 should incorporate an independent chec k of the reasonableness of the computed steering commands before it is sent to the steering actuator, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.2 Each of Actuator 1 and 2 should incorporate an independent check of the reasonableness of the received steering commands computed by the associated controller, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.2 Steering commands computed by Controller 1 and 2 are substantially different.
Design requirements:

2.2.1 Supervisory Controller should sense the discrepancy and determine the controller that fails. The System Failure Response should then be executed.

2.3 Supervisory Controller fails.
Design requirements:

2.3.1 Supervisory Controller should incorporate circuitry, such as a watchdog timer, to detect failures and to ensure the processor functions in a timely manner. If a failure is detected, the circuitry should deactivate

Supervisory Controller, send a signal to warn the driver and to ask him/her to take over steering control.

2.4 Supervisory Controller computes incorrect steering command.
Design requirements:

2.4.1 Supervisory Controller should compare the computed steering commands with those computed by Controller 1 and 2 to determine if it is working properly. If an error is detected, the driver should be warned of the failure and be asked to take over steering control.

2.5 Steering command is not communicated to Actuator 1 or 2 at appropriate time or is corrupted in transmission through interface with Controller 1 or 2.
Design requirements:

2.5.1 Each of Actuator 1 and 2 should verify that it is receiving updated steering command from the controller in a timely manner. If an error is detected, the System Failure Response should be executed.

2.6 Supervisory Controller's command data is not communicated to controllers and actuators at appropriate time, or is corrupted in transmission through interface.
Design requirements:

2.6.1 Each of the two controllers and two actuators should verify that it is receiving updated command from Supervisory Controller in a timely manner. If an error is detected, the driver should be warned of the failure and be asked to take over steering control.

Potential Failure Mode 3: Steering Actuator failure

3.1 Actuator 1 or 2 does not generate correct steering force for a given steering command.
Design requirements:

3.1.1 Each actuator should incorporate built in tests to be performed on the vehicle startup and during lane keeping operation to verify that steering force can be produced and is within the allowable range. If an error is detected, the System Failure Response should be executed.

3.1.2 The ALK system should provide for independent, redundant means to constrain the steering force generated from each steering actuator with safe ranges.

3.2 Actuator 1 or 2 fails to be deactivated when the associated control channel is determined to be deactivated.
Design requirements:

3.2.1 The ALK system should provide for two independent, redundant means of deactivating each steering actuator.

Potential Failure Mode 4: Incorrect lane reference data received from the roadway lane reference aid(s)

4.1 Some lane reference aids does not provide lane reference information to the on-board lateral dynamics sensor.
Design requirements:

4.1.1 Each lateral dynamics sensor should incorporate reliable means to detect potential failures in the associated lane reference aid. If an error is detected, the System Failure Response should be executed.

4.2 Lateral Dynamics Sensors fail.
Design requirements:

4.2.1 Same as for the design requirements in 1.1.1, 1.1.2, 1.2.1, 1.3.1, 1.3.2, 1.3.3, 1.4.1, and 1.5.1.

Key Findings

1. The driver can not be considered as a back-up to the ALK system. A fail-safe ALK system design will require considerable structure complexity and component redundancies.

2. The proposed reliability functional requirement for the ALK system is: "A single component or point failure is not allowed to cause the vehicle to depart from the lane, and there should be no common failure modes."

3. The redundant control channels in the proposed ALK system design framework need to be always kept active to ensure safe and smooth deactivation of a control channel.

Issues and Risks

1. Some lateral dynamics sensing technologies, such as vision based, may be sensitive to the environmental conditions. Due to the strict reliability requirement, the automatic lane keeping operation may be easily interrupted by poor weather. The reliability degradation in automatic longitudinal control may also affect the availability of the ALK function.

2. The considerable amount of components redundancies and roadway lane reference aids may substantially increase the cost of deploying the ALK function.

3. Since the driver may easily become overly relaxed in hands-off and feet-off driving, he/she may have difficulties in overriding the ALK system to perform lateral collision avoidance.

4. The operation of lane keeping requires the assistance of lane reference aids to provide lateral dynamics information. The reliability of the roadway lane reference aids is crucial for the availability of the vehicle ALK function.

Lateral Collision Warning

The lateral collision warning (LCW) system improves the safety of lateral control by warning the driver of potential lateral collisions. It helps the driver detect collision danger coming from both sides of the vehicle. The LCW system can provide warnings when the vehicle is changing lanes or merging, and when the vehicle is performing lane keeping in the dedicated lane.

The LCW system measures the distance, direction and lateral closing rate for vehicles in adjacent lanes. It uses these data to evaluate the lateral time to collision (TTC) and determine the direction of the collision threat. If the computed lateral TTC is smaller than the threshold setting, which takes into account the driver's steering reaction time, the LCW system sends warning signal to the driver.

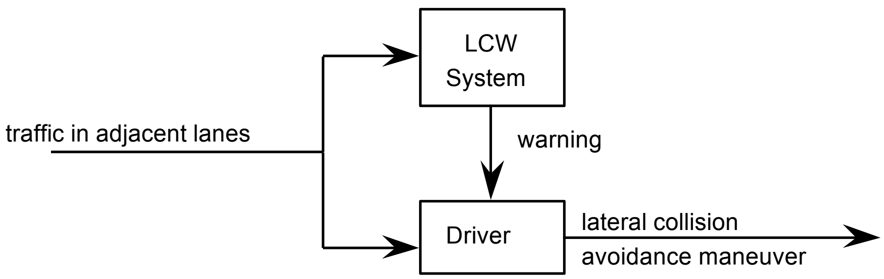


Figure 78. The LCW system interfacing with the driver.

The driver reacts to the warning by overriding the automatic lane keeping system to execute lateral collision avoidance maneuver. Figure 78 shows the interaction between the LCW system and the driver.

<u>Reliability Functional Requirement</u>
The LCW system is designed to improve the safety in the driver's steering control. It is not to replace the driver's lateral collision avoidance function. The effectiveness of the LCW system depends on the detection rates, the false/nuisance alarm rates, types of warning signals, and the driver's reaction to different warning modalities, etc.

In ERSC 3, the driver is interfacing with the ALK system and the SHM/RECA system. The driver is feet-off and hands-off in the dedicated lane. The driver can be over-relaxed and can not sense the lateral collision danger in time. A non-detection may lead to a lateral collision. The LCW system needs to have high detection rates.

Frequent false alarms may be disturbing to the driver, and may delay his/her reaction to the real collision danger. The driver may even reject the false alarms by turning off the LCW system. A sudden false collision warning may make the driver panic and even endanger the vehicle lateral control. Frequent nuisance alarms may irritate the driver. The nuisance alarm rates can be reduced by allowing the driver to adjust the warning threshold within a safe range to accommodate his/her driving skill.

The above discussion suggests that the reliability functional requirement for the LCW system be:

"The LCW system should have high detection rates and low false alarm rates."

System Level Design Requirements

The LCW system is composed of lateral sensors, a processor and a warning interface as shown in Figure 79. The lateral sensors detect vehicles in all lateral directions and from both adjacent lanes, and measure the necessary dynamic data required by the processor for computing TCC. The processor compares the computed lateral TTC with the warning threshold and determines the severity of the danger. The warning interface takes warning commands from the processor and generates warning signals to the driver. The warning signals include the information about the direction of the collision threat.

It has been recommended that at least two levels of warnings be used in the LCW system. (64), an imminent collision warning and a cautionary collision warning. The imminent collision warning informs the driver that it is necessary to take evasive action to avoid a lateral collision. If the imminent collision warning can not be sensed by the driver promptly, the driver may not be able to react to the danger in time. The LCW system is therefore required to provide redundant imminent collision warning signals. Since the driver may become less attentive to a specific type of signals, it is desirable that the redundant imminent collision warnings be different in modality, e.g., visual and audio.

To achieve the proposed requirement, the LCW system needs to have self-diagnosis element to detect potential internal failures. If a failure is detected, the driver should be notified and the LCW system may have to be deactivated. More specific design requirements at system level can be identified by analyzing major potential failure modes and causes based on the system framework shown in figure 79.

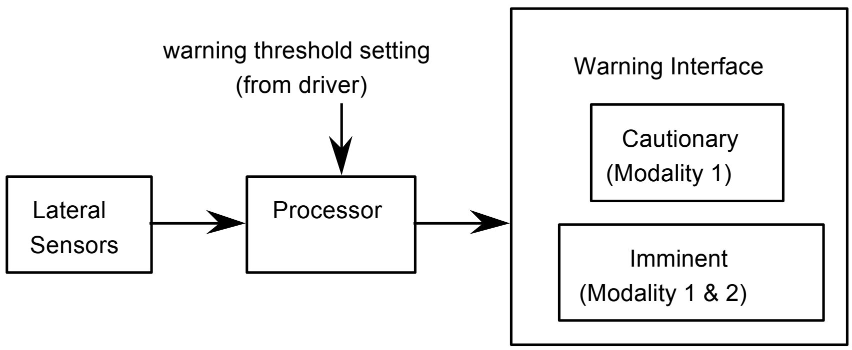


Figure 79. The LCW system framework for reliability design.

1. Lateral Sensor failure

1.1 Lateral Sensors compute incorrect lateral TTC or direction of the threat.
Design requirements:

1.1.1 Lateral Sensors need to have an internal independent check of the reasonableness of the computed data such as lateral distance, closing rate and direction of danger, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed. The System Failure Response warns the drive of the potential failure and asks him/her to turn off the LCW system.

1.1.2 Processor should incorporate an independent check of the reasonableness of the computed data from Lateral Sensors, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.2 Data from Lateral Sensors is not communicated to Processor, or is corrupted in transmission through interface.
Design requirements:

1.2.1 Processor should verify that Lateral Sensors are operating in a timely manner by verifying that new data is received from Lateral Sensors every tbd (to be determined) time interval. If an error is detected, the System Failure Response should be executed.

1.2.2 Same as for 1.1.2.

2. Processor failure

2.1 Processor command is not communicated to Warning Interface at appropriate time or is corrupted in transmission through interface with Processor.
Design requirements:

2.1.1 Warning Interface should verify that it is receiving updated warning commands from Processor in a timely manner. If an error is detected, the System Failure Response should then be executed.

3. Warning Interface failure

3.1 Warning Interface fails to warn or generate incorrect level/modality of warnings after receiving a warning command from Processor.
Design requirements:

3.1.1 Warning Interface should incorporate built in tests to be performed on the vehicle startup and during headway maintenance operation to verify that proper warning signals can be generated. If an error is detected, the System Failure response should be executed.

Key findings

1. Two levels of warning may be required. Imminent collision warning may require redundancy with different warning modalities.

2. The reliability functional requirements for the LCW system are high detection rates and low false alarm rates.

Issues and Risks

1. The driver may become over-reliant on the LCW system and degrade his/her reliability/performance in lateral collision avoidance.

2. The driver may experience warning overload and warning confusion problems while interfacing with other vehicle and roadway functions.

Roadway to Vehicle Speed and Headway Commands

The reliability analysis is mainly the same as in ERSC 1 with additional reliability requirements discussed below.

The roadway may send higher speed commands and/or shorter headway recommendations to the vehicle since the driver does not have to steer the vehicle in the dedicated lane in ERSC 3. A lane reference aid failure may cause the disabling of the on-board ALK system. Without adjusting the speed/headway, the driver may have difficulties taking over lane keeping control. The roadway therefore has to re-evaluate the safe speed commands and minimum headway recommendations for the sections of the dedicated lane that are with failed lane reference aid(s) Figure 80 shows the functional block diagram of the roadway to vehicle speed/headway command function that takes into account the operational status of the lane reference aids.

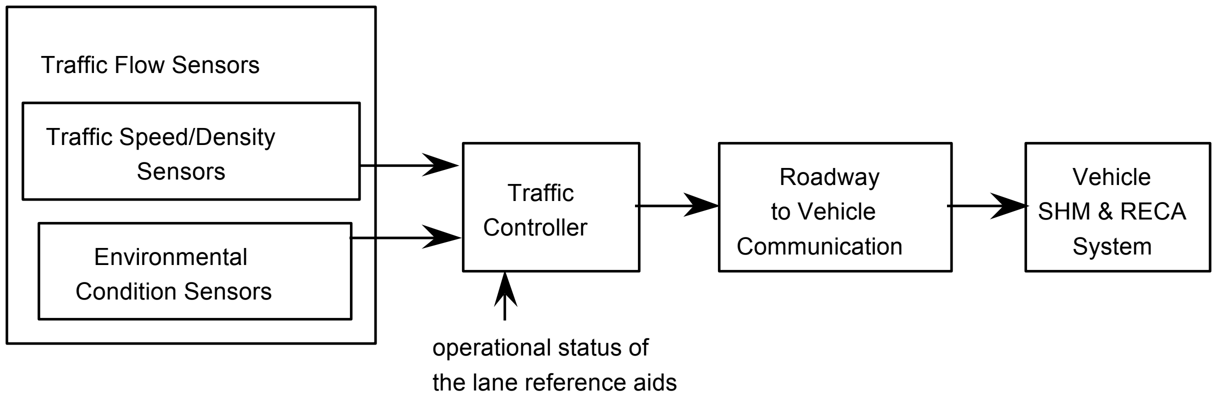


Figure 80. The functional block diagram of the roadway to vehicle speed/headway command function.

Roadway Maneuver Coordination

The roadway assists the vehicles safely getting into and out of the dedicated lane by maneuver coordination near the entry/exit points.

At an entry point, the roadway detects the vehicles that intend to enter the dedicated lane. If a vehicle ready to enter is detected, the roadway sends commands to the vehicles near the entry point in the dedicated lane to slow down and to increase the headway. This ease the merging or lane changing maneuver for the entering vehicle due to larger gaps and slower traffic speeds. The roadway also detects the exit intention of vehicles. To improve the safety in exit maneuver, the roadway can broadcast slower speed and larger headway commands to the vehicles in the highway sections near the exit point. Figure 81 shows the functional block diagram of the roadway coordination

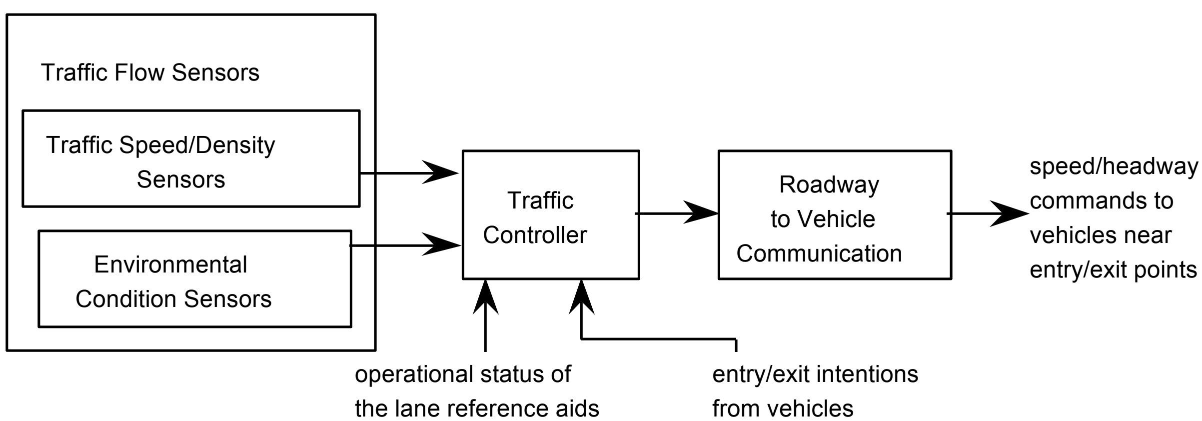


Figure 81. The functional block diagram of the roadway maneuver coordination.

For roadway with continuous entry/exit points, the traffic speed and density in the manual (or transition) lane adjacent to the dedicated lane are also important for entry and exit coordination. The roadway has to use the traffic information in the adjacent manual/transition lane to determine the desired speed and headway for the dedicated lane near entry/exit points.

In ERSC 3, the AHS may take advantages of the rear-end collision avoidance and lane keeping, and adopt an operation strategy with higher speed and smaller headway. It will be dangerous if the driver attempts to enter or exit the dedicated lane without a safe gap at lower speed being created. The roadway traffic controller thus has to have reliable means to detect the entry/exit requests from vehicles. Maneuver coordination commands must be sent through reliable communication protocols to the vehicles in the dedicated lane. The roadway can use the traffic speed/density sensors to make sure that maneuver coordination commands are executed. The roadway may permit the vehicle's entry/exit maneuver only if a safe enough merging or lane changing condition can be created.

Key Findings

1. The reliability of the roadway maneuver coordination depends heavily on the reliability of the roadway-to-vehicle communication.

Issues and Risks

1. Since the roadway involves in the dedicated lane entry and exit coordination, the roadway may be liable for accidents if it fails to send out proper speed/headway commands to coordinate the entry/exit maneuvers. The driver may still blame the roadway for an entry/exit accident even it is caused by the his/her improper merging/demerging maneuvers.

Roadway Lane Reference Aids

In ERSC 3, the roadway provides multiple lane reference aids to support the vehicle's lane keeping function. The lane reference aids are designed to provide lane reference information to the on-board automatic lane keeping (ALK) system. Independent, redundant lateral dynamics sensors are required to implement a fail-safe ALK system. Depending on the sensing technologies used by the lateral dynamics sensors, various types of lane reference aids will be needed. Figure 82 shows the functional block diagram of the roadway lane reference aids.

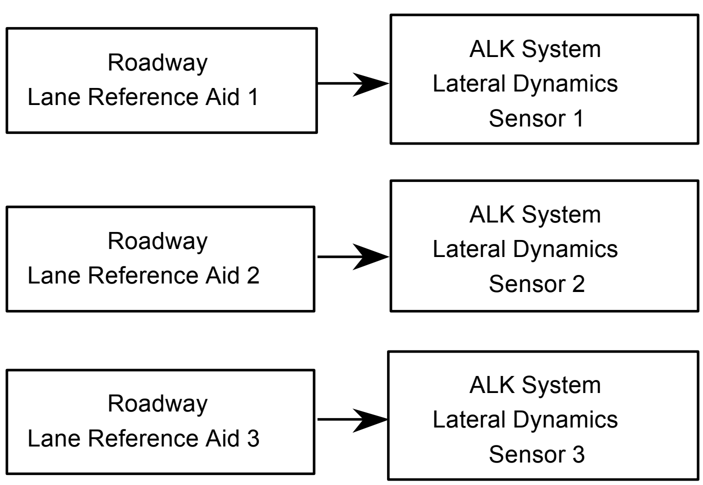


Figure 82. The functional block diagram of the roadway lane reference aids.

Based on the ALK system framework discussed earlier, if a lane reference aid fails to provide correct lane reference data to the associated lateral dynamics sensor, it may degrade the lane keeping performance or lead to the disabling of the ALK system. The lane reference aids thus have to be reliable enough to ensure efficient and safe lane keeping operation.

For magnetic-marker-based sensing, the reliability of the lane reference aid can be improved by installing markers with higher density along the dedicated lane and frequently checking the intensity of magnetic field generated by each magnetic marker. For vision-based sensing, the roadway can improve the reliability of the lane reference aid by providing lane markers with high contrast under various weather conditions. Redundant road lane reflectors may be used to improve the reliability of the radar-based lane reference aid.

The roadway needs to have reliable self-diagnostic procedure to detect any lane reference aid failure along any section of the highway. If a failure is detected, the roadway should warn the vehicle/driver of the danger through the roadway-to-vehicle communication. In this case, the AHS operation falls back to ERSC 2. It is also desirable that the data provided by the lane reference aids be designed in such a way that the lateral dynamics sensors of the ALK system can detect possible failures in the lane reference aids.

Key Findings

1. The roadway lane reference aids are to support the sensors of the ALK system. Since the proposed ALK system design will have redundant and independent lateral dynamics sensors, the roadway lane reference aids will have to be redundant and independent.

Issues and Risks

1. The roadway may be liable for the accidents caused by the failure of the lane reference aids.
2. The required redundancy in the lane reference aids may substantially increase the cost of the roadway.

Driver Tasks and Workload

This section discusses the drivers' tasks in this ERSC. It covers normal driving in the dedicated lane when all of the automated functions work perfectly. Then it covers the fall-back mode in which the vehicle switches into ERSC 2 with speed and headway maintenance and rear-end collision avoidance if the automatic lane keeping system fails or degrades. Finally we discuss the lateral collision warning and the maneuver coordination function and their interactions with the drivers.

The driver drives the car to the automated lane. The driver turns on the vehicle's turn signal and lateral collision warning system. The driver enters the lane when a safe gap appears in the traffic flow. The driver steers the car into the lane and turns on the SHM function, rear-end collision avoidance system and the automatic lane keeping function. The vehicle takes over the throttle, steering, and brake when the car is in the lane or as the vehicle enters the lane. The driver supervises the vehicle control of the steering, brake, and throttle. The driver workload in ERSC 3 is very light once the vehicle enters the dedicated lane.

The driver turns on the turn signal to leave the automated lane. This initiates check-out procedures. Check-out returns the steering, brake, and throttle control to the driver. The driver then changes lanes out of the automated lane. The driver turns off the communications links when he leaves the automated lane.

Task Analysis–Normal Driving

In normal operations, the vehicle controls the steering, throttle, and brake. The driver performs lane changes into and out of the dedicated lane. The driver also avoids lateral collisions. The roadway sends target speed commands and minimum headway information electronically to the vehicle. This data helps the vehicle compute a safe headway. The roadway also sends traffic data to the driver to help him/her select a route. The task analysis in table 27 shows the driver cues for this task.

Table 27 Driver task description for ERSC 3 driving

Task	Monitor Vehicle Operation
General	Task similar to being a passenger in the vehicle
Initiating Cue	Enter Dedicated Lane and turn on speed and headway maintenance, the rear-end collision avoidance, and the automatic lane-keeping functions–The driver sets time headway and initial speed
Feedback	Visual, auditory, and kinesthetic cues of accelerating, braking, slowing, and steering
Task Standards	Perform lane change into dedicated lane within 2-6 seconds, transfer control to vehicle
Task Conditions	Weather, road conditions, or traffic
Skills Required	Reaction times appropriate to speed and roadway conditions. Perceptional judgment of vehicle kinematics for lateral collisions
Potential Errors	Turn off or interfere with automatic lane-keeping system accidentally Turn off speed and headway maintenance system accidentally Vehicle fails to maintain speed or proper headway Vehicle selects unsafe headway Vehicle leaves roadway Roadway sends incomplete or wrong speed command to vehicle
Causes of Error	Fails to perceive or misinterprets system feedback, believes system has malfunctioned Poor judgment of speed and road curvature Hit wrong button and overrides function Sensor, controller, or actuator failure on vehicle Roadway controller malfunctions
Consequences of Error	Disrupt traffic flow and lower capacity Collision with surrounding vehicles Rear-end collision by vehicle in back Lane departure collision
Recovery Points	Minimum safe headway setting on vehicle to avoid collisions Collision warnings Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off; prevent easy override of SHM, ALK, and RECA functions Lateral collision or lane departure warning
Individual Differences	Education Age Driving Skill
Criticality	Essential

Task Analysis–Fall-back Mode

In the fall-back mode, the automatic lane-keeping system suffers a partial failure when one control channel fails, but the other one remains intact. If the steering assist or lane departure warning functions can still operate then the vehicle switches to ERSC 2 operations in which the driver is responsible for steering as described in Section 6. The vehicle warns the driver that he is now responsible for lane-keeping and slows the vehicle to a safe speed for manual steering. The vehicle should then exit the dedicated lane if it cannot safely maintain the speeds commanded by the roadway. If the warnings fail, the vehicle notifies the driver and the driver performs the task without the aid of warnings. Table 28 shows the task analysis for the lane keeping function.

Table 28 Driver resumes control of lane-keeping function.

Task	Fall-back mode to ERSC 2
General	Task may be similar to manual driving with cruise control
Initiating Cue	Vehicle warns driver to resume responsibility for lane-keeping Driver receives warning signal for lane departure from vehicle Vehicle may decrease speed for to allow for manual steering
Feedback	Visual, auditory, and kinesthetic cues for steering
Task Standards	Duration the same as manual driving, transition to manual driving must be gradual, vehicle keeps deceleration low while decreasing speed
Task Conditions	Weather, road conditions, suggestions from traffic control center
Skills Required	Reaction times appropriate to speed and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Driver inattention causes vehicle to leave lane Driver overrides lane-keeping system accidentally Driver does not respond in time to lane departure collision warning Vehicle fails to maintain speed or proper headway Vehicle selects unsafe speed Vehicle does not warn driver adequately of a control transfer
Causes of Error	Fails to perceive or misinterprets system feedback Poor judgment of speed and following distance Hits wrong button Sensor or actuator failure on vehicle Role confusion by driver-responsibilities are not clear
Consequences of Error	Disrupt traffic flow and lower capacity Lane departure or lane change/merge collision Driver confusion
Recovery Points	Maximum speed limit setting on vehicle Lane departure collision warning Vehicle warns driver that lane-keeping function is not working or is failing or has been turned off Vehicle requires active response from driver before a control transfer Driver interface shows driver control status clearly
Individual Differences	Drivers may be uncomfortable taking over steering control at high speeds or in reduced visibility [90]
Criticality	Essential

Task Analysis–Lateral Collision Warning

The lateral collision warning watches for potential lateral collisions. If the sensor detects a lateral collision then it warns the driver. This system aids the driver during lane changes, merges, and normal driving. Table 29 shows driver-lateral collision warning system operation. The lateral collision warning system should ideally warn the driver fast enough for the driver to plan and execute evasive steering actions. This warning system may just give a warning or it may also suggest course changes to avoid the accident.

Drivers avoid collisions with a combination of brakes and steering. [(82)] The less time the driver has to respond to a problem the more likely he is to use only the brakes. This affects the design of the speed and headway maintenance system and the driver override. If the driver is responsible for lateral collision avoidance, then he or she must be allowed to use all the tools available (e.g. brakes and steering) to avoid an accident.

Task Analysis–Maneuver Coordination

The maneuver coordination system helps vehicle merge into the dedicated lane by commanding larger gaps between vehicles approaching a designated entry/exit point. The driver can then merge into the dedicated lane safely. This system may require the roadway or vehicle to send a signal to the driver to let him know that a gap large enough for entry into the dedicated lane is approaching. The vehicle may also coordinate suggested lateral collision avoidance maneuvers. This arrangement is similar to the TCAS system for commercial aircraft.[(96)] This system may require special training for drivers to ensure that they respond correctly. Table 30 shows the task analysis for the maneuver coordination function.

Table 29 Driver task description for lateral collision warning.

Task	Respond to Lateral Collision Warning
General	Task similar to that in manual driving
Initiating Cue	Warning from vehicle that a lateral collision may occur Driver turns on turn signal to enter or leave dedicated lane Vehicle detects change in steering angle
Feedback	Visual, auditory, and kinesthetic cues of steering and braking
Control Functions	Perception-response time (PRT) studies have found that drivers respond to unexpected hazards by avoidance steering as well as braking
Task Standards	Avoid the collision when warned by steering (~1.4 second [21]) Look in direction of lateral collision
Task Conditions	Type and timing of warning Environmental conditions, traffic speed and density
Skills Required	Reaction times appropriate to speed, lane change speed, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Overconfidence in system-driver does not look in lane changes Driver does not use turn signals Driver does not respond to the warning or responds too late Sensor false alarms (No potential collision, system warns driver anyway) Sensor does not detect potential collision Vehicle recommends incorrect maneuver
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Driver delay in response to warning Lateral collision sensor warning threshold too high or low, malfunction Warning controller misinterprets the data and the risk
Consequences of Error	Lane change/Merge collision with potentially severe results for the system (Approximately 4% of crashes and 0.5% of fatalities are lane change/merge crashes. Some 95% of these crashes are angle/sideswipe crashes [113]) Disrupt traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it as pilots and controllers have done in TCAS system [96]
Recovery Points	Vehicle reminds driver to look before lane change Multiple warnings from detector Vehicle suggests a collision avoidance course to the driver
Individual Differences	Accident statistics, citations and self report data indicate that older drivers have difficulty in merging, changing lanes, and exiting maneuvers. Data suggests that persons over 65 may be over represented in lane change/merge crashes.[113] Size of vehicle's blind spot
Criticality	Essential

Table 30 Driver task description for maneuver coordination.

Task	Respond to maneuver coordination signals from roadway or vehicle
General	Task similar to that in manual driving for merges
Initiating Cue	Cue from vehicle that a gap in traffic is approaching Driver turns on turn signal to enter dedicated lane Vehicle detects change in steering angle
Feedback	Visual, auditory, and kinesthetic cues of steering and accelerating
Control Functions	Drivers must be able to merge safely

Task Standards	Safely merge into traffic Accelerate as directed by vehicle or roadway
Task Conditions	Type and timing of warning Environmental conditions, traffic speed and density
Skills Required	Reaction times appropriate to speed, lane change speed, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Overconfidence in system-driver does not look in lane changes Driver does not use turn signals to signal merge Driver does not respond to the cue or responds too late Maneuver coordination does not open a gap Maneuver coordination opens large gaps Vehicle recommends incorrect maneuver
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Driver delay in response may cause unsafe lane change Warning controller misinterprets the data and the risk
Consequences of Error	Lane change/Merge collision with potentially severe results for the system (Approximately 4% of crashes and 0.5% of fatalities are lane change/merge crashes. Some 95% of these crashes are angle/sideswipe crashes [113]) Disrupt traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it [96]
Recovery Points	Vehicle reminds driver to look before lane change Multiple cues from vehicle and roadway Vehicle suggests an acceleration profile to the driver for merging Vehicle suggests an avoidance path to driver
Individual Differences	Accident statistics, citations and self report data indicate that older drivers have difficulty in merging, changing lanes, and exiting maneuvers. Data suggests that persons over 65 may be over represented in lane change/merge crashes [113]
Criticality	Essential

Issues and Risks

1. Driver confidence in warning

If the driver has too much confidence in the collision warning systems then she may not pay enough attention during lane changes or while following another vehicle. This could lead to accidents if the warning system does not detect an object or the system fails. Driver lack of confidence in the warning could cause the driver to disable or ignore the warning system. Research needs to be done on how many false alarms and detection failures are acceptable.

2. Enabling/Disabling Automatic Systems

This ERSC includes a speed and headway maintenance system, lane keeping, lateral collision warnings, and communication systems. Research needs to be done on the instrumentation needed to control these different systems. The question of whether or not all of the automatic systems need to be controlled with one switch or many needs to be answered.

3. Multiple Warnings

The lateral collision warnings may occur simultaneously. The vehicle must prioritize the alarms so that the driver only has to work with one task at a time.

4. Driver override of braking

Even with multiple sensors the vehicle may not see and recognize everything that a human driver sees. This is especially true of unexpected objects such as animals or debris on the roadway. It may be necessary for the driver to override the rear-end collision avoidance system on the vehicle to avoid these objects. The driver is also responsible for lateral collision avoidance. The lack of a braking override may put the driver in an unsafe position. The existence of such an override may also put the driver in an unsafe position if the driver brakes unnecessarily. Research needs to be done on whether or not this driver override should be allowed to occur.

Key Results

Benefits

1. Automatic lane keeping will reduce the collisions caused by vehicle lane departures. It is helpful to the driver in particular for long trip driving.

2. Lateral collision warning improves the safety of the changing lanes and merging. It also helps the driver for lateral collision avoidance.

3. Dedicated lane capacity can be improved by adopting higher speed and/or smaller headway since the driver is hands-off and feet-off in normal driving.

4. Roadway maneuver coordination improves the safety for entry and exit. It may also help reduce the effect of traffic flow disturbance caused by vehicles entering and leaving the lane.

Issues and Risks

1. A potential ALK system design to fulfill the reliability functional requirement will need two redundant, independent steering control channels. This substantially increases the cost of automated vehicles in ERSC 3 due to the design complexity and required redundant components.

2. The operation of lane keeping control requires preview information. The on-board automatic lane keeping (ALK) system obtains it with the help from roadway lane reference aids. The sensing technologies used by the ALK system determine the types of lane reference aids. It might not be easy for some types of lane reference aids, such as vision based, to reliably provide preview information under various environmental conditions.

3. The sensors of the automatic lane keeping (ALK) system interface with roadway lane reference aids to obtains lateral dynamics information. The reliability functional requirement implies that redundant, independent control channels are needed for the ALK system design. The lateral dynamics sensors will be based on independent sensing technologies. Since a lane reference aid needs to be made compatible with a lateral dynamics sensors, there will be multiple lane reference aids. This may substantially increase the cost of the roadway infrastructure.

4. Lateral collision avoidance may require combined lateral and longitudinal control. In ERSC 3, the driver can override the automatic lane keeping system but not the longitudinal control. The effectiveness of the driver’s lateral collision avoidance, using steering control only, is yet to be verified.

Key Findings

1. The on-board-automatic lane keeping system will require redundant active control channels for fail-safe design.

2. It may be impractical to have driver perform lateral collision avoidance while giving him/her only steering override authority.

3. AHS with narrow lanes has the potential of increasing traffic capacity and real estate saving. However, the automatic lane keeping and lateral collision warning will be difficult to implement on a narrow dedicated lane.

4. A malfunction in the ALK system will result in the vehicle operation falling back from ERSC 3 to ERSC 2. However, a malfunction in the SHM and RECA system will cause the operation to fall back from ERSC 3 to ERSC 1 or 0.

Section 8: ERSC 4 Analysis

Description of ERSC 4

In ERSC 4 the vehicle is fully automated. Automatic lane changing and lateral collision avoidance capabilities are added to the vehicles of ERSC 3. The roadway provides and maintains dedicated lanes and provides emergency vehicle response. It also provides lane reference aids for lane keeping and lane changing. The dedicated lanes could be segregated and accessed from dedicated ramps or they could be next to manual lanes and accessed through transition lanes depending on the particular entry/exit configuration. As in ERSC 2 and 3 the roadway receives vehicle status information, assists in the check-in and merging process and sends target speed, headway commands and traffic information to the vehicles.

The additional capabilities of automatic lane-changing and lateral collision avoidance allow the vehicle to drive automatically when the vehicle is in the dedicated lanes. Each vehicle coordinates its maneuvers, such as lane changes, merges, and speed changes, with the vehicles around it. The vehicles use cooperative communications and their own sensor measurements for this coordination. Each vehicle broadcasts its position, heading, and intent to the vehicles around it. These communications may be routed through the roadway so that the roadway can monitor the highway status and coordinate communication traffic and protocols. The vehicle plans, coordinates, and performs all collision avoidance maneuvers. The vehicle must have no single point or common mode fault that could cause the automated lateral and longitudinal control to fail. The vehicle uses its on-board diagnostics to check the fitness of the vehicle for operating in the automated mode and notifies the driver accordingly.

The vehicle plans its route according to the trip destination entered by the driver and the traffic information receives from the roadway. The vehicle may display the planned route and the estimated travel time to the driver. The vehicle alerts the driver and assists him/her in resuming manual control at the end of the trip. It has a contingency plan if the driver cannot resume manual control at the end of the trip or during certain emergencies.

The vehicle has a fall-back mode that allows the driver to briefly take over some of the automated functions in case of vehicle malfunctions. The purpose of this mode is to allow the vehicle to leave the dedicated lanes on the highway if a malfunction occurs. This mode must be designed so that no single point fault will cause the vehicle to be unable to transfer control to the driver.

The driver enters the destination and manually drives the vehicle to the entry point. If the vehicle passes a check-in test, then the driver switches on the automatic mode. The vehicle assumes control of all vehicle functions. Once the automated mode is on the driver becomes a passenger until he/she requests a switch back to a lower ERSC or to manual mode. The vehicle initiates a check-out procedure and the driver gradually regains full manual control in a transition lane or at the exit ramp depending on the exit configuration. When malfunctions occur and the fall-back mode of the vehicle becomes active the driver is responsible for operating the vehicle as in lower ERSCs.

The motivation behind ERSC 4 is to analyze the benefits in terms of driver comfort, safety and capacity that could be achieved by full vehicle automation. ERSC 4 allows us to focus on the analysis of the vehicle fully automated functions as they interact with each other to perform the various driving and emergency tasks without relying too much on the roadway infrastructure. Table 31 shows the functions for ERSC 4.

Table 31. ERSC 4 functions and driver/vehicle/roadway performance requirements.

Function	Requirement	Driver/Vehicle/Roadway Tasks
Automatic Lane Changing and Keeping	– Smoothly and safely change lanes – Keeps vehicle in the center of the lane around curves and on straight-a-ways	– Senses the position and course of the vehicle in the lane and generates the appropriate commands for the steering actuator – Sense or receive preview information about roadway geometry and number of lanes – Keep vehicle in the center of the lane – High reliability required since the driver cannot serve as a back-up in case of failure – Transfer of lane keeping/changing function to driver should be done gradually in a smooth way – Interact with speed and headway maintenance function
Collision Avoidance	Avoid collisions due to moving or stationary obstacles around the vehicle	– Detect objects on both sides of vehicle – High detection rate and a low rate of false or nuisance alarms – Plan evasive actions to avoid collision – Coordinate actions with surrounding vehicles
Navigation/Route Selection	Select a route to reach the driver's destination	– Receive traffic data from roadway information systems – Dynamically select lanes and route for trip
Maneuver Coordination	Coordinate lane change, merge, speed change and collision avoidance maneuvers in the dedicated lanes	– Roadway sends commands for maneuver protocols – Vehicles send their heading, position, and intention to the vehicles around them – Vehicles send out or respond to emergency signals
Driver Interface	– Show driver route and allow driver to change route and destination – Show driver what functions are operable at any given time	– Driver should be able to: » adjust headway » enable/disable automatic functions – Interface should be simple to understand and use – No adjustments should be required that take driver's attention away from driving

Fall-back Mode to ERSC 2 or 3	Driver should be warned of system failures or degradation in time to recover from dangerous situations	- Sense status of different vehicle control channels - Safely transfer control of steering to the driver if lane keeping function fails or degrades
Speed and Headway Maintenance	- Maintain the selected cruising speed when no vehicle is ahead. - Calculate and maintain a headway for collision-free vehicle following.	Same as in ERSC 2. Coordinate with lateral control functions for safe lane changes and collision avoidance
Roadway/Vehicle speed & headway commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow; Performs check-in and vehicle status monitoring	– Roadway commands different speeds for each dedicated lane.

Performance Requirements

Automatic Lane Changing

The automatic lane changing function moves the vehicle from the center of one lane to the center of an adjacent lane on normal highway geometries if it is safe. The vehicle must first check if the lane change is safe and signal its intention to change lanes. When there is an appropriate gap between vehicles in the adjacent lane then the vehicle selects a trajectory and performs the lane change. The vehicle should accurately follow a desired path and provide satisfactory ride comfort over a wide range of speeds, roadway conditions, and disturbing forces. The automatic lane changing function controls the vehicle's steering smoothly and without oscillations. The automatic lane changing function should also prevent the vehicle from rolling over or going out of control when the rear-end collision avoidance system needs to brake on curved roads. The lane changing function works with the vehicle's throttle and brake controller to keep safe gaps between vehicles.

The driver checks-in and then enters the automated lane. The point at which the driver releases manual control could be on the dedicated ramp or in the dedicated lane depending on the entry configuration. Once the vehicle has entered the automated highway the driver starts the automated systems for steering and speed and headway maintenance. The vehicle smoothly takes over control from the driver. The lane changing function allows the vehicle to change lanes. The vehicle merges itself into the dedicated lane with the aid of maneuver coordination between the vehicles and roadway.

The automatic lane changing system requires sensors, a computer with control algorithms, and steering, brake, and throttle actuators. The navigation system chooses when the vehicle should change lanes. The communications system allows the vehicle to coordinate their actions and avoid accidents. The sensors measure the vehicle's dynamics and the forward roadway geometry. Lane reference aids.[30] help the vehicle sensors measure roadway geometry information. The computer generates control signals for vehicle steering as shown in figure 83.

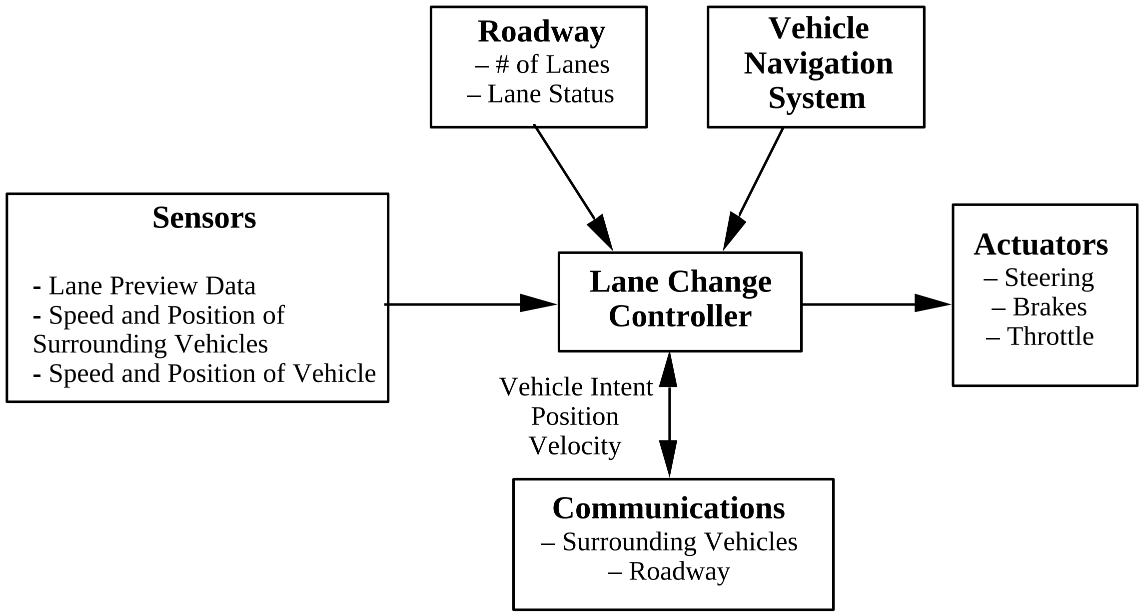


Figure 83 Block diagram for the automatic lane changing system. Sensors and communication systems give information about the surrounding vehicles and their intent. The vehicle navigation system tells the vehicle when it should change lanes to following the vehicle's course. The roadway gives the vehicle information on the number of lanes available for traffic and their status.

<u>Sensors</u>

The vehicle must sense vehicles in the lane that they wish to change into. The vehicle must also sense roadway geometry such as curvature and the number of lanes at their current position and during the duration of the lane change. Figure 84 shows the sensor range for the automatic lane changing system.

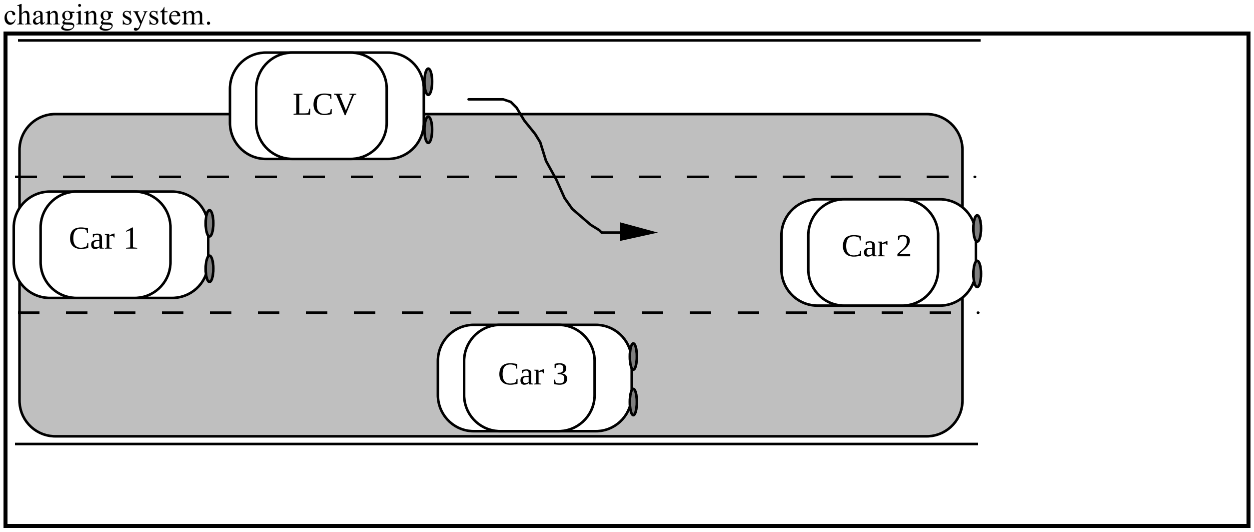


Figure 84. Sensor range for the automatic lane changing system for a lane change to the left side. The vehicle must detect all vehicles that could affect its lane change.

The vehicle sensors must detect the vehicle's position in the lane and the curvature of the roadway. The sensors must also measure or estimated the vehicle's yaw rate and slip angle for smooth response. Section 6 on vehicle control discusses sensors for detecting the vehicle's position in a lane.

Drivers use preview information to track the roadway. The driver extracts the information to align the vehicle and to anticipate future actions.. Several studies cited in McLean and Hoffman show that human drivers need a preview time of around 3 seconds at most highway speeds. [69] This number corresponds to the "effective" preview time. Distances beyond this limit do not improve system performance. The effective preview time depends on the control bandwidth and reaction time [62]:

$$T_p \approx -0.5 + \frac{4}{BW} \approx \frac{3}{BW}$$

T_p is the preview time. BW is the bandwidth of the controller. Automatic controllers with steering assist will need less preview information if they have larger controller bandwidths than a human driver. The vehicle must have preview data for the entire time that it takes to change lanes. This could mean that the vehicle needs 6-8 seconds of preview data.

Preview information is important for safe lane changing. [84,4] Automatic steering with preview information feedback can tolerate the actuators with lower bandwidth than the one designed without preview.[62] However, more preview means more complex data processing and delays for the sensors.

The accuracy of the lane position and preview sensors depends on the lane and vehicle width. Since the goal is to keep the vehicle within a few inches of the center of the lane at all times the sensors must at least detect the vehicle's position within a few inches. There are several combinations of sensors that can meet these requirements: magnetic markers, vision-based sensors, radar systems, navigation data from the roadway, and global positioning data.

1. Magnetic Markers

Magnetic-markers sensing requires a lane reference aid with high degree of roadway instrumentation. The road geometry information can be stored in an on-board database or in the markers as binary codes. When the vehicle is traveling in the lane, the on-board magnetic reference sensor measures the magnetic field to determine the lateral deviation and direction. The sensor can also read the lane geometry information from the markers or the on-board database. The sensor described above requires the vehicle to loose track of the sensor for part of the lane change. This lack of exact position information may make it difficult to perform collision avoidance or emergency maneuvers during a lane change. Magnetic markers may restrict the vehicle to only changing lanes when the magnetic markers lay out a path for the vehicle or an extra row of magnetic markers may be required between lanes.

2. Vision-Based

Vision-based sensing uses cameras to detect a vehicle's position on the road. [86,4] Vision-based sensing needs more instrumentation on the vehicle. The vehicle will be equipped with a forward looking camera to sense the vehicle's lateral deviation and roadway geometry. The image signals are sent to a on-board real-time image processing unit that processes the image data. The processor extracts roadway parameters by finding the edges of the roadway and fitting these edges to a roadway mode. The camera needs to cover wide angles and large distances to provide the required preview information. Vision-based systems can track the vehicle's position through the entire lane change. The vehicle is never "blind" at any part of the lane change.

Vision based sensing requires few infrastructure changes. However, it requires more instrumentation on the vehicle. The lane reference aid can be as simple as standard lane markers (stripes) on the roadway to indicate the lane. The lane markers on the lane surface needs to give clear contrast for the video camera. The lane lines can be easily furnished and maintained. However, vision systems might not be effective in some weather conditions or at night.

3. Radar-Based
Radar-based sensing tracks the vehicle's lateral position with respect to reflector(s) mounted along the road lane. Radar-based sensing only works for vehicles in the side lanes of a freeway if side wall reflectors are used. The reflectors can also be corner cubes [103] installed along the road lane. The vehicle has transceiver(s) to emit and receive laser beam signals. When the vehicle passes through the corner cubes, the vehicle recognize the corner cubes by detecting the reflected laser beam. The vehicle then measures the moved distances and estimates the lateral position and heading relative to the corner cubes based on the triangulation principle. The estimated information is then used as the initial values in the iterated calculation for final position and heading determination. Experimental results [103] show that tracking errors within millimeters can be achieved at speed 20 km/h.

The main disadvantage in the radar sensing is that it provides little preview information. Without adequate preview information, the vehicle may not improve its tracking performance especially when it travels at high speeds.

4. Navigation Data from Roadway
The roadway could also send data to the vehicles about roadway curvature. [33] This approach uses beacons at fixed spots to tell the vehicles about the roadway ahead. The vehicle then uses information on the location of the beacon and dead-reckoning for preview information. [55] Dead-reckoning systems use wheel odometers accelerometers to measure distance and gyroscopes to measure the vehicle's heading. This approach has already been tested in the Prometheus project. [10]

5. Global Positioning System
The global positioning system (GPS) provides absolute position data free from error accumulation.[55] However GPS accuracy is degraded by tall buildings, tunnels, and large trees that are common in large cities. The vehicle can then use on-board maps and dead-reckoning to calculate the preview data.[55] The absolute position accuracy of GPS can then provide feedback and calibration signals to correct dead-reckoning errors. These systems can be integrated with algorithms that switch between systems depending on which has better conditions for operation or a filter can combine all sensor information to get the best estimate . [55] This method suffers from time delays which may make it impractical for real-time control applications.

Controllers
The control algorithms need to assess the safety of a lane change and move the vehicle from the center of one lane to the center of an adjacent lane. The lane change controller needs to control the steering actuators and send inputs to the speed and headway maintenance system. The controller accuracy depends on the lane width, the vehicle length and width, and the roadway design parameters such as curvature. The controller must not oscillate in position. The controller should also restrict the amount of lateral acceleration to less than 0.08 g and the jerk to less than 0.17 g/s for driver comfort.[15]

A more difficult task is to assess the safety of a lane change. Most systems use an intelligent system approach to decide when to change lanes. [81,79] Fuzzy logic systems use commonsense rules in an IF-THEN form to determine when and how a vehicle should change lanes. Fuzzy systems can generalize between similar situations. Expert systems have also been applied in simulation to this problem.

Actuators
This system will use hydraulic or electronic steering components. Electronic steering may increase the energy efficiency, driver comfort and stability of the steering system. [94] The actuator should have a small delay and respond accurately to the commands from the driver. The steering actuator needs to be reliable and fail-safe since the driver will not be able to regain control if the steering fails suddenly.[24]

Lane Change Coordination
Lane changes may be performed more efficiently if the vehicle coordinates its maneuvers with the vehicles around it. Studies done by the California PATH program investigate using a communication link to coordinate a lane change. Before making a lane change the vehicle sends out a signal of its intent to change lanes. This signal serves as an electronic turn signal. Any vehicles that are affected by this maneuver must acknowledge the lane change and grant permission. If acknowledgments are not received then the intent signal is repeated. The analysis in Streisand and Walrand only assumed that one vehicle needs to acknowledge the maneuver and in effect promise to maintain its current course for a given period of time. Realistically the vehicle needs responses from all the vehicles in its sensor range. However this could cause problems in coordinating the maneuver if there are problems of signal collision. In some vehicle following situations the vehicles may need to request cooperative actions from the other vehicles. This could include asking the vehicle to speed up or slow down so the maneuvering vehicle can change lanes. But asking other vehicles to change speeds affects traffic flow and possibly causes traffic jams.

Lane change coordination requires a sophisticated communications system that coordinates the timing and synchronization of messages. Figure 85 shows the message structure for a lane change.

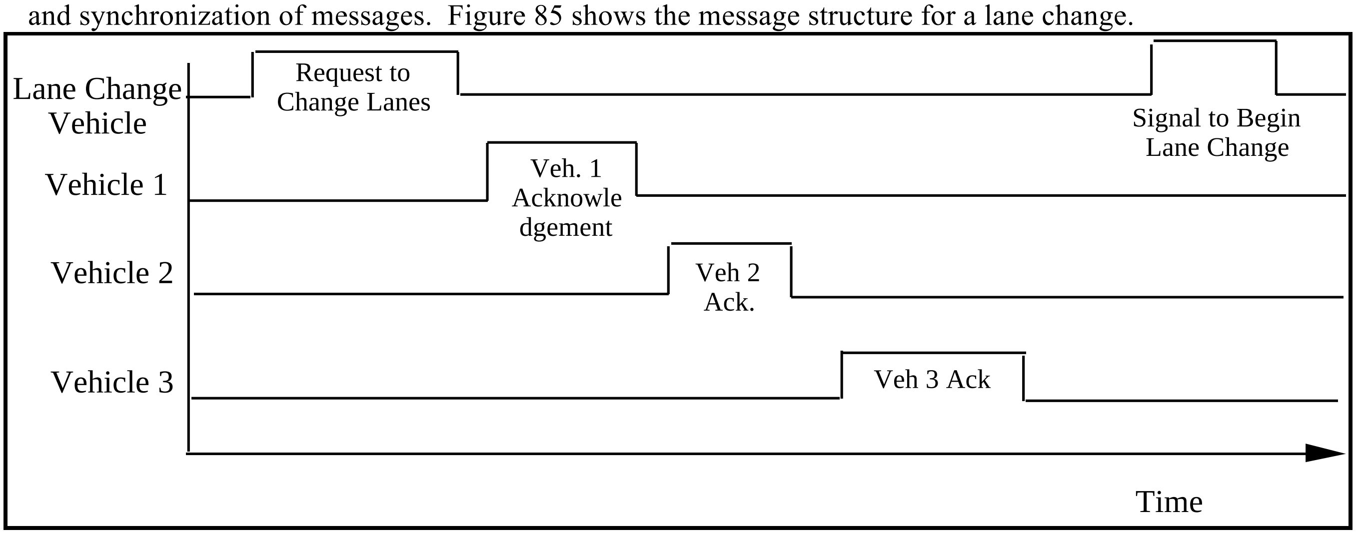


Figure 85. Message timeline for lane change coordination messages. The lane changing vehicle (LCV) sends out a request to change lanes. The surrounding vehicles send back acknowledgments. The vehicle then begins the lane change.

Other possibilities are lane change protocols over a section of roadway. For instance one section of roadway may only allow lane changes to the left, while the next section could allow only right lane changes.

Issues and Risks

1 Lane Change Coordination

Coordinating sensors and communications will be a very difficult task. This will require very sophisticated algorithms to coordinate the lane changes.

2 Automated lateral and longitudinal control

Lane changes require a combination of lateral and longitudinal control. Some work has been done combining these modes. Under normal driving conditions, lateral and longitudinal control is decoupled. Studies need to be done for lane changing to verify that this holds true for most lane changing conditions.

Lateral Collision Avoidance

The collision avoidance system combines lateral and longitudinal control to avoid collisions due to moving or stationary obstacles around the vehicle. This system must be designed so that no single point faults or common mode faults will permit the collision avoidance system to fail. The collision avoidance system must also send out an emergency signal when it must take evasive actions or a control system fails. Figure 86 shows the block diagram of the collision avoidance controller.

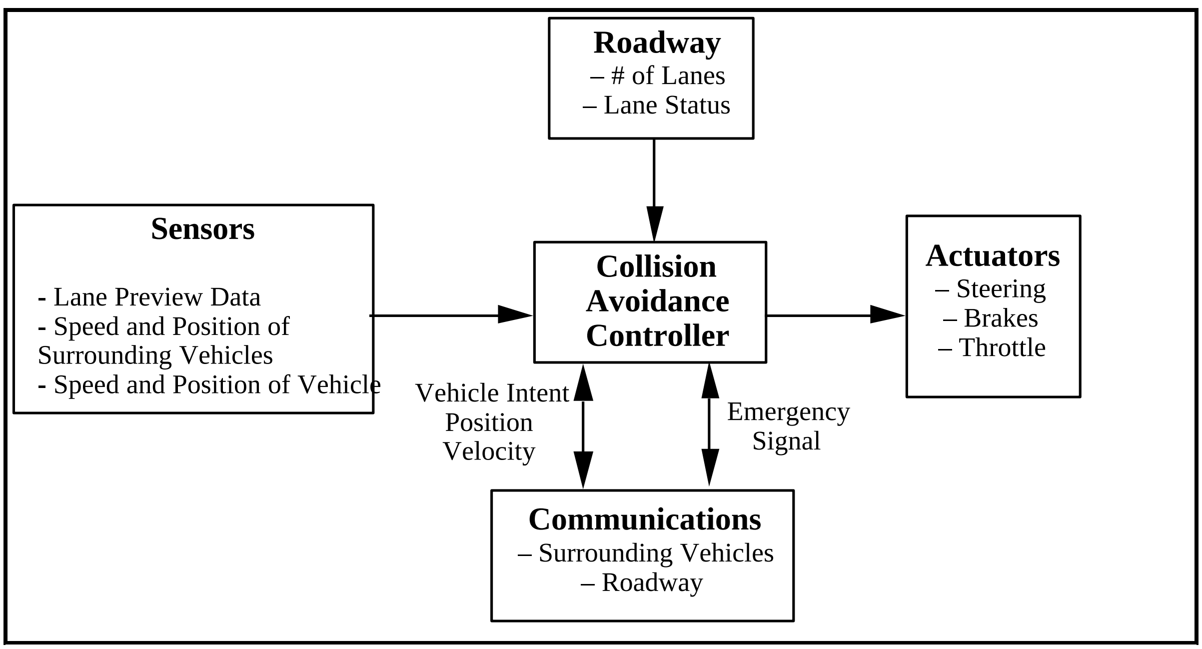


Figure 86. Block diagram for the collision avoidance controller. This controller uses lateral and longitudinal control to avoid collisions.

Sensors
Collision avoidance requires multiple sensors that use different technology to avoid single point failures. These sensors must detect vehicles all around the primary vehicle as shown in figure 87. This system uses preview information from the roadway to predict the path of the other vehicles. The collision avoidance system sensors and communications system allows the vehicle to create a model of the highway and vehicle’s behavior. This allows it to predict hazardous situations and avoid collisions.

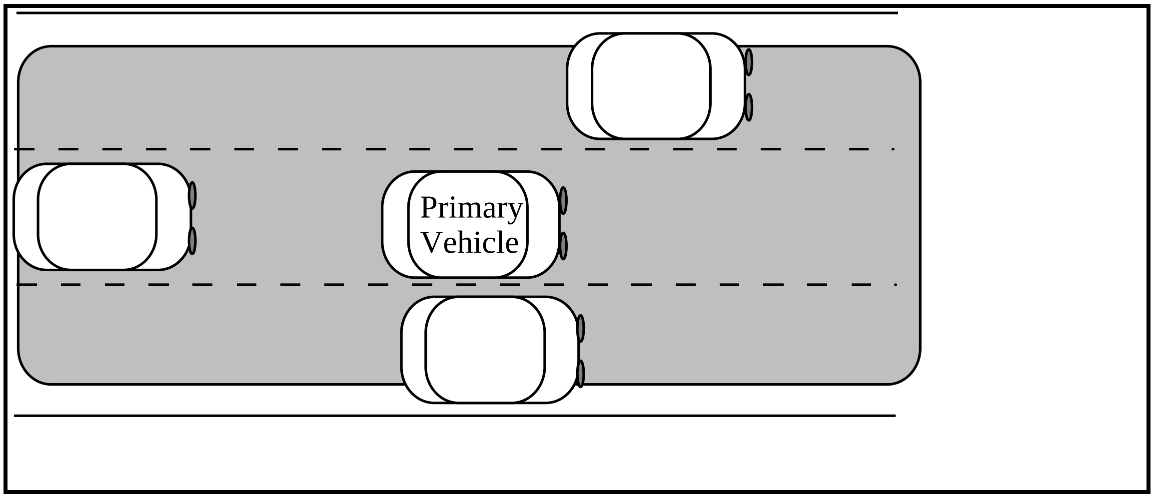


Figure 87. The shaded area shows the sensor range for the primary vehicle.

Possible sensors include radar, ultrasound, vision-based and infrared systems. These sensor have been discussed in the section on lateral collision warnings. Communications can also help the vehicles to plan coordinated actions for collision avoidance.

Controllers

The collision avoidance system sends commands to the brake, throttle and steering actuators. Drivers use all three of these systems to avoid accidents. (66) The controllers must keep the vehicle under control while making the evasive action. There are no limits on the vehicle's lateral and longitudinal acceleration due to driver comfort. The collision avoidance system for the aircraft control system uses a Time-to-collision (TTC) system to assess danger. When the TTC is less than a given threshold then the planes take evasive actions.

The collision avoidance system could have an expert system structure that creates a "mental" model of the vehicles and the roadway. The system then uses fuzzy rules or an artificial intelligence system to select the best evasive action. This system is used in many path planning robots. The problem with this design is that these models require a lot of computation and sensor data to create and they are cumbersome to work with. They are also not very flexible to sudden changes in situations and uncertain data.

An alternative approach is the "subsumption architecture" proposed by Rodney Brooks [Brooks, 1989]. This architecture uses local measurement data to make decisions. It does not explicitly create a detailed world model. This approach has created many simple robots that perform tasks such as giving tours and finding soda cans and are quite robust. However it is not known how well these techniques will scale up to tasks such as driving.

Actuators

The actuators for the brake, throttle and steering must be reliable, accurate and fast. These actuators will probably be a combination of hydraulic and electronic similar to today's airplanes. The speed of response depends on how quickly the vehicle detects a dangerous situation.

Emergency Collision Avoidance

If the vehicle needs to take emergency action due to failures in the automated system, then it sends out an emergency signal to the vehicles around it. The vehicle may sense or have a problem and need to warn other vehicles. Emergency messages must be transmitted quickly and reliably. This signal gives the vehicle's position, heading, and intentions.

Emergency signals identify what vehicle sent the message. The destination address may be a selective broadcast address specifying the affected section of the highway. [100] Emergency messages have high priority depending on the type of emergency. The data field of the message contains essential emergency information such as the location, nature (such as flat tire, debris in roadway, or sudden loss of control), and suggested actions to be taken. Research at California PATH indicates that this message may be up to 1 kilobyte long. [100]

The emergency signal system must be extremely reliable so that no single point or common mode faults will cause the system to malfunction. The emergency system requires an emergency channel for emergency use only. This system may need to be tested regularly to be sure that each vehicle is working properly and can respond quickly to an emergency message.

Issues and Risks

1 Emergency Dynamics

Very little modeling work has been done to characterize vehicle dynamics under extreme conditions. This work needs to be extended.

2 Coordination

Collision avoidance is most effective when done early before an emergency exists. The collision avoidance system must coordinate actions in ways similar to the TCAS system to keep vehicles safe.

3 Path Planning

All of the work on path planning has used robots in fairly static environments. Research needs to be done on real-time systems in a dynamic environment.

Route Selection and Navigation

The driver selects the destination at the check-in point or at the beginning of the trip. The vehicle then chooses a route based on traffic information, road conditions, and driver preference. Route selection will be a dynamic process so the route may changes as conditions change. The driver has the final say in the route selection. The vehicle decides what lanes to use for the trip and when to change lanes as it navigates on the highway.

Route Selection
The vehicle selects a route based on traffic conditions, distance and roadway status. The driver can then approve or disapprove the route. If the driver disapproves the route then the vehicle or driver selects an alternative route. The vehicle or driver can change the route at any time during the trip if traffic or personal conditions warrant it.

Navigation
The roadway could also send data to the vehicles about roadway curvature. [33] This approach uses beacons at fixed spots to tell the vehicles about the roadway ahead. The vehicle then uses

information on the location of the beacon and dead-reckoning for preview information. (55) Dead-reckoning systems use wheel odometers accelerometers to measure distance and gyroscopes to measure the vehicle's heading. This approach has already been tested in the Prometheus project. (10)

The global positioning system (GPS) provides absolute position data free from error accumulation.(55) However GPS accuracy is degraded by tall buildings, tunnels, and large trees that are common in large cities. The vehicle can then use on-board maps and dead-reckoning to calculate the preview data.(55) The absolute position accuracy of GPS can then provide feedback and calibration signals to correct dead-reckoning errors. These systems can be integrated with algorithms that switch between systems depending on which has better conditions for operation or a filter can combine all sensor information to get the best estimate. (55) This method suffers from time delays which may make it impractical for real-time control applications.

Issues and Risks

1 Information Sources

Traffic and road status data may be available from public or private sources. The driver may choose to obtain information from a private source that is more detailed than public data.

2 Lemming Effect

If all drivers get data from the same source then most drivers may end up taking the same route to avoid traffic tie-ups. This could create severe problems on the roadway. Studies need to be done on what type of information is available to drivers and vehicles and how they respond to it.

Maneuver Coordination

The vehicles coordinate their maneuvers with a communications system to make the maneuvers safer and easier. Work at PATH suggests that there are three basic types of maneuvers needed for platoons on automated highways: lane change, platoon split, and platoon merge. (111) Since we are looking at a collision-free system without platooning these basic maneuvers can be restated as lane change, maintain gap, maintain a constant speed, and change speed up or down. These basic maneuvers will allow a vehicle to move on the automated lanes. Maneuver coordination will require communications between vehicles. Figure 88 shows the block diagram for the maneuver coordination system. This system uses sensors to figure out which vehicles need to be communicated with. The surrounding vehicles need to know the position, intentions and heading of the vehicle.

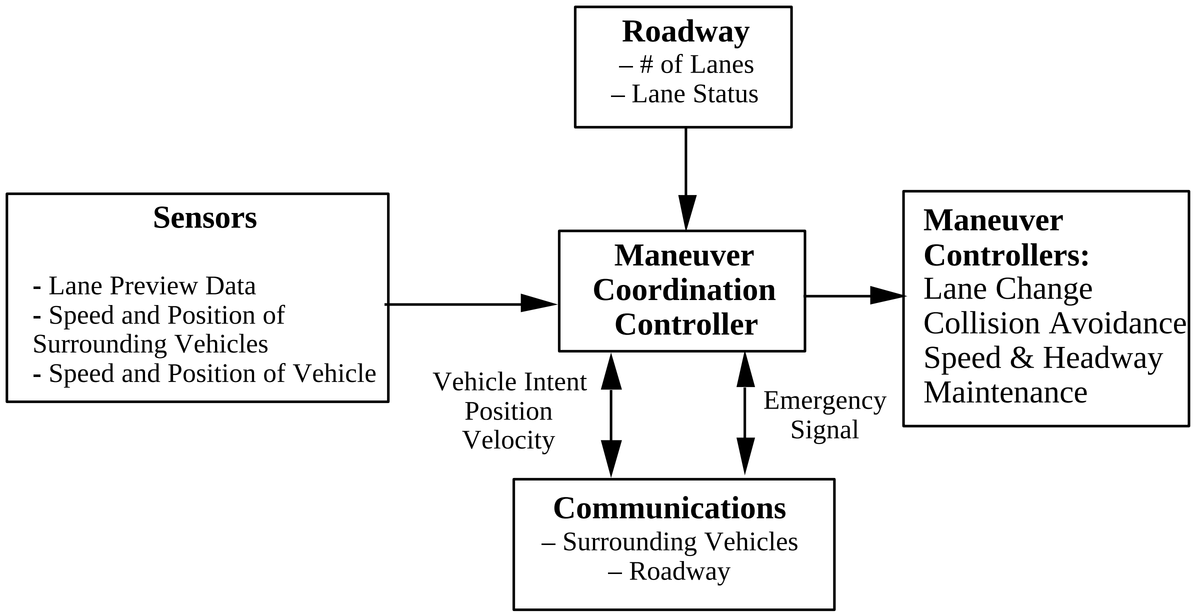


Figure 88 Block diagram for the maneuver coordination system.

<u>Sensors</u>

The sensors help the vehicle determine which vehicles must be informed of different maneuvers. The sensor range is the same as that shown in figure 87 for collision avoidance. Single-lane maneuvers such as speed up, brake or change headway only require information from the vehicles in the same lane.

<u>Communications</u>

Table 32 summarizes the basic message types for maneuver coordination. The information needed column show the contents or data for the message. The type of communication column lists the requirements for the communications system. Possible requirements include whether the message must be acknowledged by other vehicles, the priority of the message, and whether the message is directed at any particular vehicle.

Table 32. Types of communications needed for maneuver coordination.

Maneuver Name	Information Needed	Type of communication
Lane Change	Direction and duration of lane change Acceleration Position Course and Heading	One to many Message directed to certain vehicles Acknowledgments needed from surrounding vehicles Medium priority
Collision Avoidance	Type and nature of emergency What Action is being taken Acceleration Position Course and heading	One to many Message sent to all vehicles in vicinity Acknowledgments needed from surrounding vehicles High priority message
Braking	Degree of braking Road-tire coefficient	One to one Message sent to vehicle behind only
Change speed	Acceleration Position Course and Heading	One to one Message sent to vehicle behind only
Change headway	Acceleration Position Course and Heading	One to one Message sent to vehicle behind only
Status	Acceleration Position Course and Heading	One to many Unacknowledged Low priority

<u>Controllers</u>
The controller must synchronize the messages for all of the vehicles.

<u>Maneuver Protocols</u>
The message frequency may be minimized by the use of protocols for maneuvers. These protocols control which vehicle has the right of way and which one must maneuver. These protocols give a fixed set of rules for lane changes and collision avoidance.

<u>Issues and Risks</u>

The needed information and the types of communication may have to be re-evaluated to ensure that maneuver coordination controller can always follow the protocols for safe maneuvers.

Driver/Vehicle/Roadway Interface

The driver should be able to override the automated lateral and longitudinal control systems if a control channel fails. However the driver must go through a check-out procedure first to verify that he/she is ready to resume control of the vehicle. The driver also receives highway traffic information through the vehicle and may use it for route planning. The driver may also receive preview information from the roadway. This data may tell the driver about sharp curves up ahead or other roadway conditions. The driver also monitors the vehicle’s operational status and backs up failed vehicle functions if possible. If the automated lane keeping system fails the driver takes over manual steering of the vehicle in the fall-back mode.

The driver interface must show the driver that the automated functions are operating correctly or that a function has failed. This interface should be simple to understand and use. No adjustments should be required that take the driver's attention away from the driving task. Input systems like touch pads or buttons may be distracting and may require too much driver attention. [8] The driver must be able to tell what the vehicle is doing at all times and why it is doing it. This shows the driver that the vehicle is operating correctly. Studies show that drivers cooperate more when they know the reasons for an action.[10]

Head-up displays may be particularly useful for visual indicators of the system operation. For example a heads-up display could show the measured distance to the vehicle ahead as well as the minimum time headway and target speed. Other technologies include liquid crystal displays (LCDs), light-emitting diodes (LEDs), computer generated voice messages, sudden vehicle accelerations/decelerations (jerk), tactile feedback, and directional audio displays. [64,8,9]

The interface may be continuous or only active when a driver action is needed. The best design of the driver interface for human factors is an open issue and involves selecting a display technology, type and duration of warnings, user control types and locations, etc. User acceptance is crucial to user interface design.

Issues and Risks

1 Role Confusion

The driver needs to know what he/she is responsible for at all times. It may not be a good idea to allow a vehicle to have different modes of operation.

2 Driver Training

The driver may have to be trained in order to effectively interface with the roadway and the vehicle under various operation conditions.

Fall-back Mode

The system needs to degrade gracefully if a failure occurs. Many failures such as communications systems or isolated sensors may not cause the vehicle to be non-operational. Vehicles with different capabilities may coexist in the dedicated lanes without incident for short periods of time.

In case of failure in a single control channel of the automatic lane-changing or lateral collision avoidance system, the vehicle can operate in ERSC 3 control mode with the SHM, ALK, and rear-end collision avoidance functions. The vehicle may decrease its speed to a safe value for ERSC 2 and the driver resumes control of the steering function with the help of the steering assist system and the lane departure warning. However, according to Riley decoupling warning and avoidance modes can cause "role confusion" for the driver. [90] The driver may also be uncomfortable dealing with a sudden change in responsibility especially during hands-off, feet-off driving. The driver may also be uncomfortable taking over steering control at higher speeds or if there is reduced visibility. [90] Safe system design may require that the driver can force the vehicle not to transfer control until the vehicle is ready to leave the dedicated lane. [90] Meisner et al believe that such transfers between automated and manual functions need to be handled jointly by the driver and the vehicle. [70] The vehicle should not transfer control to the driver in dangerous situations.. The driver should not be forced into an uncomfortable situation by the vehicle.

If the maneuver coordination functions fail the vehicle informs the driver. Failure of these functions may not require a transfer of control to the driver so they do not require the vehicle to return to ERSC 3 control.

If the longitudinal controller fails the vehicle should send out an emergency signal and exit the dedicated lanes as soon as possible. While multiple paths of degradation are technologically possible they are not desirable from a human factors point of view since it may require extensive driver training and practice to handle potential failures safely.

Roadway/Vehicle Speed and Headway Commands

The roadway measures the average speed and traffic density, assesses environmental conditions, and calculates vehicle target speeds and minimum safe headways for the dedicated lanes. The vehicles follow the target speeds for their lane set by the roadway using the speed and headway maintenance function. The vehicles should respond to headway recommendations for longer headways due to changes in environmental conditions such as slick roads. The vehicles use the environmental data from the roadway to adjust their time headways. The vehicles check-in with the roadway by sending their identification, automated function status, and location. [108] The vehicles may also display relevant traffic information from the roadway to the driver for route planning purposes. This section covers roadway sensing systems and roadway-vehicle communications.

Roadway Sensing Systems

The roadway needs to sense the average traffic density over sections of the roadway in each lane. [58] This data can be measured by sensors that are part of the infrastructure or the vehicles can transmit their measured speed and headway to the roadway with a vehicle-roadway communication system for each lane. The vehicle may also transmit its operational status and identification to the roadway for check-in or incident management. The roadway also needs to measure roadway weather data to select a safe target speed for the environmental conditions . [57] Section 5 in the ERSC 1 analysis gives more details on these sensors.

Vehicle to Roadway Communications (VRC)

The roadway sends speed data to the cars in each lane to smooth traffic densities and manage incidents. The roadway needs to avoid large speed differences between lanes for safe transitions. The vehicles may also send their measured velocity and headway to the roadway. This system may also be used for check-in. This allows the roadway to monitor the operational status of the vehicles and ensure that they are correctly operating in the automatic mode. These messages only need to be sent once per section. There needs to be separate messages for each lane. The vehicles will also check-in with the roadway to ensure that they are working correctly. Each vehicle sends status data on all of its automated functions to the roadway. In ERSC 4 these functions are: combined lateral and longitudinal control, collision avoidance, communication systems, and critical engine functions [108].

VRC systems can be mounted on the side of the roadway, on overpasses, or embedded in the roadway.[85] These systems may use automated toll collection technology with variable registers or a system that covers a wider range. [22,53] Appendix A covers the operation of these systems. A separate system may be required for each lane.

Target speed messages from the roadway to the vehicles do not need a high data rate since it will not change very often. Each field will need 6-8 bits to give a resolution of 1 meter for the gap limit and 1 mile per hour for the velocity limit. Since the message goes to all cars in a given lane a destination ID code must tell which lane the message is intended for. The source ID code indicates that the message is from the roadway. Error detection coding looks for bit errors in the message. Retransmission requests are unnecessary since we can rely on repeating the message. This message should be repeated at most one time per second. The bit error rate can also be high since the message changes slowly and rarely. Repetition of messages can compensate for the high error rate. If the roadway sends preview data to the vehicles, the messages may need to be longer in curvy regions of the roadway.

The VRC may also send messages from the vehicles to the roadway. Each vehicle sends its speed and the distance to the preceding vehicle (6-8 bits each). The vehicles may also send a unique identifying code (28 bits) to the roadway for check-in. The vehicle must also send its lane position to the roadway. The operational status of the automated system can be sent as well, this could take 8-16 bits depending on the amount of detail required by the roadway. Other variables such as estimates of the road-tire friction coefficient can take 4 or more bits. Table 33 shows the possible variables to be sent to the roadway for check-in. [108] This gives a data length of around 95 bits.

Table 33. Potential status variables to be sent to the roadway by the vehicles for check-in.

Function	Components	Number of Bits
Speed & Headway Maintenance	Sensors, Actuators, Controller	1-6
Rear-end Collision Avoidance	Sensors, Actuators, Controller, Vehicle-Vehicle Communications System	1-8
Lateral Collision Avoidance	Sensors, Actuators, Controller, Vehicle-Vehicle Communications System	1-2
Vehicle-Roadway Communication System	Transmitter, receiver, variable register	1-2
Vehicle Identification Code		28
Other Vehicle Functions	Critical fluids level and pressures, brake conditions, tire pressure, engine temperature, headlights	12-16

A broadcast system with a range of 100 meters for multiple automated lane must communicate with 0.3 to 0.75*NL vehicles per second. NL is the number of dedicated lanes. Analysis by Polydoros et al shows that the current Hughes VRC system and automatic toll collection systems can meet the data transmission requirements for VRC in ERSC 4. [85]

Issues and Risks

1 Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short. The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

2 Sensors

Roadway weather sensors only cover small regions of roadway. These sensors could easily miss patches of ice or puddles on the roadway. The roadway may then choose an unsafe headway. Research needs to continue into these sensors to improve their capabilities.

3 Privacy

The vehicles "Check-in" with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

4 Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

5 Coordination between lanes

The roadway must coordinate the traffic speed in adjacent lanes to smooth traffic flow. Speed differences of more than 10-20 mph will make lane changes and merges unsafe as well as slowing down traffic in the high speed lanes. This requires a more sophisticated roadway controller than in the previous ERSCs.

Reliability Requirement Analysis

In ERSC 4, the vehicle is heavily instrumented and fully automated. The on-board automatic lateral and longitudinal control (ALLC) system can carry out vehicle functions such as speed and headway maintenance, lane keeping, lane changing, and collision avoidance. Automated vehicles in the multiple dedicated lanes perform maneuver coordination. The ALLC system uses vehicle-to-vehicle communication to help maneuver coordination with neighboring vehicles. The vehicle also has a navigation system to guide the vehicle to the destination specified by the driver.

The ALLC system uses the speed/headway commands from the roadway, maneuver commands from the navigation system, and neighboring vehicles' operating conditions from vehicle-to-vehicle communication to determine its lateral and longitudinal control actions. The vehicle takes over all driving tasks from the driver once the vehicle passes the check-in procedure. When the vehicle is in the dedicated lanes, the driver can not override the ALLC system. The ALLC system needs to be reliable in itself so that all lateral and longitudinal maneuvers can be safely performed.

The roadway sends speed and headway commands to vehicles to smooth traffic flow and to improve safety as described in earlier ERSCs. The roadway provides lane reference aids in multiple dedicated lanes to assist the ALLC system. The roadway may assist the vehicle-to-vehicle communication by relaying the communicated messages between vehicles. The roadway is required to be reliable so that safe and efficient operation of the ALLC system can be guaranteed.

Automatic Lateral and Longitudinal Control

In ERSC 4, the vehicle is instrumented with the automatic lateral and longitudinal control (ALLC) system to perform cooperative driving in the multiple dedicated lanes. The ALLC system carries out the functions such as speed and headway maintenance, lane keeping, lane changing, and lateral/longitudinal collision avoidance. The ALLC system receives target speed commands and headway recommendations from the roadway, and maneuver commands from the on-board navigation system. It also receives neighboring vehicles' dynamics data and maneuver intentions from vehicle-to-vehicle communication. The vehicle coordinates its lateral and longitudinal maneuvers with other neighboring vehicles.

The ALLC system is mainly composed of the lateral/longitudinal dynamics sensor, the controller (computer with control algorithms), and the actuator. Figure 89 shows a functional block diagram of the ALLC system.

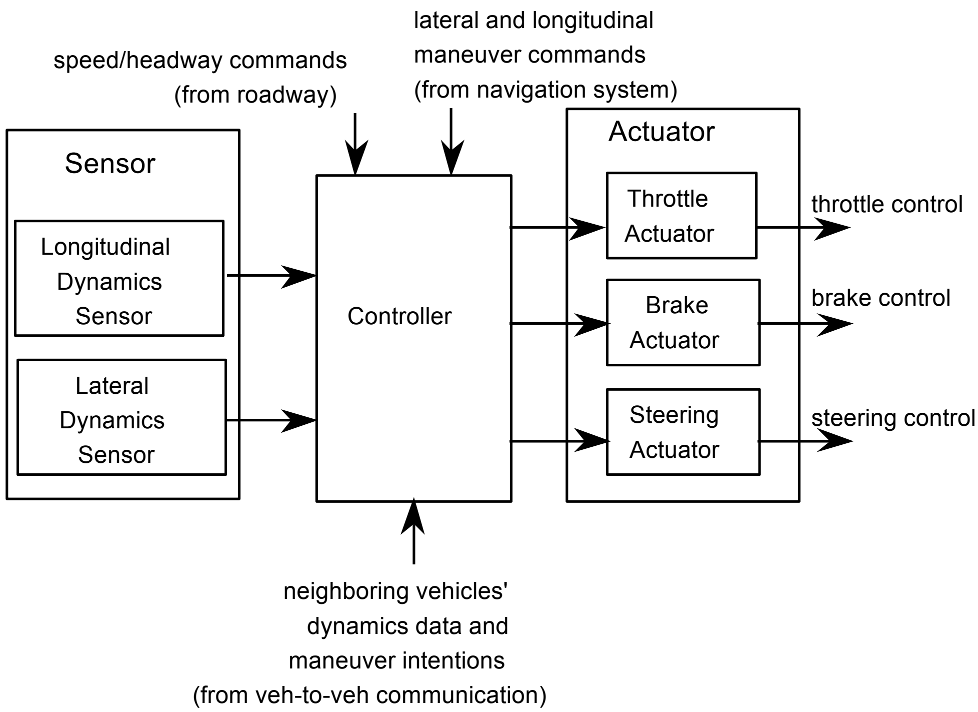


Figure 89. The functional block diagram of the automatic lateral and longitudinal control system.

The longitudinal dynamics sensor detects the relative distances and speeds for the neighboring vehicles in multiple lanes. The lateral dynamics sensor collects data such as lateral deviations and deviation rates of the vehicle and the neighboring vehicles. It also senses multiple lane preview information with the help from the roadway lane reference aids. The controller receives the lateral/longitudinal dynamics data provided by the sensors, and the neighboring vehicles' dynamics data and maneuver intentions from the vehicle-to-vehicle communication. The controller also receives the speed/headway commands from the roadway, and maneuver commands from the navigation system. The controller follows some "right of way" protocols to determine the lateral and longitudinal control actions to be taken. The controller uses the lateral/longitudinal dynamics data provided by the sensors to help verify the reasonableness of the determined control actions. The data from sensors allows the controller to generate timely throttle, brake and steering commands to the actuators. The actuators follow the controller commands and carry out control actions.

Reliability Requirement Estimation

The ALLC system allows the driver complete feet-off and hands-off driving once the driver switches on the automated mode at an AHS entry point. Since the vehicles are in cooperative driving, the driver is not allowed to override the ALLC system. Consequently, the driver's reliability has no contribution at all to the lateral and longitudinal control operation. The driver's improper override actions may even endanger the automated driving.

The reliability of the vehicle control depends fully on the ALLC system reliability. The ALLC system needs to be so reliable that the traffic accident rates in rear-end collisions, lane departure collisions and lane changing collisions, can be significantly improved from today’s manual driving.

Reliability Functional Requirement

If the ALLC system is not designed to be failed-safe, a single component or point failure will lead to a system failure. Since the driver plays no role in controlling the vehicle once he/she gives vehicle control to the ALLC system, an ALLC system failure will result in catastrophe, even series collisions. The reliability functional requirement for the ALLC system is thus proposed as

> “Under no circumstances, should a single component/point failure result in a lateral or longitudinal collision, and there should be no common failure mode.”

Safe Lateral and Longitudinal Control Operation

The ALLC system receives neighboring vehicles' dynamics data and maneuver intentions from the vehicle-to-vehicle communication. This information allows the ALLC system to generate throttle/brake and steering commands for maneuver coordination. A failure in the vehicle-to-vehicle communication may lead to an ALLC system failure. For safe operation, the ALLC system should not rely only on the vehicle-to-vehicle communication for providing the neighboring vehicles' dynamics data. It should take advantages of the on-board sensors and use them to verify the correctness and to improve the accuracy of the data received from the vehicle-to-vehicle communication.

The ALLC system receives maneuver commands from the on-board navigation system and speed/headway commands from the roadway. The ALLC system communicates with other vehicles for maneuver coordination. Furthermore, the ALLC system needs to perform collision avoidance maneuvers if its sensors detect potential collision danger. All the above mentioned can affect the vehicle lateral and longitudinal control. For safety concern, the ALLC system controller should properly set up the priority of the external commands and sequence the maneuvers to be executed. It is essential that all the maneuvers be performed under the condition that collision avoidance can be guaranteed.

Required Redundancy

Safe lateral and longitudinal control depends on the reliability of sensor, controller and actuator. Since these major components are connected in series, as shown in figure 89, a single component/point failure will lead to an ALLC system failure. The proposed reliability functional requirement does not allow a single component/point failure to be catastrophic. For fail-safe design, redundancy will be required to implement the ALLC system. A proposed ALLC system design framework that can potentially satisfy the proposed reliability functional requirement is shown in figure 90.

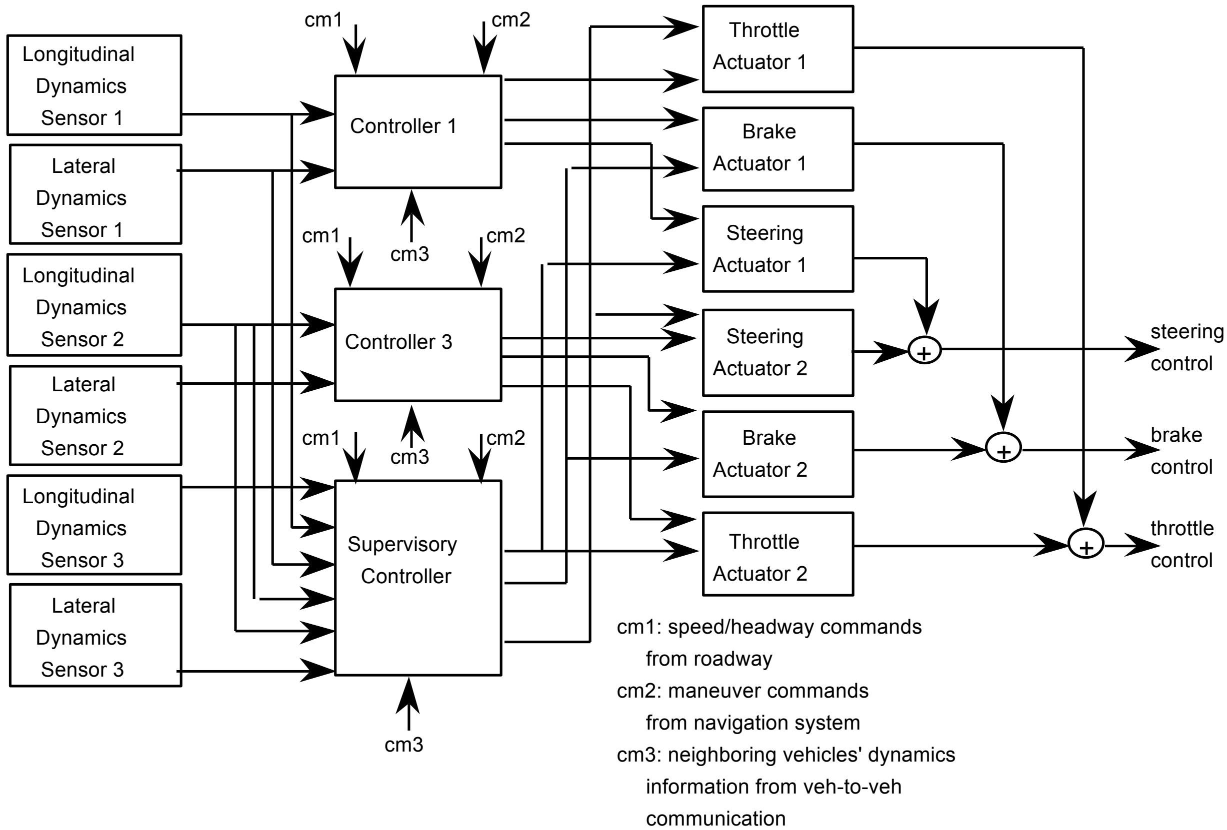


Figure 90. The ALLC system framework for reliability design.

The reliability functional requirement do not allow the existence of any common failure mode, since a common failure mode can cause simultaneous failures in redundant components. Common failure modes can destroy the merits of redundancy. This requirement demands that the redundancies in the proposed framework be independent. The redundant sensors, controllers and actuators have to operate with different technologies, and be supported by independent hardware/software.

The proposed system framework has two redundant control channels. Each control channel contains a lateral dynamics sensor, a longitudinal dynamics sensor, a controller, a throttle actuator, a brake actuator and a steering actuator. Each control channel is capable of performing lateral and longitudinal control functions. If a component/point failure causes one control channel to fail, the other channel can still operate. In this case, the ALLC system is not fail-safe and has to notify the driver of the failure and automatically start the check-out procedure. A third lateral dynamics sensor and a third longitudinal dynamics sensor are used to improve the accuracy of the sensed data and to help identify any failed sensors in the two control channels. A supervisory controller is used to help detect any failed component and to deactivate the failed control channel. Since the probability that any additional component/point fails while the vehicle is checking out of the AHS is negligible, the reliability functional requirements thus can be satisfied.

When the ALLC system is not fail-safe, any additional component/point failure may cause collisions. In this case, the ALLC system needs to be able to guide the vehicle out of the AHS. The driver takes over vehicle control after the vehicle leaves the dedicated lane. Consequently, a non-fail-safe ALLC system does not allow the vehicle longitudinal and lateral control to fall back to the previous ERSCs.

Important System Level Design Requirements

When one control channel is deactivated due to a potential component/point failure, the ALLC system may need a period of transition time in order to have the other channel operate effectively. Since the vehicle may be traveling at high speeds, a performance degradation like this may have safety implications. To reduce the transition time required for fully activating or deactivating a control channel, it is desirable that the two redundant control channels be kept active all the time as long as the ALLC system is in operation. In this case, one can activate or deactivate a control channel by quickly adjusting its control gain. Feedback design can be used to efficiently adapt the control gains based on the operational status.

In addition to the above discussed, more design requirements are needed to implement a fail-safe ALLC system. The detailed design requirements can be derived by exercising the failure mode and effect analysis (FMEA). Complete FMEA may require more specific and detailed system design framework. Simply examining the proposed system design framework in figure 90, one can easily identify the following important potential failure modes that may affect the safe operation of the ALLC system:

1. Longitudinal Dynamics Sensor failure
2. Lateral Dynamics Sensor failure
3. Controller failure
4. Throttle Actuator failure
5. Brake Actuator failure
6. Steering Actuator failure
7. Incorrect speed/headway commands received from the roadway
8. Incorrect lane reference data provided by the lan e reference aids
9. Incorrect information received form the vehicle-to-vehicle communication

The following proposed design requirements attempt to protect the longitudinal and lateral control functions from the above potential failure modes. In particular, once a potential failure mode is detected, the ALLC system needs to perform the System Failure Response. In the response, the ALLC system disables the control channel in which the failed component or fail point is. It notifies the driver of the detected failure and broadcast its operational status to the roadway and to the neighboring vehicles. It then initiates the check-out procedure by asking the navigation system to deliver maneuver commands for guiding the vehicle out of the dedicated lanes.

Potential Failure Mode 1: Longitudinal Dynamics Sensor failure

1.1 Longitudinal Dynamics Sensor 1 or 2 computes incorrect headways or closing rates data.
Design requirements:

1.1.1 Longitudinal Dynamics Sensor 1 and 2 need to have an internal independent ch eck of the reasonableness of the computed headways and closing rates data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.1.2 Controller 1 and 2 and Supervisory Controller should verify that each Longitudinal Dynamics Sensor is operating in a timely manner by verifying that new data is received from each sensor every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

1.2 The data values generated by Longitudinal Dynamics Sensor 1 and 2 are substantially different.
Design requirements:

1.2.1 Supervisory Controller should sense the discrepancy and use the data from Longitudinal Dynamics Sensor 3 to determine the failed sensor. The System Failure Response should then be executed.

1.3 Longitudinal Dynamics Sensor 3 computes incorrect headways or closing rates data.
Design requirements:

1.3.1 Longitudinal Dynamics Sensor 3 needs to hav e an internal independent check of the reasonableness of the computed headways and closing rates data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.3.2 Supervisory Controller should compare the data computed by Longitudinal Dynamics Sensor 3 with those computed by Longitudinal Dynamics Sensor 1 and 2 to check if Longitudinal Dynamics Sensor 3 is working properly. If an error is detected, the System Failure Response should be executed.

1.3.3 Supervisory Controller should verify that Longitudinal Dynamics Sensor 3 is operating in a timely manner by verifying that new data is received from Longitudinal Dynamics Sensor 3 every tbd time interval. If an error is detected, the System Failure Response should be executed.

1.4 Data from Longitudinal Dynamics Sensor 1 or 2 is not communicated to the controllers, or is corrupted in transmission through interface.
Design requirements:

1.4.1 Each controller should incorporate an independent check of reasonableness of the computed headways and closing rates data from Longitudinal Dynamics Sensor 1 and 2, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.4.2 Same as for 1.1.2.

1.5 Data from Longitudinal Dynamics Sensor 3 is not communicated to Supervisory Controller, or is corrupted in transmission through interface.
Design requirements:

1.5.1 Supervisory Controller should incorporate an independent check of the reasonableness of the computed headway and closing rate data from Longitudinal Dynamics Sensor 3, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

1.5.2 Same as for 1.3.2.

Potential Failure Mode 2: Lateral Dynamics Sensor failure

2.1 Lateral Dynamics Sensor 1 or 2 computes incorrect lateral dynamics or lane reference data.

Design requirements:

2.1.1 Lateral Dynamics Sensor 1 and 2 need to have an internal independent check of the reasonableness of the computed data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.1.2 Controller 1 and 2 and Supervisory Controller should verify that the lateral dynamics sensors are operating in a timely manner by verifying that new data is received from each sensor every to be determined (tbd) time interval. If an error is detected, the System Failure Response should be executed.

2.2 The data values provided by Lateral Dynamics Sensor 1 and 2 are substantially different.
Design requirements:

2.2.1 Supervisory Controller should sense the discrepancy and use the data from Lateral Dynamics Sensor 3 to determine the sensor that fails. The System Failure Response should then be executed.

2.3 Lateral Dynamics Sensor 3 computes incorrect lateral dynamics or lane reference data.
Design requirements:

2.3.1 Lateral Dynamics Sensor 3 needs to have an internal independent check of the reasonableness of the computed data, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.3.2 Supervisory Controller should compare the data computed by Lateral Dynamics Sensor 3 with that computed by Sensor 1 and 2 to check if Lateral Dynamics Sensor 3 is working properly. If an error is detected, the System Failure Response should be executed.

2.3.3 Supervisory Controller should verify that the processor of Lateral Dynamics Sensor 3 is operating in a timely manner by verifying that new data is received every tbd time interval. If an error is detected, the System Failure Response should be executed.

2.4 Data from Lateral Dynamics Sensor 1 or 2 is not communicated to the controllers, or is corrupted in transmission through interface.
Design requirements:

2.4.1 Each controller should incorporate an ind ependent check of reasonableness of the computed data from Lateral Dynamics Sensor 1 and 2, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.4.2 Same as for 2.1.2.

2.5 Data from Lateral Dynamics Sensor 3 is not communicated to Supervisory Controller, or is corrupted in transmission through interface.
Design requirements:

2.5.1 Supervisory Controller should incorporate an independent check of the reasonableness of the computed data from Lateral Dynamics Sensor 3, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

2.5.2 Same as for 2.3.2.

Potential Failure Mode 3: Controller failure

3.1 Controller 1 or 2 computes incorrect throttle or brake or steering commands.
Design requirements:

3.1.1 Each of Controller 1 and 2 should incorporate an independent check of the reasonableness of the computed throttle, brake and steering commands before they are sent to the actuators, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

3.1.2 Each of the throttle actuators, brake actuators, and the steering actuators should incorporate an independent check of reasonableness of the received commands computed by the associated controller, based on the physical attainability and valid known ranges of the system variables. If an error is detected, the System Failure Response should be executed.

3.2 Throttle (or brake/steering) commands computed by Controller 1 and 2 are substantially different.
Design requirements:

3.2.1 Supervisory Controller should sense the discrepancy and determine the controller that fails. The System Failure Response should then be executed.

3.3 Supervisory Controller fails.
Design requirements:

3.3.1 Supervisory Controller should incorporate circuitry, such as a watchdog time r, to detect failure and to ensure the processor functions in a timely manner. If a failure is detected, the System Failure Response should be executed.

3.4 Supervisory Controller computes incorrect throttle or brake or steering command.
Design requirements:

3.4.1 Supervisory Controller should compare the computed commands with those computed by Controller 1 and 2 to determine if it is working properly. If an error is detected, the System Failure Response should be executed.

3.5 Control commands are not communicated to actuators at appropriate time or is corrupted in transmission through interface with Controller 1 or 2.
Design requirements:

3.5.1 Each of the actuators should verify that it is receiving updated commands from the controller in a timely manner. If an error is detected, the System Failure Response should be executed.

3.6 Supervisory Controller's command data is not communicated to controllers and actuators at appropriate time, or is corrupted in transmission through interface.

Design requirements:

3.6.1 Each of the controllers and actuators should verify that it is receiving updated commands from Supervisory Controller in a timely manner. If an error is detected, the System Failure Response should be executed.

Potential Failure Mode 4: Throttle Actuator failure

4.1 Throttle Actuator 1 or 2 produces incorrect throttle angle for a given throttle command.

Design requirements:

4.1.1 Each throttle actuator should incorporate built in tests to be performed on the vehicle startup and during speed/headway maintenance operation to verify that proper throttle angle can be produced and is within the allowable range. If an error is detected, the System Failure Response should be executed.

4.2 Throttle Actuator 1 or 2 can not be deactivated when the associated control channel is determined to be deactivated.

Design requirements:

4.2.1 The ALLC system should provide for two independent, redundant means of deactivating the throttle actuators.

Potential Failure Mode 5: Brake Actuator failure

5.1 Brake Actuator 1 or 2 generates incorrect brake force for a given brake command.

Design Requirements:

5.1.1 Brake Actuator 1 and 2 should incorporate built in tests to be performed on the vehicle startup and during speed/headway maintenance operation to verify that proper brake force can be produced. If an error is detected, the System Failure Response should be executed.

5.2 Brake Actuator 1 or 2 can not be deactivated when the associated control channel is determined to be deactivated.

Design Requirements:

5.2.1 The ALLC system should provide for two independent, redundant means of deactivating the brake actuators.

Potential Failure Mode 6: Steering Actuator failure

6.1 Steering Actuator 1 or 2 does not generate correct steering force for a given steering command.

Design requirements:

6.1.1 Each of the steering actuators should incorporate built in tests to be performed on the vehicle startup and during lane keeping operation to verify that steering force can be produced and is within the allowable range. If an error is detected, the System Failure Response should be executed.

6.1.2 The ALLC system should provide for independent, redundant means to constrain the steering force generated from each steering actuator with safe ranges.

6.2 Actuator 1 or 2 fails to be deactivated when the associated control channel is determined to be deactivated.

Design requirements:

6.2.1 The ALLC system should provide for two independent, redundant means of deactivating each steering actuator.

Potential Failure Mode 7: Incorrect target speed commands or minimum time headway recommendations received from the roadway

7.1 The roadway target speed commands or minimum time headway recommendations is not communicated to the ALLC system controllers, or is corrupted during transmission.

Design requirements:

7.1.1 The data/commands sent from the roadway should contain error detection and error correction codes to improve the accuracy of the data received by the ALLC system controller.

7.1.2 Supervisory Controller should verify that target speed commands and minimum time headway recommendations are received in a timely manner. If updated data is not received for tbd consecutive times, Supervisory Controller should re-evaluate a new lower target speed and/or a more conservative safe time headway for speed and headway maintenance and rear-end collision avoidance, based on the known roadway surface characteristics and traffic conditions. Supervisory Controller should also notify the driver the speed and headway adjustment actions taken by the controllers.

7.1.3 Supervisory Controller should incorporate an independent check of the reasonableness of the received target speed commands and minimum time headway recommendations from the roadway, based on the physical attainability and known ranges of the system variables. If unreasonable data is received over tbd consecutive times, the ALLC system should respond as described in 7.1.2.

7.2 Roadway-to-vehicle communication fails.

Design requirements:

7.2.1 Same as for 7.1.2 and 7.1.3.

Potential Failure Mode 8: Incorrect lane reference data received from the roadway lane reference aid(s)

8.1 Some lane reference aid does not provide lane reference information to the associated on-board lateral dynamics sensor(s).

Design requirements:

8.1.1 Each lateral dynamics sensor should incorporate reliable means to detect potential failures in the associated lane reference aid. If an error is detected, the System Failure Response should be executed.

8.2 Some Lateral Dynamics Sensor fails.
Design requirements:

8.2.1 Same as for the design requirements in 2.1.1, 2.1.2, 2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.4.1, and 2.5.1.

Potential Failure Mode 9: Incorrect vehicle dynamics information received from the vehicle-to-vehicle communication

9.1 The dynamics data and maneuver intentions from the neighboring vehicles are not communicated to the ALLC controllers or are corrupted during transmission.
Design Requirements:

9.1.1 The communicated data should contain error detection and correction codes to improve the accuracy of the data received by the ALLC system controllers.

9.1.2 Supervisory Controller should verify that neighboring vehicles' dynamics data and maneuver intentions are received in a timely manner. If updated data is not received for tbd consecutive times, the System Failure Response should be executed.

9.1.3 Supervisory Controller should incorporate an independent check of the reasonableness of the received dynamics data from the neighboring vehicles, based on the physical attainability and known ranges of the system variables. If unreasonable braking data is received over tbd consecutive times, the System Failure Response should be executed.

9.2 The vehicle-to-vehicle communication fails.
Design Requirements:

9.2.1 Same as for 9.1.2 and 9.1.3.

Key Findings

1. The driver can not be considered as a back-up to the ALK system. A fail-safe ALK system design will require considerable structure complexity and component redundancies.

2. The proposed reliability functional requi rement for the ALK system is: "A single component or point failure is not allowed to cause a lateral or longitudinal collision, and there should be no common failure modes."

3. A potential system design to guarantee reliability will require two active control channels with substantial amount of components. The redundant control channels in the proposed ALK system design framework need to be always kept active to ensure safe and smooth deactivation (or full activation) of a control channel.

Issues and Risks:

1. The required reliability enormously increases the system complexity and design difficulty. The required instrumentation on both the vehicle and the roadway will be very costly.

2. The roadway may be liable for some accidents since it may assist vehicle maneuver coordination.

Roadway to Vehicle Speed and Headway Commands

The roadway sends target speed commands and headway recommendations to the vehicles in the multiple dedicated lane. Depending on the traffic conditions in each lane, even in the same roadway section, different lanes may have different speed and headway commands. The reliability requirement analysis for ERSC 1, 2 and 3 applies to each dedicated lane in ERSC 4.

Roadway Lane Reference Aids

The lane reference aids help the vehicle in lane keeping and lane changing control. They assist the lateral dynamics sensors of the ALLC system in collecting information such as position deviation from the lane center, roadway preview data, lane identification, and number of lanes around the vehicle, etc.

The lane reference aids need to support the lane keeping and lane changing functions in each dedicated lane. If the ALLC system is required to have triple redundancy of independent lateral dynamics sensors, there should be three corresponding lane reference aids for each dedicated lane. Figure 91 shows the functional block diagram of the roadway lane reference aids in ERSC 4.

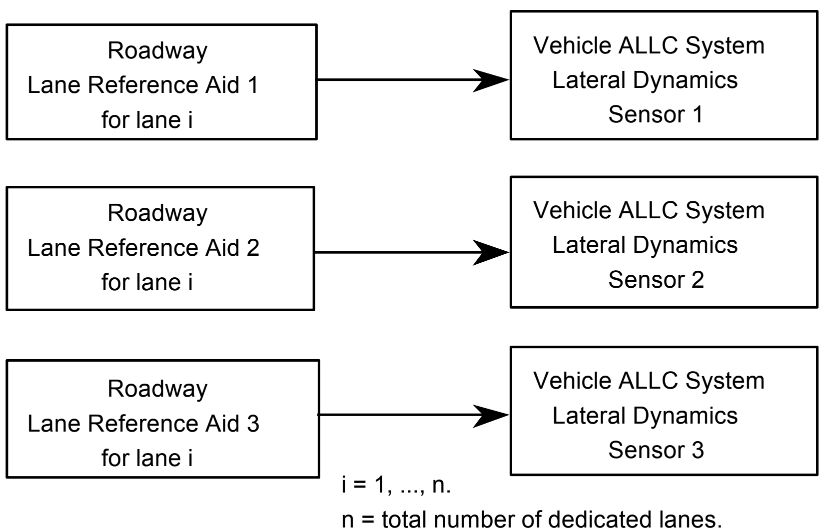


Figure 91. The functional block diagram of the lane reference aids in ERSC 4.

A lane reference aid failure will result in non-safe ALLC operation. For safety concern, the vehicles on the lane with a failed lane reference aid will have to leave the lane as soon as possible. The vehicles should also avoid getting into the lane with a failed lane reference aid. If we allow the vehicles to operate in the lane with a failed lane reference aid, the vehicle functions will fall back to ERSC 1 or 2 in this lane. This is not desirable, since such a mixed modes operation in some section of the roadway may affect the safety and efficiency of the overall AHS operation.

For magnetic-marker-based sensing, the reliability of the lane reference aid can be improved by installing markers with higher density along the dedicated lane and frequently checking the intensity of magnetic field generated by each magnetic marker. For vision-based sensing, the roadway can improve the reliability of the lane reference aid by providing lane markers with excellent contrast under various weather conditions. Redundant road lane reflectors may be used to improve the reliability of the radar-based lane reference aid.

The roadway needs to have reliable self-diagnostic procedure to detect any lane reference aid failure along any section of the highway. If a failure is detected, the roadway should warn the vehicle/driver of the danger through the roadway to vehicle communication. It is also desirable that the data provided by the lane reference aids be designed in such a way that the lateral dynamics sensors can detect possible failures in the lane reference aids.

<u>Key Findings:</u>

1. Multiple types of lane reference aids are necessary in each dedicated lane. The design of lane reference aids depends on the sensing technologies used by the sensors of the ALLC system.

<u>Issues and Risks:</u>

1. The roadway may be liable for accidents that are contributed by failures in the lane reference aids.

2. If a dedicated lane has lane reference aids failure in some roadway sections, the AHS may have to prohibit vehicles from entering those sections. This will reduce the highway flow rate and cause traffic control problems.

Vehicle Navigation

The on-board navigation system guides the vehicle to the trip destination entered by the driver. The navigation system plans a route to the destination that minimizes the trip time or/and travel distance. It performs route planning while taking into accounts the traffic information provided by the roadway and the vehicle's operational status (such as the amount of fuel available). The navigation system needs to have frequently updated vehicle position data, including the highway and the lane the vehicle is on, and the relative distance from highway entry/exit points or intersections. The navigation system evaluates the above information with the planned route to generate lateral and longitudinal commands to the ALLC system. Figure 92 shows the functional block diagram of the vehicle navigation system.

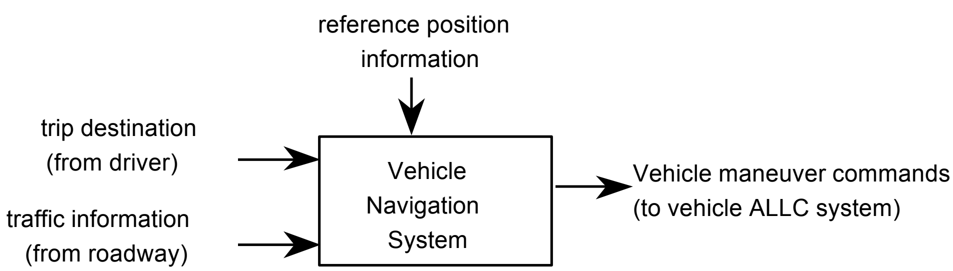


Figure 92. The functional block diagram of the lane reference aids in ERSC 4.

The navigation system displays to the driver the location of the vehicle and the path it plans to take. During the trip, the driver can re-enter the trip destination to the navigation system. The driver can also specify a desirable path that can lead the vehicle to the destination.

The maneuver commands sent to the ALLC system include lane changing or merging. A command can be as simple as changing lanes from lane 3 to lane 2 between locations A and B, or merging to left at location C. Since the maneuver commands will be processed by the controller of the ALLC system before the maneuver action is carried out, an incorrect maneuver commands will not immediately endanger the vehicle operation. However, vehicles with failed navigation systems may elongate the trip time. The efficiency of AHS will be affected by the vehicles that can not navigate themselves. It is essential that the vehicle with a failed navigation system get off the dedicated lanes as soon as possible.

The ALLC system carries out the check-out procedure with the help of maneuver commands from the navigation system. The navigation system generates the check-out maneuver commands in any one of the following situations:

1. The vehicle arrives its destination.

2. The driver initiates the check-out procedure.

3. The navigation system detects an internal malfunction.

4. The ALLC system performs its System Failure Response to leave the dedicated lanes.

Some navigation system internal failures, such as losing the map database, may affect the system's capability of guiding the vehicle accurately. There will be safety and implications if the vehicle can not check out of the AHS when it has to.

With the above discussion, we propose the reliability functional requirement for the navigation system as:

> "The navigation system should provide for redundant means to guide the vehicle out of the dedicated lanes."

This requirement can be achieved if the vehicle has redundant methods to accurately evaluate the positions of the vehicle and the next available AHS exit point. Dead-Reckoning and map matching techniques.[44,52], global positioning system (GPS). [55,107], and roadway-to-vehicle communication can be used to implement a navigation system that can fulfill the above reliability functional requirement.

Key Findings:

1. The navigation system is required to be able to guide the vehicle out of the dedicated lanes reliably.

Issues and Risks:

1. More research needs to be done in finding methods for locating the vehicle position and for improving the accuracy of the position data. This may require substantial instrumentation on the vehicle and the roadway.

Driver Tasks and Workload

This section discusses the drivers' tasks in this ERSC. It covers normal driving in the dedicated lane when all of the automated functions work perfectly. In ERSC 4 this consists of starting the automated systems and selecting a destination. Then it covers the fall-back mode in which the vehicle switches to ERSC 3 control with speed and headway maintenance, rear-end collision avoidance, and automatic lane keeping if the coordination or maneuver coordination system fails or degrades. The driver has only the role of a passenger in this ERSC.

The driver drives the car to the automated lane. The driver turns on the vehicle's automated systems for longitudinal and lateral control. The vehicle enters the lane when a safe gap appears in the traffic flow. The vehicle steers into the lane and turns on the SHM function, collision avoidance system and the automatic steering function. The vehicle takes over the throttle, steering, and brake when the car is on the highway or as the vehicle enters the highway.

The vehicle turns on the turn signal to leave the automated lane. This initiates check-out procedures. Check-out returns the steering, brake, and throttle control to the driver. The vehicle then changes lanes out of the automated lane. The driver turns off the communications links when he leaves the automated lanes.

Task Analysis–Normal Driving

In normal operations, the vehicle controls the steering, throttle, and brake. The vehicle performs lane changes into and out of the dedicated lane. The vehicle also avoids lateral collisions. The driver selects a destination and turns on the automated systems on the vehicle. The roadway sends target speed commands and minimum headway information electronically to the vehicle. This data helps the vehicle compute a safe headway. The roadway also sends traffic data to the driver to help him/her select a route. The task analysis in table 34 shows the driver cues for this task.

Table 34. Driver task description for ERSC 4 driving.

Task	Select destination and turn on automated systems
General	Task similar to being a passenger in the vehicle
Initiating Cue	Enter Check-in point and turn on automated systems –The driver sets destination
Feedback	Situation display that shows vehicle location and status
Task Standards	Select destination before vehicle enters designated lane
Task Conditions	Weather, road conditions, or traffic
Skills Required	Choose destination Correctly turn on automated systems
Potential Errors	Choose wrong destination Turn on wrong systems Do not turn on proper automated systems Fail Check-in, enter highway anyway Vehicle chooses wrong or inefficient route
Causes of Error	Fails to perceive or misinterprets system feedback, believes system has malfunctioned Poor judgment of location Hit wrong button and overrides function Sensor, controller, or actuator failure on vehicle Roadway controller malfunctions

Consequences of Error	Disrupt traffic flow and lower capacity Collision with surrounding vehicles Disturbance due to sudden route changes
Recovery Points	Minimum safe headway setting on vehicle to avoid collisions Collision warnings from other vehicles Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off; prevent easy override of SHM, ALK, and RECA functions
Individual Differences	Education Age Technology background
Criticality	Essential

Task Analysis–Fall-back Mode

In the fall-back mode, the automatic lane-changing or maneuver coordination system suffers a partial failure when one control channel fails, but the other one remains intact. If the automatic lane keeping functions can still operate then the vehicle switches to ERSC 3 operations in which the driver is responsible for lane changing. The vehicle warns the driver that he is now responsible for lane-changing and slows the vehicle to a safe speed for manual steering. The vehicle should then exit the dedicated lanes if it cannot safely maintain the speeds commanded by the roadway. If the warnings fail, the vehicle notifies the driver and the driver performs the task without the aid of warnings. Table 35 shows the task analysis for the lane changing function.

Table 35. Driver resumes control of lane-changing function.

Task	Fall-back mode to ERSC 3
General	Task may be similar to manual driving and lane changing with cruise control
Initiating Cue	Vehicle warns driver to resume responsibility for lane-changing Driver receives warning signal for lane departure from vehicle Vehicle may decrease speed for to allow for manual steering
Feedback	Visual, auditory, and kinesthetic cues for steering
Task Standards	Duration the same as manual driving, transition to manual driving must be gradual, vehicle keeps deceleration low while decreasing speed
Task Conditions	Weather, road conditions, suggestions from traffic control center
Skills Required	Reaction times appropriate to speed and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Driver inattention causes vehicle to collide or leave lane Driver overrides lane-changing system accidentally Driver does not respond in time to lateral collision warning Vehicle fails to maintain speed or proper headway Vehicle selects unsafe speed Vehicle does not warn driver adequately of a control transfer
Causes of Error	Fails to perceive or misinterprets system feedback Poor judgment of speed and following distance Hits wrong button Sensor or actuator failure on vehicle Role confusion by driver-responsibilities are not clear
Consequences of Error	Disrupt traffic flow and lower capacity Lane departure or lane change/merge collision Driver confusion

Recovery Points	Maximum speed limit setting on vehicle Lane departure collision warning Vehicle warns driver that lane-changing function is not working or is failing or has been turned off Vehicle requires active response from driver before a control transfer Driver interface shows driver control status clearly
Individual Differences	Drivers may be uncomfortable taking over steering control at high speeds or in reduced visibility [90]
Criticality	Essential

The maneuver coordination system helps vehicle merge into the dedicated lanes, change lanes, and avoid collisions. The vehicles can then maneuver safely. The vehicles may also coordinate suggested lateral collision avoidance maneuvers. This arrangement is similar to the TCAS system for commercial aircraft.[96] If this system fails then the driver takes over the maneuver coordination task by pre-approving all maneuvers before the vehicle executes them. Table 36 shows the task analysis for the maneuver coordination function.

Table 36. Driver resumes control of maneuver coordination.

Task	Driver resumes control of maneuver coordination
General	Driver approves all maneuvers before execution
Initiating Cue	Cue from vehicle that a gap in traffic is approaching Driver turns on turn signal to enter dedicated lanes Vehicle detects change in steering angle
Feedback	Visual, auditory, and kinesthetic cues of steering and accelerating
Control Functions	Drivers must be able to merge and change lanes safely
Task Standards	Safely merge into traffic Accelerate as directed by vehicle or roadway
Task Conditions	Type and timing of warning Environmental conditions, traffic speed and density
Skills Required	Reaction times appropriate to speed, lane change speed, and roadway conditions. Perceptual judgment of vehicle kinematics
Potential Errors	Overconfidence in system-driver does not look in lane changes Driver does not use turn signals to signal merge Driver does not respond to the cue or responds too late Maneuver coordination does not open a gap Maneuver coordination opens large gaps Vehicle recommends incorrect maneuver
Causes of Error	Fails to perceive or misinterprets the indication of an emergency Driver delay in response may cause unsafe lane change Warning controller misinterprets the data and the risk
Consequences of Error	Lane change/Merge collision with potentially severe results for the system (Approximately 4% of crashes and 0.5% of fatalities are lane change/merge crashes. Some 95% of these crashes are angle/sideswipe crashes [(113)]) Disrupt traffic flow and lower capacity Loss of confidence by the driver and public in the system In the case of false alarms the driver may defeat or ignore it [(96)]
Recovery Points	Vehicle reminds driver to look before lane change Multiple cues from vehicle and roadway Vehicle suggests an acceleration profile to the driver for merging Vehicle suggests an avoidance path to driver
Individual Differences	Accident statistics, citations and self report data indicate that older drivers have difficulty in merging, changing lanes, and exiting maneuvers. Data suggests that persons over 65 may be over represented in lane change/merge crashes [(113)]
Criticality	Essential

Issues and Risks

1. Driver confidence in automated system

If the driver has too much confidence in the automated systems then she may not pay attention if the vehicle needs to fall-back to manual driving. This could lead to accidents if the warning system does not detect an object or the system fails. Driver lack of confidence in the automated system could cause the driver to disable or ignore the system. Research needs to be done on when and how the driver may disable automated functions.

2. Enabling/Disabling Automatic Systems

This ERSC includes a speed and headway maintenance system, lane keeping, lateral collision avoidance, and communication systems. Research needs to be done on the instrumentation needed to control these different systems. The question of whether or not all of the automatic systems need to be controlled with one switch or many needs to be answered.

3 Driver override of automated functions
Even with multiple sensors the vehicle may not see and recognize everything that a human driver sees. This is especially true of unexpected objects such as animals or debris on the roadway. It may be necessary for the driver to override the collision avoidance system on the vehicle to avoid these objects. Research needs to be done on whether or not this driver override should be allowed to occur.

Key Results

Key Findings

1. The driver can not back up the automatic lateral and longitudinal control (ALLC) system if it fails. The reliability functional requirement of the ALLC system is: "Under no circumstances should a single component/point failure result in a lateral or longitudinal collision, and there should be no common failure modes.

2. A potential ALLC system design to achieve the reliability functional requirement will need two active redundant control channels with substantial amount of components.

3. The fully automated vehicles perform maneuver coordination to further reduce accident rates and improve traffic flow rates. This will require complicated vehicle-to-vehicle communication and maneuver protocols.

Issues and Risks

1. Cost
The required reliability of the ALLC system enormously increases the system complexity and design difficulty. The required instrumentation on the vehicle will be very costly.

2. Legal/Liability
The roadway may be liable for traffic accidents due to its involvement in the vehicle lateral and longitudinal control.

3. Cost
There are multiple dedicated lanes in ERSC 4. Since each lane needs to be equipped with redundant independent lane reference aids, the cost of the roadway infrastructure will be increased considerably.

Section 9: ERSC 5 Analysis

Description of ERSC 5

In ERSC 5, the roadway provides multiple dedicated lanes as described in ERSC 4. The roadway is responsible for maintaining these dedicated lanes and the communications infrastructure.

The roadway receives position, speed, destination, and capabilities data from the vehicles. The roadway senses traffic flow and environmental conditions on the dedicated lanes. The roadway uses this data to provide detailed course commands to the vehicles. These commands tell the vehicle what lane to travel in, when to change lanes and what speed and headway to use. The roadway coordinates these maneuvers to avoid collisions and smooth traffic flow. Based on the indicated trip destination the roadway plans the vehicle's route.

The vehicle has all the capabilities for full lateral and longitudinal control described in ERSC 4. Additionally the vehicle receives detailed course commands from the roadway. The vehicle responds to these commands automatically as long as it judges the maneuver to be safe. The vehicle sends its position, speed, maneuver status, and capabilities to the roadway. The vehicle coordinates each roadway-commanded maneuver with the vehicles around it. The vehicle provides the driver with traffic information and trip status data. It responds to driver commands for changes in destination. In case of malfunctions the vehicle may fall-back to a lower ERSC and notify the roadway and driver appropriately.

The driver manually drives the vehicle to the dedicated lane check-in point. The driver initiates the check-in procedure and releases control to the vehicle and roadway. The driver inputs its trip destination that is used by the vehicle and roadway for route planning. The driver, as in ERSC 4, can request a check-out procedure and resume manual control at the next chosen exit ramp or transition lane.

The motivation behind ERSC 5 is:

- to maximize highway system throughout by permitting full roadway control of all vehicle activities.

- to improve driver comfort and reduce trip time.

- to efficiently detour traffic around traffic incidents and roadwork’s.

ERSC 5 allows us to focus on the analysis of a highly coordinated AHS where the roadway plays an active role in the lateral and longitudinal control of the automated vehicles by planning their path and coordinating their maneuvers. Table 37 summarizes the functions of this ERSC.

Table 37. ERSC 5 functions and driver/vehicle/roadway performance requirements.

Function	Requirement	Driver/Vehicle/Roadway Tasks
Automatic Lateral and Longitudinal Control and Maneuver Coordination	– Smoothly and safely change lanes – Keeps vehicle in the center of the lane around curves and on straight-a-ways – Vehicle performs maneuvers commanded by roadway if they are safe	– Same as ERSC 4 – Receive commands from roadway – Perform maneuver within the given period of time if safe and inform roadway of status
Navigation/Route Selection	Select a route to reach the driver's destination	– Dynamically select lanes and route for trip – Send destination to roadway – Receive route commands from the roadway
Driver Interface	– Show driver route and allow driver to change route and destination – Show driver vehicle status	– Driver should be able to: » select a destination » initiate check-out – Interface should be simple to understand and use
Fall-back Mode to ERSC 4	Vehicle selects its own route through traffic if communication links to roadway fail	- Sense status of different vehicle control channels - Safely transfer control of course selection and navigation to vehicle
Roadway/Vehicle maneuver commands	Senses vehicle average speed and density and environmental conditions then sends commands directly to vehicle to smooth traffic flow; Performs check-in and vehicle status monitoring	– Roadway commands maneuvers to each vehicle.

Performance Requirements

Automatic Lateral and Longitudinal Control

The automatic lane changing function moves the vehicle from the center of one lane to the center of an adjacent lane on normal highway geometries if it is safe. The vehicle must first check if the lane change is safe and signal its intention to change lanes. When there is an appropriate gap between vehicles in the adjacent lane then the vehicle selects a trajectory and performs the lane change. The vehicle should accurately follow a desired path and provide satisfactory ride comfort over a wide range of speeds, roadway conditions, and disturbing forces. The automatic lane changing function controls the vehicle's steering smoothly and without oscillations. The automatic lane changing function should also prevent the vehicle from rolling over or going out of control when the rear-end collision avoidance system needs to brake on curved roads. The lane changing function works with the vehicle's throttle and brake controller to keep safe gaps between vehicles.

The driver checks-in and then enters the automated lane. The point at which the driver releases manual control could be on the dedicated ramp or in the dedicated lane depending on the entry configuration. Once the vehicle has entered the automated highway the driver starts the automated systems for steering and speed and headway maintenance. The vehicle smoothly takes over control from the driver. The lane changing function allows the vehicle to change lanes. The vehicle merges itself into the dedicated lane with the aid of maneuver coordination between the vehicles and roadway.

The automatic lane changing system requires sensors, a computer with control algorithms, and steering, brake, and throttle actuators. The navigation system chooses when the vehicle should change lanes. The communications system allows the vehicle to coordinate their actions and avoid accidents. The sensors measure the vehicle's dynamics and the forward roadway geometry. Lane reference aids [30] help the vehicle sensors measure roadway geometry information. The computer generates control signals for vehicle steering.

Lane Change Coordination

Lane changes may be performed more efficiently if the vehicle coordinates its maneuvers with the vehicles around it. Studies done by the California PATH program investigate using a communication link to coordinate a lane change. Before making a lane change the vehicle sends out a signal of its intent to change lanes. This signal serves as an electronic turn signal. Any vehicles that are affected by this maneuver must acknowledge the lane change and grant permission. If acknowledgments are not received then the intent signal is repeated. The analysis in Streisand and Walrand only assumed that one vehicle needs to acknowledge the maneuver and in effect promise to maintain its current course for a given period of time. Realistically the vehicle needs responses from all the vehicles in its sensor range. However this could cause problems in coordinating the maneuver if there are problems of signal collision. In some vehicle following situations the vehicles may need to request cooperative actions from the other vehicles. This could include asking the vehicle to speed up or slow down so the maneuvering vehicle can change lanes. But asking other vehicles to change speeds affects traffic flow and possibly causes traffic jams.

Lane change coordination requires a sophisticated communications system that coordinates the timing and synchronization of messages. Other possibilities are lane change protocols over a section of roadway. For instance one section of roadway may only allow lane changes to the left, while the next section could allow only right lane changes.

Issues and Risks

1 Lane Change Coordination

Coordinating sensors and communications will be a very difficult task. This will require very sophisticated algorithms to coordinate the lane changes.

2 Automated lateral and longitudinal control

Lane changes require a combination of lateral and longitudinal control. Some work has been done combining these modes. Under normal driving conditions, lateral and longitudinal control is decoupled. Studies need to be done for lane changing to verify that this holds true for most lane changing conditions.

Emergency Collision Avoidance

The collision avoidance system combines lateral and longitudinal control to avoid collisions due to moving or stationary obstacles around the vehicle. This system must be designed so that no single point faults or common mode faults will permit the collision avoidance system to fail. The collision avoidance system must also send out an emergency signal when it must take evasive actions or a control system fails. Possible sensors include radar, ultrasound, vision-based and infrared systems. These sensor have been discussed in the section on lateral collision warnings. Communications can also help the vehicles to plan coordinated actions for collision avoidance.

If the vehicle needs to take emergency action due to failures in the automated system, then it sends out an emergency signal to the vehicles around it. The vehicle may sense or have a problem and need to warn other vehicles. Emergency messages must be transmitted quickly and reliably. This signal gives the vehicle's position, heading, and intentions.

Emergency signals identify what vehicle sent the message. The destination address may be a selective broadcast address specifying the affected section of the highway. [100] Emergency messages have high priority depending on the type of emergency. The data field of the message contains essential emergency information such as the location, nature (such as flat tire, debris in roadway, or sudden loss of control), and suggested actions to be taken. Research at California PATH indicates that this message may be up to 1 kilobyte long. [100]

The emergency signal system must be extremely reliable so that no single point or common mode faults will cause the system to malfunction. The emergency system requires an emergency channel for emergency use only. This system may need to be tested regularly to be sure that each vehicle is working properly and can respond quickly to an emergency message.
The vehicles coordinate their maneuvers with a communications system to make the maneuvers safer and easier. Work at PATH suggests that there are three basic types of maneuvers needed for platoons on automated highways: lane change, platoon split, and platoon merge. [47] Since we are looking at a collision-free system without platooning these basic maneuvers can be restated as lane change, maintain gap, maintain a constant speed, and change speed up or down. These basic maneuvers will allow a vehicle to move on the automated lanes. Maneuver coordination will require communications between vehicles. Figure 93 shows the block diagram for the maneuver coordination system. This system uses sensors to figure out which vehicles need to be communicated with. The surrounding vehicles need to know the position, intentions and heading of the vehicle.

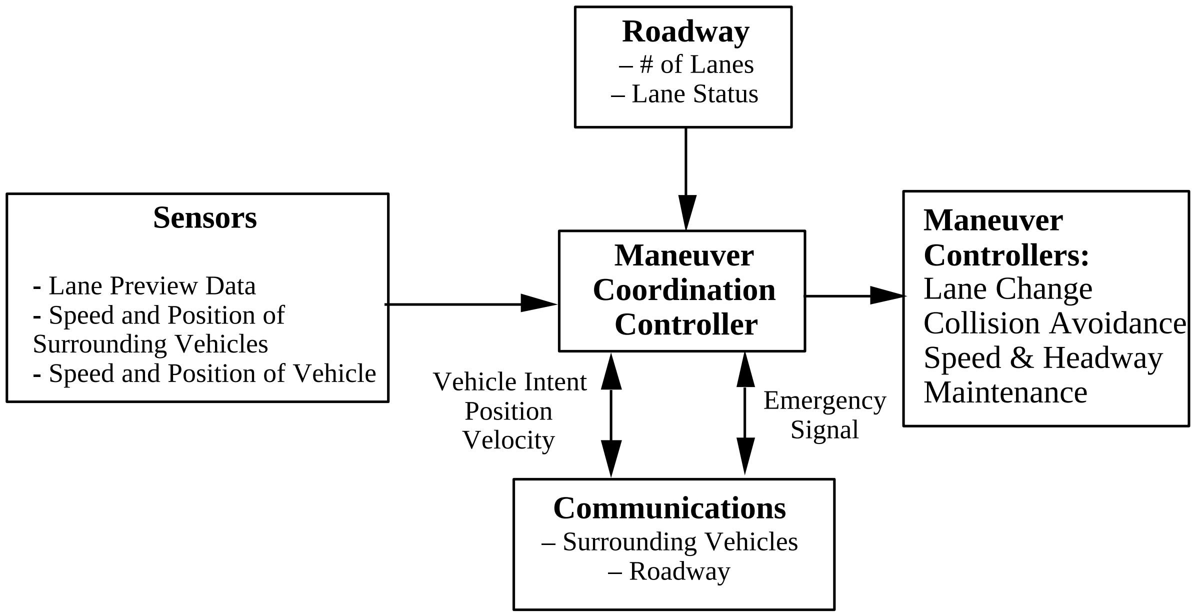


Figure 93 Block diagram for the maneuver coordination system.

<u>Sensors</u>
The sensors help the vehicle determine which vehicles must be informed of different maneuvers. Intra-lane maneuvers such as speed up, brake or change headway only require information from the vehicles in the same lane.

<u>Communications</u>
Table 38 summarizes the basic message types for maneuver coordination. The information needed column show the contents or data for the message. The type of communication column lists the requirements for the communications system. Possible requirements include whether the message must be acknowledged by other vehicles, the priority of the message, and whether the message is directed at any particular vehicle.

Table 38 Types of communications needed for maneuver coordination.

Maneuver Name	Information Needed	Type of communication
Lane Change	Direction and duration of lane change Acceleration Position Course and Heading	One to many Message directed to certain vehicles Acknowledgments needed from surrounding vehicles Medium priority
Collision Avoidance	Type and nature of emergency What Action is being taken Acceleration Position Course and heading	One to many Message sent to all vehicles in vicinity Acknowledgments needed from surrounding vehicles High priority message
Braking	Degree of braking Road-tire coefficient	One to one Message sent to vehicle behind only
Change speed	Acceleration Position Course and Heading	One to one Message sent to vehicle behind only
Change headway	Acceleration Position Course and Heading	One to one Message sent to vehicle behind only
Status	Acceleration Position Course and Heading	One to many Unacknowledged Low priority

Controllers

The controller must synchronize the messages for all of the vehicles.

Maneuver Protocols

The message frequency may be minimized by the use of protocols for maneuvers. These protocols control which vehicle has the right of way and which one must maneuver. These protocols give a fixed set of rules for lane changes and collision avoidance.

Issues and Risks

1 Emergency Dynamics

Very little modeling work has been done to characterize vehicle dynamics under extreme conditions. This work needs to be extended.

2 Coordination

Collision avoidance is most effective when done early before an emergency exists. The collision avoidance system must coordinate actions in ways similar to the TCAS system to keep vehicles safe.

3 Path Planning

All of the work on path planning has used robots in fairly static environments. Research needs to be done on real-time systems in a dynamic environment.

Route Selection and Navigation

The driver selects the destination at the check-in point or at the beginning of the trip. The vehicle broadcasts the destination to the roadway at check-in or if the destination changes at any time during the trip. The roadway then chooses a route based on traffic information, road conditions, and driver preference. Route selection will be a dynamic process so the route may changes as conditions change. The driver(?) has the final say in the route selection. The roadway decides what lanes the vehicle should use for the trip and when it should change lanes as it navigates on the highway.

Route Selection

The roadway selects a route based on traffic conditions, distance and roadway status. The driver can then approve or disapprove the route. If the driver disapproves the route then the vehicle or driver selects an alternative route. The driver can change the route at any time during the trip if traffic or personal conditions warrant it.

Navigation

The roadway could also send data to the vehicles about roadway curvature. (33) This approach uses beacons at fixed spots to tell the vehicles about the roadway ahead. The vehicle then uses information on the location of the beacon and dead-reckoning for preview information. (55) Dead-reckoning systems use wheel odometers accelerometers to measure distance and gyroscopes to measure the vehicle's heading. This approach has already been tested in the Prometheus project. (10)

The global positioning system (GPS) provides absolute position data free from error accumulation.(55) However GPS accuracy is degraded by tall buildings, tunnels, and large trees that are common in large cities. The vehicle can then use on-board maps and dead-reckoning to calculate the preview data .(55) The absolute position accuracy of GPS can then provide feedback and calibration signals to correct dead-reckoning errors. These systems can be integrated with algorithms that switch between systems depending on which has better conditions for operation or a filter can combine all sensor information to get the best estimate. (55) This method suffers from time delays which may make it impractical for real-time control applications.

Issues and Risks

Information Sources

Traffic and road status data may be available from public or private sources. The driver may choose to obtain information from a private source that is more detailed than public data.

Driver/Vehicle/Roadway Interface

The driver should be able to override the automated lateral and longitudinal control systems if a control channel fails. However the driver must go through a check-out procedure first to verify that he/she is ready to resume control of the vehicle. The driver also monitors the vehicle's operational status and backs up failed vehicle functions if possible.

The driver interface must show the driver that the automated functions are operating correctly or that a function has failed. This interface should be simple to understand and use. Input systems like touch pads or buttons may be distracting and may require too much driver attention. [8] The driver must be able to tell what the vehicle is doing at all times and why it is doing it. This shows the driver that the vehicle is operating correctly. Studies show that drivers cooperate more when they know the reasons for an action. [10]

Head-up displays may be particularly useful for visual indicators of the system operation. For example a heads-up display could show the measured distance to the vehicle ahead as well as the minimum time headway and target speed. Other technologies include liquid crystal displays (LCDs), light-emitting diodes (LEDs), computer generated voice messages, sudden vehicle accelerations/decelerations (jerk), tactile feedback, and directional audio displays. [64,8,9]

The interface may be continuous or only active when a driver action is needed. The best design of the driver interface for human factors is an open issue and involves selecting a display technology, type and duration of warnings, user control types and locations, etc. User acceptance is crucial to user interface design.

Fall-back Mode

The system needs to degrade gracefully if a failure occurs. Many failures such as communications systems or isolated sensors may not cause the vehicle to be non-operational. Vehicles with different capabilities may coexist in the dedicated lanes without incident for short periods of time.

In case of failure in a single control channel of the vehicle-roadway communication system, the vehicle can operate in ERSC 4 control mode. The vehicle selects its route and its maneuver timing.

If the maneuver coordination functions fail the vehicle informs the driver. Failure of these functions may not require a transfer of control to the driver so they do not require the vehicle to return to ERSC 3 control.

If the longitudinal controller fails the vehicle should send out an emergency signal and exit the dedicated lanes as soon as possible. While multiple paths of degradation are technologically possible they are not desirable from a human factors point of view since it may require extensive driver training and practice to handle potential failures safely.

Roadway/Vehicle Maneuver Commands

The roadway measures the average speed and traffic density, assesses environmental conditions, and calculates vehicle target speeds and route for the dedicated lanes. The vehicles follow the target speeds for their lane set by the roadway using the speed and headway maintenance function. The vehicles should respond to headway recommendations for longer headways due to changes in environmental conditions such as slick roads. The vehicles use the environmental data from the roadway to adjust their time headways. The vehicles check-in with the roadway by sending their identification, automated function status, and location. (108) The vehicles may also display relevant traffic information from the roadway to the driver for route planning purposes. This section covers roadway sensing systems and roadway-vehicle communications.

Roadway Sensing Systems

The roadway needs to sense the position, heading, and speed on each vehicle on the highway. This data can be measured by sensors that are part of the infrastructure or the vehicles can transmit their measured speed, position, and headway to the roadway with a vehicle-roadway communication system for each lane. The vehicle may also transmit its operational status and identification to the roadway for check-in or incident management. The roadway also needs to measure roadway weather data to select a safe target speed for the environmental conditions. (57) Section 5 on roadway sensors gives more details on these sensors.

Vehicle to Roadway Communications (VRC)

The roadway needs to have one-to-one communications with each vehicle on the roadway. The roadway sends lane change, merge, and demerge commands directly to individual vehicles. The roadway sends speed and headway data to the cars in each lane to smooth traffic densities and manage incidents. The roadway needs to avoid large speed differences between lanes for safe transitions. The vehicles may also send their measured velocity, position, and heading to the roadway. This system may also be used for check-in. This allows the roadway to monitor the operational status of the vehicles and ensure that they are correctly operating in the automatic mode. These messages only need to be sent once per section depending how directly the roadway controls maneuvers. There needs to be separate messages for each lane and vehicle. The vehicles will also check-in with the roadway to ensure that they are working correctly. Each vehicle sends status data on all of its automated functions to the roadway. In ERSC 4 these functions are: combined lateral and longitudinal control, collision avoidance, communication systems, and critical engine functions.(108)

VRC systems can be mounted on the side of the roadway, on overpasses, or embedded in the roadway.(85) These systems may use automated toll collection technology with variable registers or a system that covers a wider range. (22,53) Appendix A covers the operation of these systems. A separate system may be required for each lane.

Target speed messages from the roadway to the vehicles do not need a high data rate since it will not change very often. Each field will need 6-8 bits to give a resolution of 1 meter for the gap limit and 1 mile per hour for the velocity limit. Since the message goes to all cars in a given lane a destination ID code must tell which lane the message is intended for. The source ID code indicates that the message is from the roadway. Error detection coding looks for bit errors in the message.

Retransmission requests are unnecessary since we can rely on repeating the message. This message should be repeated at most one time per second. The bit error rate can also be high since the message changes slowly and rarely. Repetition of messages can compensate for the high error rate. If the roadway sends preview data to the vehicles, the messages may need to be longer in curvy regions of the roadway.

The VRC may also send messages from the vehicles to the roadway. Each vehicle sends its speed and the distance to the preceding vehicle (6-8 bits each). The vehicles may also send a unique identifying code (28 bits) to the roadway for check-in. The vehicle must also send its lane position to the roadway. The operational status of the automated system can be sent as well, this could take 8-16 bits depending on the amount of detail required by the roadway. Other variables such as estimates of the road-tire friction coefficient can take 4 or more bits. Table 39 shows the possible variables to be sent to the roadway for check-in [(108)] This gives a data length of around 95 bits.

Table 39. Potential status variables to be sent to the roadway by the vehicles for check-in.

Function	Components	Number of Bits
Longitudinal and Lateral Control	Sensors, Actuators, Controller, Vehicle-Vehicle Communications System	8-?
Vehicle-Roadway Communication System	Transmitter, receiver, variable register	1-2
Vehicle Identification Code		28
Other Vehicle Functions	Critical fluids level and pressures, brake conditions, tire pressure, engine temperature, headlights	12-16

A broadcast system with a range of 100 meters for multiple automated lane must communicate with 0.3 to 0.75*NL vehicles per second. NL is the number of dedicated lanes. Analysis by Polydoros et al shows that the current Hughes VRC system and automatic toll collection systems can meet the data transmission requirements for VRC in ERSC 4. [(85)]

Issues and Risks

1 Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short. The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

2 Sensors

Roadway weather sensors only cover small regions of roadway. These sensors could easily miss patches of ice or puddles on the roadway. The roadway may then choose an unsafe headway. Research needs to continue into these sensors to improve their capabilities.

3 Privacy

The vehicles “Check-in” with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

4 Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

5 Coordination between lanes

The roadway must coordinate the traffic speed in adjacent lanes to smooth traffic flow. Speed differences of more than 10-20 mph will make lane changes and merges unsafe as well as slowing down traffic in the high speed lanes. This requires a more sophisticated roadway controller than in the previous ERSCs.

Reliability Requirement Analysis

In ERSC 5, the automated vehicle functions are basically the same as in ERSC 4. In addition to the roadway functions in ERSC 4, the roadway can further improve the AHS efficiency by providing route planning and navigation commands to each vehicle in the roadway network. The roadway has better scope of the entire roadway network traffic conditions, thus can come up with strategies for more efficient traffic flow control. The roadway carries out the traffic control strategies by sending navigation commands to vehicles through roadway-to-vehicle communication.

As discussed in ERSC 4, the ALLC system uses maneuver coordination and on-board sensors to ensure the safe execution of navigation commands. This reduces the safety concern when incorrect navigation commands are received from the roadway. However, failures in the roadway navigation can potentially affect the AHS traffic flow if incorrect navigation commands are adopted by vehicles. Potential problems caused by the roadway navigation failure can be dealt with by using the on-board vehicle navigation system to verify the correctness of the roadway navigation commands and to serve as a back-up to the roadway navigation. The reliability of the roadway navigation can be improved by designing reliable roadway-to-vehicle communication and roadway navigation controller.

Reliability of Roadway to Vehicle Navigation Commands

In ERSC 5, the roadway can guide the vehicle to its destination by sending navigation commands to vehicles. The roadway receives the speed, position and destination data of all vehicles in the roadway network. The roadway uses the above information and the roadway network geometry to determines an optimal route for each vehicle to get to its destination. The optimal routes for vehicles are computed in such a way that the efficiency of the overall roadway network is maximized. The roadway sends navigation commands to the vehicle so that the vehicle can follow the route planned by the roadway. The roadway updates the planned routes frequently to cope with the roadway network traffic condition.

For safety concern, it is desirable that the roadway navigation commands be sent to the vehicle navigation system instead of the ALLC system. This allows the on-board navigation system to verify the reasonableness of the roadway navigation commands before they are forwarded to the ALLC system for execution. The ALLC system uses vehicle-to-vehicle communication and on-board sensors to ensure safe execution of the navigation commands. Figure 94 shows the functional block diagram of the roadway navigation system interfacing with vehicles in the roadway network.

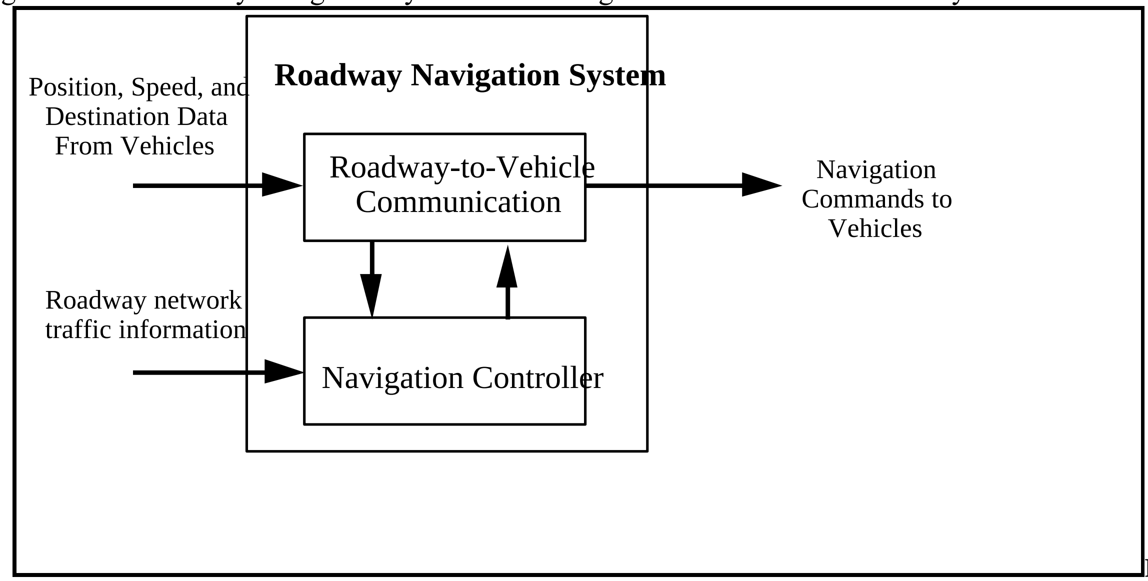


Figure 94. The functional block diagram of the roadway navigation system.

The roadway navigation system is mainly composed of the roadway-to-vehicle communication and the navigation controller. The roadway-to-vehicle communication receives position, speed and destination data of all vehicle in the network and forwards the information to the navigation controller. The navigation controller computes on-line an optimal route for each vehicle. It also generates navigation commands for vehicles. The navigation commands are sent to vehicles through the roadway-to-vehicle communication.

Reliability Functional Requirement

A failure in the roadway navigation system may result in sending wrong navigation commands to vehicles. Since the roadway navigation commands will be filtered by the on-board navigation system before they can be executed by the ALLC system, failures in the roadway navigation system impose no immediate danger to vehicles in the network. However, failures in roadway navigation may reduce the efficiency of the roadway network. For the roadway network efficiency, the reliability functional requirement of the roadway navigation system is proposed as

‘The navigation commands sent to the vehicles should have low error rates.’

System Level Design Requirements

To achieve the above reliability functional requirement, the roadway needs to have reliable roadway-to-vehicle communication to accurately collect the operational status of each vehicle and to transmit navigation commands. The roadway navigation controller needs to have efficient and reliable algorithms to process the enormous amount of data and to generate correct navigation commands for each vehicle. Some important system level design requirements can be identified by analyzing major potential system failure modes and their causes, based on the system framework shown in figure 94.

Potential Failure Mode 1: Roadway-to-Vehicle Communication failure

1.1 The position, speed and destination data of some vehicle(s) can not be received by the roadway or is corrupted during reception.

Design requirements:

– The roadway should verify that the reasonable position, speed and destination data from each vehicle is received in a timely manner. If an error is detected, the roadway navigation controller should use the previously available information to estimate. The roadway should also notify the vehicle(s) whose position, speed and destination data can be properly received by the roadway.

– The Roadway-to-Vehicle communication should provide communication protocol that contains error detection and correction codes to minimize the probability of incorrect message reception. The position, speed and destination data should be sent to the roadway frequently enough so as to minimize the effects of no communication.

1.2 Navigation commands can not be sent to the vehicles or are corrupted in transmission.

Design requirements:

– The roadway-to-vehicle communication should provide communication protocol that contains error detection and correction codes to minimize the probability of incorrect message transmission. The navigation commands should be sent to vehicles frequently enough so as to minimize the effects of no communication.

Potential Failure Mode 2: Roadway Navigation Controller failure

2.1 Roadway Navigation Controller computes incorrect navigation commands.

Design requirements:

– Navigation Controller should incorporate an independent check of the reasonableness of the computed navigation commands before they are sent to the Roadway-to-Vehicle Communication. If an error is detected, the navigation commands should be canceled and warnings should be sent to vehicles through the Roadway-to-Vehicle Communication.

– The Roadway-to-Vehicle Communication should incorporate an independent check of the reasonableness of the navigation commands provided by the Navigation Controller. If an error is detected, the navigation commands should be canceled and warnings should be sent to vehicles through the Roadway-to-Vehicle Communication.

2.2 Navigation commands are not communicated to the Roadway-to-Vehicle Communication at appropriate time or is corrupted in transmission through interface.

Design requirements:

– The Roadway-to-Vehicle Communication should verify that it is receiving updated navigation commands from the Navigation Controller in a timely manner. If an error is detected, the navigation commands should be canceled and warnings should be sent to vehicles through the Roadway-to-Vehicle Communication.

Issues and Risks

1. The roadway navigation needs to communicate on a one-to-one basis with a great number of vehicles in the roadway network. Designing a reliable roadway-to-vehicle communication system to properly transmit and receive huge amount of data will not be trivial.

2. The controller of the roadway navigation system has to process enormous amount of data received from vehicles. The hardware needed to implement the controller will be considerable so as to satisfy the capacity requirement. The software (control algorithms) run by the controller will be very sophisticated. These impose substantial difficulties in designing a reliable controller.

3. The on-board vehicle navigation system achieves user optimality, while the roadway navigation system strives for AHS system optimality. The required reliability makes the roadway navigation very costly. Unless the roadway navigation can reliably improve AHS efficiency to a satisfactory degree from ERSC 4, it will probably not cost effective.

Vehicle Navigation

The reliability requirements of the on-board navigation system in ERSC 5 contain those in ERSC4 and the following additional requirements.

In ERSC 5, each automated vehicle receives navigation commands from the roadway. The roadway navigation commands are to maximize the efficiency of the entire roadway network. However, if the roadway navigation commands are directly forwarded to the ALLC system for execution, failures in the roadway navigation can cause unnecessary interruptions in the network traffic. It is desirable that the on-board navigation system should verify the reasonableness of the roadway navigation commands as shown in figure 95. The roadway navigation commands will be sent to the ALLC system for execution only if they are approved by the on-board navigation system. If a potential roadway navigation failure is detected, the roadway navigation commands should be discarded and replaced by the commands generated by the on-board navigation system.

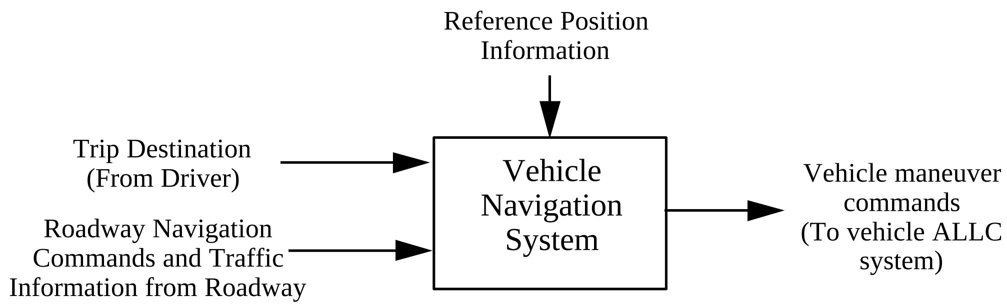


Figure 95. The functional block diagram of the vehicle navigation system in ERSC 5.

Roadway to Vehicle Speed and Headway Commands

The reliability requirements of the roadway to vehicle speed/headway commands are the same as in ERSC 4.

Roadway Lane Reference Aids

The reliability requirements of the roadway lane reference aids are the same as in ERSC 4.

Automatic Lateral and Longitudinal Control

The reliability requirement of the automatic lateral and longitudinal control system is the same as in ERSC 4.

Driver Tasks and Workload

This section discusses the drivers' tasks in ERSC 5. It covers normal driving on the dedicated highway when all of the automated functions work perfectly. In ERSC 5 this consists of starting the automated systems and selecting a destination. This case is identical to ERSC 4. Then it covers the fall-back mode in which the vehicle switches to ERSC 4 control with maneuver coordination and selection performed by the vehicle. The driver has only the role of a passenger in this ERSC.

The driver drives the car to the automated lane. The driver turns on the vehicle's automated systems for longitudinal and lateral control. The vehicle enters the lane when a safe gap appears in the traffic flow. The vehicle steers into the lane and turns on the SHM function, collision avoidance system and the automatic steering function. The vehicle takes over the throttle, steering, and brake when the car is on the highway or as the vehicle enters the highway.

The vehicle turns on the turn signal to leave the automated lane. This initiates check-out procedures. Check-out returns the steering, brake, and throttle control to the driver. The vehicle then changes lanes out of the automated lane. The driver turns off the communications links when he leaves the automated lanes.

Task Analysis–Normal Driving

In normal operations, the vehicle controls the steering, throttle, and brake. The vehicle performs lane changes into and out of the dedicated lane. The vehicle also avoids lateral collisions. The driver selects a destination and turns on the automated systems on the vehicle. The roadway sends target speed commands and minimum headway information electronically to the vehicle. This data helps the vehicle compute a safe headway. The roadway also sends traffic data to the driver to help him/her select a route. The task analysis in table 40 shows the driver cues for this task.

Table 40. Driver task description for ERSC 5 driving.

Task	Select destination and turn on automated systems
General	Task similar to being a passenger in the vehicle
Initiating Cue	Enter Check-in point and turn on automated systems –The driver sets destination
Feedback	Situation display that shows vehicle location and status
Task Standards	Select destination before vehicle enters designated lane
Task Conditions	Weather, road conditions, or traffic
Skills Required	Choose destination Correctly turn on automated systems
Potential Errors	Choose wrong destination Turn on wrong systems Do not turn on proper automated systems Fail Check-in, enter highway anyway Vehicle chooses wrong or inefficient route
Causes of Error	Fails to perceive or misinterprets system feedback, believes system has malfunctioned Poor judgment of location Hit wrong button and overrides function Sensor, controller, or actuator failure on vehicle Roadway controller malfunctions
Consequences of Error	Disrupt traffic flow and lower capacity Collision with surrounding vehicles Disturbance due to sudden route changes
Recovery Points	Minimum safe headway setting on vehicle to avoid collisions Collision warnings Vehicle warns driver that headway maintenance function is not working or is failing or has been turned off; prevent easy override of SHM, ALK, and RECA functions
Individual Differences	Education Age Technology background
Criticality	Essential

Task Analysis–Fall-back Mode

In the fall-back mode, the communication between the roadway and the vehicle suffers a partial failure when one control channel fails, but the other one remains intact. The maneuver coordination system helps vehicle merge into the dedicated lanes, change lanes, and avoid collisions. The vehicles can then maneuver safely. The vehicles may also coordinate suggested lateral collision avoidance maneuvers. This arrangement is similar to the TCAS system for commercial aircraft [96] If this system fails then the driver takes over the maneuver coordination task by pre-approving all maneuvers before the vehicle executes them.

Issues and Risks

Driver override of automated functions

Even with multiple sensors the vehicle may not see and recognize everything that a human driver sees. This is especially true of unexpected objects such as animals or debris on the roadway. It may be necessary for the driver to override the collision avoidance system on the vehicle to avoid these objects. The lack of an override may put the driver in an unsafe position. The existence of such an override may also put the driver in an unsafe position if the driver brakes unnecessarily. Research needs to be done on whether or not this driver override should be allowed to occur.

Key Results

Benefits

The roadway controller proposed in ERSC for vehicle velocity control was local in nature. That controller aimed to improve local traffic conditions on a single stretch of road without coordination with other related systems such as ramp metering. The roadway controller is also isolated from other traffic control systems for route selection and navigation. Freeway network control uses real-time and predicted information to smooth traffic flow throughout the traffic network. This ERSC proposes an integrated controller that makes route and course recommendations and ramp metering decisions to achieve a common goal. The goal of freeway network control can be either user optimality or network optimality [71] User optimality can be in terms of trip time or fuel expended. Network optimality can be in terms of overall travel time at the cost of some vehicles taking longer paths to meet their goals.

Simulation studies by Messmer and Papageorgiou indicate that there is a high potential for improving traffic flow in freeway networks in terms of travel time reduction and congestion avoidance or limitation [71,7] More detailed controllers will select lanes and speeds for each vehicle on the highway.

Issues and Risks

1. Network freeway control needs extensive study and simulation before appropriate controllers can be selected. The system must also offer demonstrable improvements from the driver’s existing ERSC 4 route selection system. Otherwise drivers will not use the network controller and will rely directly on their own vehicle to choose their route.

2. Driver overrides would allow individual drivers and vehicles to disregard commands from the roadway and use their own navigation systems. While this may benefit one driver, it may hurt overall traffic flow and cause safety problems if one vehicle makes many lane changes in an attempt to go a certain speed. The effect of having network guided vehicles and independent vehicles on the same traffic network needs to be studied.

3. Some researchers [111] have proposed network controllers that send control signals directly to each individual vehicle. This puts stringent performance and reliability constraints on the communications system since the messages are frequent and time-sensitive. System reliability considerations dictate that the communications system must be fail-safe with no single point failures for autonomous vehicles. This could lead to multiple independent communications systems.

4. Guided vehicles with wires or cables provide another option for direct roadway control since vehicle maneuverability is restricted.

Key Findings

Network controllers may improve traffic flow through traffic networks in terms of travel time reduction and congestion avoidance or limitation. The communication system to the vehicles must be highly reliable since incorrect speed or lane change messages could cause congestion or unsafe situations.

Section 10: Conclusions

Summary of Key Findings and Issues

1. Communication systems and sensors such as radar will be used on vehicles in all stages of AHS deployment. When multiple radar operate in a small area at similar frequencies, the radar on different vehicles may interfere with one another. This interference could lead to shorter sensor ranges and poor performance. Such interference is a safety issue since the sensors or communications systems may not work as expected. This issue may also affect how the highways are built and what separation is required between lanes.

2. Vehicle-to-vehicle communication can reduce the number of false alarms in rear-end collision warning systems without reducing the detection rates. Each vehicle sends its braking data to the vehicle behind it. These communications can serve as a sort of electronic brake light for the vehicle behind. This lets the following vehicle anticipate the braking of the vehicle ahead. This warning can decrease the number of false alarms in the rear-end collision warning system. However, the government will need to set communication frequencies and protocols so that a common communication system can be used on all highways.

3. A roadway traffic controller can decrease traffic congestion even in case of low levels of automation. This controller eases roadway congestion by regulating vehicle speed and traffic density along sections of the roadway. This can smooth traffic flow and decrease backups due to incidents on the roadway. Studies at USC show considerable improvements in congestion reduction and stability of traffic flow by using appropriate roadway traffic controller.

4. Multiple types of driver warnings for lateral/longitudinal collisions will be installed on vehicles in the early stages of AHS deployment. Some examples are rear-end collision and lateral collision warnings. The driver may experience warning overload and warning confusion problems while interacting with other vehicle and roadway functions. More research needs to be done on the interaction and prioritization of these warnings for the driver.

5. Collision avoidance systems use braking and steering to avoid crashing into other vehicles or stationary obstacles in the lane. Under the current system, the vehicle manufacturer may be liable for collisions caused by vehicle failures. This may have an impact on the automobile manufacturer's willingness to produce automated vehicles. It may also affect the design and operation of the automated systems. The legal system may need to limit manufacturer's liability.

6. Collision avoidance requires combined lateral and longitudinal control. Our work proposes an evolutionary system for the development of AHS. In one partial automation scenario the driver can override the automatic lane keeping system but not the longitudinal control for the throttle. The driver may not be able to perform lateral collision avoidance maneuvers using steering control only. This issue needs more human factors studies.

7. Our original evolutionary design split the development of full lateral control into two parts. The first part was automated lane keeping. The second part was lane changing and lateral collision avoidance. These control modes should not be separated since the driver becomes a passenger once the vehicle takes over lane keeping. Human factors studies show that humans do not perform monitoring tasks well.

8. A roadway controller that sends speed commands to vehicles can smooth vehicle speeds and improve traffic flow when incidents occur. The vehicle can respond to the roadway controller commands automatically as proposed in the Prometheus project or the driver can change the vehicle's cruising speed. If the vehicle automatically responds to the speed commands from the roadway, the driver's reliability in detecting rear-end collision danger may be degraded. The driver may be put into a situation that he/she can not handle and may blame the roadway for any rear-end collision. The roadway may be liable for accident caused by incorrect speed commands. However, if the vehicle does not respond directly to roadway speed commands, the effectiveness of the roadway traffic flow control will be reduced since the driver may not follow the roadway commands.

9. At each stage of the AHS evolution, drivers are requi red to have a basic understanding about the system operation so they can interface with AHS safely and efficiently. Drivers may need to be trained to handle the necessary tasks and workload.

10. Vehicles require a distance and closing rate sensor for speed and headway maintenance or intelligent cruise control. This system can also warn the driver of potential rear-end collisions. The rear-end collision warning system computes the Time-to-Collision and warns the driver of a potential collision in time to avoid the collision (about 1.5 s before the collision). The sensors for this type of system only need to be accurate to within 3-5 km/hr.

11. As the AHS evolves to higher ERSCs, the driver 's functions are gradually replaced by the automatic control systems of vehicle and roadway. These systems needs to be more reliable than human drivers so that the AHS can be accepted by the public. They also need to be fail-safe to guarantee the safety of drivers. These reliability requirements may substantially increase the component redundancy and design complexity.

12. The reliability requirements for automatic systems in each ERSC can be used to assess the required component redundancy and design complexity. This gives us a way to estimate the gaps between ERSCs in terms of technical difficulties, cost and risks.

13. Safety and efficiency benefits in higher ERSCs can only be realized by heavily instrumented vehicles, using roadway lane reference aids and a roadway navigation system. It will take joint efforts of the public, the automobile manufacturers and the government to settle the potential legal and liability problems arising from AHS operation.

14. The communication requirements for AHS increase rapidly with the level of automation. When the vehicles have only longitudinal control, each vehicle needs to communicate only with the vehicle behind and in front. In a fully automated system the vehicles must communicate with the roadway and the surrounding vehicles to coordinate maneuvers. This change requires increases in bandwidth and reliability and more sophisticated communication protocols.

15. The human factors issues are very complex in the ERSCs that mix automated and manual control systems. Humans do not perform well as supervisors of automated systems. Systems that rely on a human driver who is not actively involved in lateral or longitudinal control to respond to infrequent warnings for collision avoidance or other emergencies may not work well. Once the vehicle can perform hands-off, feet-off driving in the dedicated lane, the human factors issues may be less critical to system design.

ERSC 1 Key Findings

1 The speed and headway maintenance function does not have to be very accurate in this ERSC (5-10%) since it is limited by human perception and reaction times. This suggests that speed and headway maintenance systems at this level may be derived from the intelligent cruise control systems planned by several companies. [74,26] The next ERSC requires a more accurate speed and headway maintenance function. The components for a more accurate speed and headway maintenance function need to be designed with AHS requirements in mind instead of taking commercial technology off the shelf.

2 There are significant safety and performance benefits even with low levels of automation. Simple systems like the roadway velocity controller can give large increases in capacity and traffic flow volumes. This system uses technology available today in traffic control centers and toll roads.

3 Vehicle to vehicle communication systems can reduce the number of false alarms in collision warning systems without reducing the detection rates.

4 The driver can serve as a back up to the automated systems at this level. If the speed and headway maintenance or rear end collision warning systems fails, the driver takes over system performance.

5 There are significant human factors issues associated with warnings and driver interface that must be researched for even low levels of automation. The warning systems will require multiple levels of warnings.

6 The combined speed and headway maintenance-driver system needs to have mean time to failure much more than 50 years. The reliability functional requirement for the speed and headway maintenance system is that it must safely and reliably return control to the driver in case of override.

7 The reliability functional requirement for the warning systems is that they have high detection rates and low false alarm rates.

ERSC 1 Issues and Risks

1. Controller Algorithms

The controller algorithms need to smoothly adjust the brake and throttle to avoid sudden accelerations when the vehicle ahead leaves the lane. Driver tests indicate that drivers feel unsafe when the controller suddenly accelerates. [26] The speed and headway maintenance controller needs to use algorithms that limit accelerations to make drivers feel comfortable and accept automatic control. [51,25]

2. Electromagnetic Interference

Full deployment of ERSC 1 means that most vehicles will have active sensors such as radar. When multiple radar operate in a small area at similar frequencies the radar may interfere with one another. This interference could lead to shorter sensor ranges and poor performance.

3. Driver Interface

Research needs to be done on the driver interface with the speed and headway maintenance, rear end collision warning, and blind spot warning functions. Each function may have separate controls for enable/disable and adjustments. It may be too much of a burden on the driver to expect him/her to change lanes and enable the automated systems immediately. The driver may need to preset the target speed, minimum headway, and warning thresholds when he/she starts the vehicle.

4. Sensor Capabilities

The rear end collision warning and blind spot warning functions may increase safety and reduce certain types of collisions by decreasing driver reaction time. But there are sensor and human factor issues that still must be resolved. The sensors must detect small vehicles or debris, such as motorcycles with few nuisance alarms.

5. Warning system design

First the designers need to decide when the warning system should be turned on: always on, only when turn signal on, or turned on when steering column shows lane change. The warning thresholds for emergencies and driver awareness must also be set. The system must avoid nuisance alarms, yet detect vehicles accurately. The types of alarms and warnings must also be researched. The emergency alarm needs to be directional to get fast driver response. ERSC 1 introduces multiple types of driver warnings for blind spot and rear-end collision avoidance. Research needs to be done on the interaction and prioritization of these warnings for the human driver.

6. Dedicated Lane

The biggest social issue for AHS is how to get a separate lane for automated vehicles. The driving public rebels when a lane is taken away from active use. [(99)] The solution for most highway departments has been to add a new lane on the shoulder or median strip, but most urban highways do not have any more space to spare for the sole use of automated vehicles. This infrastructure change may have to wait until enough vehicles have speed and headway maintenance systems and traffic flow benefits can be easily seen.

7. Legal/Liability

In this ERSC the roadway sends recommended target speeds and minimum headways directly to the vehicles. This may make state and local governments liable for any accidents that may occur if the minimum recommended headway is too short. [(102)] The government may not wish to deploy such a system until it has been shown to be reliable and fail-safe.

8. Privacy

This ERSC gives the vehicles the option to “Check-in” with the roadway. This may leave a record of when and where a vehicle traveled. This raises user privacy concerns about governmental use of this data.

9. Communication Protocols

The government will need to set communication frequencies and protocols so that a common communication system can be used on all U.S. highways.

10. Driver Reliability

The driver may become over-reliant on the speed and headway maintenance system and degrade his/her reliability in rear-end collision avoidance.

11. Roadway Speed Commands

The vehicle's automatic response to the roadway's target speed command imposes safety concerns. For example, the speed and headway maintenance system headway/speed sensor fails while the controller is responding to a target speed command by accelerating the vehicle. In this case, the driver may perceive that the speed and headway maintenance system is properly following the roadway's command and fail to sense a rear-end collision danger in time. The driver's reliability as a back-up to the speed and headway maintenance system may be seriously degraded since the speed and headway maintenance operation puts the driver into a situation that he/she can not handle safely. This potential failure mode has serious reliability implications.

12 Warning Overload and Confusion
The driver may experience warning overload and warning confusion problems while interfacing with other vehicle and roadway functions.

13. Activation of Blind Spot Warning
If the warning signal of the BSW system is to be activated only by the turn signal or steering wheel motion, there might not be enough time for the driver to react to the danger. This is because some drivers may perform changing lanes without turning on the turn signal. Warnings may be too late if the driver has already started turning the steering wheel. If the warning signal is to be generated without activation from the driver, the warnings created by the adjacent lanes traffics moving into and out of the blind zone will be irritating to the driver.

ERSC 2 Key Findings

1. The mean time to failure of the speed and headway maintenance and rear end collision avoidance system needs to be much more than 50 years.

2. The driver can not act as a back-up for an automated rear-end collision avoidance system that uses short time headways. In this case there is not enough time for the driver to react to dangerous situations. The reliability requirement for the rear-end collision avoidance system is: “Under no circumstances should a single component/point failure let the vehicle crash into any moving or stationary object in the lane, and there should be no common failure modes.” One possible design leads to multiple control paths and sensors to ensure system reliability. This increases the cost and complexity of automated rear-end collision avoidance systems.

3. The redundant control channels in the p roposed speed and headway maintenance and rear end collision avoidance system framework need to be always kept active. This ensures safe and smooth deactivation of a control channel.

4. Driver warnings from the lane departure warning system and the blind spot warning system must be prioritized to avoid driver confusion if multiple warnings occur. Great care must be taken in ERSCs that combine automated systems with manual driving to make sure that the driver interface is simple to understand and operate.

ERSC 2 Issues and Risks

1. Driver Confidence

The driver may not trust the collision avoidance system to handle emergency braking itself. This may cause the driver to choose larger headways than the automated system requires. This reduces the capacity of the automated lane. The driver is not a truly parallel system to the speed and headway maintenance function with rear-end collision avoidance since the driver has a much slower reaction time. Extra redundancy may be needed to make the collision avoidance system as reliable as a human driver.

2. Legal/Liability
Rear end collision avoidance gives rise to new liability issues. If a vehicle collides with the vehicle in front, then who is at fault? The driver may set the time headway too small or the collision avoidance system may have not worked properly.

3. Driver Attention to Driving Task
As the vehicle assumes more of the driver tasks, the driver may pay less attention to the other vehicles or the highway. This increases driver reaction time to emergencies requiring lateral collision avoidance. The type of feedback that the driver needs from the system needs to be studied.

4. Rear-end Collision Avoidance Sensors
The sensors for rear-end collision avoidance must recognize hazardous situations quickly and accurately. More research needs to done to reduce the number of false alarms and improve the detection performance of these systems.

5. Driver Override of Braking
The driver may need to override the automated braking system if he/she sees an object that the collision avoidance sensors do not. However, this could lead to dangerous situations and a loss of vehicular control. This issue needs further study.

6. Driver's Reliability in Lateral Control
Complete feet-off driving may make the driver over-reliant on the vehicle and degrade the driver's reliability in lateral collision avoidance.

7. Cost
The required reliability of the speed and headway maintenance and rear end collision avoidance system imposes much complexity in the design. This increases the cost and technical difficulty in deploying this system.

8. Fully automated longitudinal control with manual lateral control
When only the longitudinal control is automated, the speed/headway maintenance and rear-end collision avoidance system may have difficulties in avoiding crashing into stationary obstacles that suddenly appear in the lane. This can happen when, for example, the preceding vehicle abruptly changes lanes to avoid hitting a stationary object in the lane. In this case, the vehicle may not have enough distance to stop the vehicle without a collision. The probability of such collisions can be reduced if we increase the headway used in vehicle following control. However, the capacity of the AHS will be affected by increasing the headway.

9 Warning Overload and Confusion
The driver may experience warning overload and warning confusion problems while interfacing with BSW, LDW and other vehicle and roadway functions.

ERSC 3 Key Findings

1. The on-board-automatic lane keeping (A LK) system will require redundant active control channels for fail-safe design.

2. It may be impractical to have the driver perform lateral collision avoidance while giving him/her only steering override authority.

3. AHS with narrow lanes has the potential of increasing traffic capacity and real estate saving. However, the automatic lane keeping and lateral collision warning will be difficult to implement on a narrow dedicated lane.

4. A malfunction in the automatic lane keeping system will result in t he vehicle operation falling back from ERSC 3 to ERSC 2. However, a malfunction in the speed and headway maintenance and rear end collision avoidance system will cause the operation to fall back from ERSC 3 to ERSC 1 or 0.

5. Automatic lane keeping will reduce the collisions caused by vehicle lane departures. The most destructive lane departure accidents take place when the driver is fatigued during a long drive. Automatic lane keeping should help reduce this type of accident.

6. Lateral collision warn ing improves the safety of the changing lanes and merging. It also helps the driver for lateral collision avoidance.

7. Dedicated lane capacity can be improved by adopting higher speed and/or smaller headway since the driver is hands-off and feet-off in normal driving.

8. Roadway maneuver coordination improves the safety for entry and exit. It may also help reduce the effect of traffic flow disturbance caused by vehicles entering and leaving the lane.

9. The mean time to failure of the automatic lane k eeping system needs to be much longer than 150 years.

10. The driver can not back up the automatic lane keeping system if it fails. The reliability functional requirement of the automatic lane keeping system is: “Under no circumstances, should a single point/component failure let the vehicle depart from the lane, and there should be no common failure modes”.

11. The operation of lane keeping control requires preview information about the roadway. The on-board automatic lane keeping (ALK) system obtains this data with the help of roadway lane reference aids. The sensing technologies used by the automatic lane keeping system determine the types of lane reference aids. Possible lane reference aids include vision based systems, magnetic nails, radar, and GPS with dead-reckoning. Some types of lane reference aids may not reliably provide preview information under certain environmental conditions such as rain or snow. Reliability studies show that two independent control paths may be necessary for reliable fail-safe lane keeping. Each control path needs to have an independent sensor type.

ERSC 3 Issues and Risks

1. System Complexity

A potential automatic lane keeping system design to fulfill the reliability functional requirement will need two redundant, independent steering control channels. This substantially increases the cost of automated vehicles in ERSC 3 due to the design complexity and required redundant components.

2. Reliability of Lane Reference Aids

The operation of lane keeping control requires preview information. The on-board automatic lane keeping (ALK) system obtains it with the help of roadway lane reference aids. The sensing technologies used by the automatic lane keeping system determine the types of lane reference aids. It might not be easy for some types of lane reference aids, such as vision based, to reliably provide preview information under certain environmental conditions.

3. Cost

The sensors of the automatic lane keeping (automatic lane keeping) system interface with roadway lane reference aids to obtains lateral dynamics information. The reliability functional requirement implies that redundant, independent control channels are needed for the automatic lane keeping system design. The lateral dynamics sensors will be based on independent sensing technologies. Since a lane reference aid needs to be made compatible with a lateral dynamics sensors, there will be multiple lane reference aids. This may substantially increase the cost of the roadway infrastructure.

4. Availability of the automatic lane keeping function

Some lateral dynamics sensing technologies, such as vision based, may be sensitive to the environmental conditions. Due to the strict reliability requirement, the automatic lane keeping operation may be easily interrupted by poor weather. The reliability degradation in automatic longitudinal control may also affect the availability of the automatic lane keeping function.

5. Driver’s Lateral Collision Avoidance

Lateral collision avoidance may require combined lateral and longitudinal control. In ERSC 3, the driver can override the automatic lane keeping system but not the longitudinal control. The effectiveness of the driver’s lateral collision avoidance, using steering control only, has not yet been verified and requires further study.

6. Legal/Liability

Since the roadway is involved in the dedicated lane entry and exit coordination, the roadway may be liable for accidents if it fails to send out proper speed/headway commands to coordinate the entry/exit maneuvers. The driver may still blame the roadway for an entry/exit accident even it is caused by the his/her improper merging/demerging maneuvers.

7. Legal/Liability of lane reference aids

The roadway may be liable for accidents caused by failures of the lane reference aids.

ERSC 4 Key Findings

1. The driver will not be able to back up the automatic lateral and longitudinal control (ALLC) system if it fails. The reliability functional requirement of the ALLC system is: “Under no circumstances should a single component/point failure result in a lateral or longitudinal collision, and there should be no common failure modes.

2. A potential ALLC system design to achieve the reliability functional requirement will need two active redundant control channels with substantial doubling of components.

3. The fully automated vehicles perform maneuver coordination to further reduce accident rates and improve traffic flow rates. This will require complicated vehicle-to-vehicle communication and maneuver protocols.

ERSC 4 Issues and Risks

1. Cost
The required reliability of the ALLC system enormously increases the system cost and design complexity. The required instrumentation on the vehicle will be very costly.

2. Legal/Liability
The roadway may be liable for traffic accidents due to its involvement in the vehicle lateral and longitudinal control, such as sending speed/headway commands, assisting maneuver coordination, and providing lane reference aids, etc.

3. Cost
There are multiple dedicated lanes in ERSC 4. Since each lane needs to be equipped with redundant independent lane reference aids, the cost of the roadway infrastructure will be increased considerably.

4. Reliability of Lane Reference Aids
If a dedicated lane has lane reference aids failure in some roadway sections, the AHS may have to prohibit vehicles from entering those sections. This will reduce the highway flow rate and cause traffic control problems.

ERSC 5 Key Findings

1. Network controllers may improve traffic flow through traffic net works in terms of travel time reduction and congestion avoidance or limitation. The roadway to vehicle communication system must be highly reliable since incorrect speed or lane change messages could cause congestion or unsafe situations.

2. The roadway controller proposed in earlier ERSCs for vehicle velocity control was local in nature. That controller aimed to improve local traffic conditions on a single stretch of road without coordination with other related systems such as ramp metering. The roadway controller is also isolated from other traffic control systems for route selection and navigation. Freeway network control uses real-time and predicted information to smooth traffic flow throughout the traffic network. ERSC 5 proposes an integrated controller that makes route and course recommendations and ramp metering decisions to achieve a common goal. The goal of freeway network control can be either user optimality or network optimality. [71] User optimality can be in terms of trip time or fuel expended. Network optimality can be in terms of overall travel time at the cost of some vehicles taking longer paths to meet their goals.

3. Simulation studies by Messmer and Papageorgiou indicate that there is good potential for improving traffic flow in freeway networks in terms of travel time reduction and congestion

avoidance or limitation.[71,7] More detailed controllers will select lanes and speeds for each vehicle on the highway.

ERSC 5 Issues and Risks

1. Network Traffic Control Effectiveness

Network freeway control needs extensive study and simulation before appropriate controllers can be selected. The system must also offer demonstrable improvements from the driver's existing ERSC 4 route selection system. Otherwise drivers will not use the network controller and will rely directly on their own vehicle to choose their route.

2. Driver's Navigation

Driver overrides would allow individual drivers and vehicles to disregard commands from the roadway and use their own navigation systems. While this may benefit one driver, it may hurt overall traffic flow and cause safety problems if one vehicle makes many lane changes in an attempt to go at a certain speed. The effect of having network guided vehicles and independent vehicles on the same traffic network needs to be studied.

3. Communication

Some researchers [111] have proposed network controllers that send control signals directly to each individual vehicle. This puts stringent performance and reliability constraints on the communications system since the messages are frequent and time-sensitive. System reliability considerations dictate that the communications system must be fail-safe with no single point failures for autonomous vehicles. This could lead to multiple independent communications systems.

4. Options

Guided vehicles with wires or cables provide another option for direct roadway control since vehicle maneuverability is restricted. Direct roadway control of free moving vehicles is not practical due to the communications requirements for controller commands. Controller commands need to be transmitted frequently and with little delay. This does not seem to be practical for a roadway communications system.

Appendix A: Communication Systems

Automated highway systems will integrate vehicular navigation, route guidance, vehicle location, and control systems. Direct communication between vehicle control systems will help vehicles drive safely at short time headways. Systems for vehicular navigation and vehicle location will allow the roadway to coordinate and smooth traffic flow. Our ERSCs combine these advances in road transport informatics.[33] with control algorithms.

Vehicle-roadway communication (VRC) links let the roadway traffic control center send navigation, route and control commands to the vehicles. The vehicle sends status and position data to the roadway. This communication link also supports check-in/check-out procedures on the automated highway. For the low level ERSCs vehicle-roadway communications occur infrequently over sections of roadway. Data can be sent between vehicles and the roadway with either a broadcast media such as radio or an advanced vehicle identification (AVI) system similar to those already used by some automatic toll collection systems. AVI systems uniquely identify vehicles as they pass specific locations. These systems may also include roadside or central computers to analyze or handle the data. AVI systems can be used for check-in and check-out on automated highways, enforcement of dedicated lanes, or congestion based pricing schemes.
Navigation aids provide turn-by-turn route guidance. [33] These systems use the Global Positioning System (GPS), proximity beacons, and dead-reckoning to determine the vehicle location. Electronic maps allow the system to select a route based on distance and traffic information.

Vehicle to vehicle communication links permit the direct exchange of information between vehicle control systems. This lets the control system anticipate the actions of other vehicles before change in speed, acceleration, or position can be sensed by on-board sensors. The communication link can also work in parallel with the sensors to speed response and reduce false alarms. Control systems require constant communication with short delays. Maneuver coordination between vehicles requires a two-way link to ensure that messages are received.

AHS applications for control, identification, and navigation have different communications requirements for message size and contents, maximum allowable delay, frequency of transmission, and connectivity (vehicle to vehicle, roadway to vehicle). We will look at message format and requirements for different systems at the different ERSCs. Next we will look at two methods for sending data between vehicles and between vehicles and the roadway: broadcast media such as radio or directional line-of-sight links such as infrared or ultrasonics. Finally we discuss why communications systems can improve detection performance for collision avoidance.

Specification of Communication Requirements

Communication needs are specified with message content and length, the allowable delay, the frequency of transmission, the error rate and the type of communications needed.

Message Structure: Figure 96 shows the general structure of a message between cars. Most of the bits in a message are overhead. Synchronization bits allow the receiver to synchronize to an incoming message (16-32 bits). [100] The destination ID tells who should receive the message. The source ID tells who sent the message. The size of the ID fields may be quite large if each car in the United States is uniquely identified. There were 193 million cars in the U.S. in 1990 (2^{28} = 268 million).[77] This number can be reduced if the roadway gives each vehicle a local ID number over a section of roadway, possibly at each check-in and check-out point. Data is the variable-length contents of the message. The message ends with an error detection code. These codes check the parity of the message to look for bit errors. If the system detects an error the message is retransmitted or ignored. Error coding can help the receiver detect transmission errors. Larger numbers of bits increase the chance of detecting an error. [100]

$$P(\text{Undetected Error}) = (1 - P(s))\,2^{-M} = 2^{-M} \tag{A-1}$$

P(s) is the probability of successful reception of a message. M is the number of error detection bits.

Synchronization	Destination ID	Source ID	Message Type	Data	Error Detection Codes

Figure 96. Structure of message for communications between vehicles and between vehicles and the roadway

Acceptable Delay: The delay is the time after which the received information is so late that it is no longer useful to the system. Communications between vehicle controllers may have short delays on the order of 0.05 seconds. Communications between vehicles and the roadway may have delays on the order of seconds for the roadway traffic controllers.

Transmission Speed: The transmission speed is a function of the message length, the number of messages sent by each vehicle, the number of vehicles that transmit per second and the delay. This decides the number of bits/second that the system needs to transmit. The number of vehicles on the highway and the range of the communication system give a bound on the amount of message traffic. The number of vehicles within the range of the communications system n_v is:

$$n_v = n_l \left\lceil R_t / (L + S_d) \right\rceil \tag{A-2}$$

n_l is the number of automated lanes. R_t is the range of the transmitter with an omnidirectional antenna. L is the average vehicle length. S_d is the average headway between vehicles. Each vehicle spends $T_c = R_t / V$ seconds in the zone of the communications system. The communications link must be able to handle all the required traffic while the vehicle is in this communications zone.

Error Rates: The bit error rate is the probability that one bit is received incorrectly. The probability of message error P_m for a single bit modulation scheme with independent bits is [97]:

$$P_m = \sum_{j=1}^{M} \binom{M}{j} P_{be}^{\,j} (1 - P_{be})^{M-j} \tag{A-3}$$

M is the number of bits in the message. P_{be} is the probability of bit error. j is the number of errors in the message. This assumption is valid for fast-fading radio channels. The number of ways in which j bits out of M may be in error is:

$$\binom{M}{j} = \frac{M!}{j!\,(M-j)!}$$

For a message length of 50 bits and $P_m = 10^{-4}$, $P_{be} = 10^{-5}$. More complex modulation schemes give different results for the bit error probability. The bit error rate depends on the average received signal to noise ratio per bit (E_b/N_o).(97) The dimensionless ratio (E_b/N_o) is a standard measure for digital communications system performance. The equation for the received power can also be modeled as (85; 97):

$$P_r = P_t L_t G_t L_p G_r L_r \tag{A-4}$$

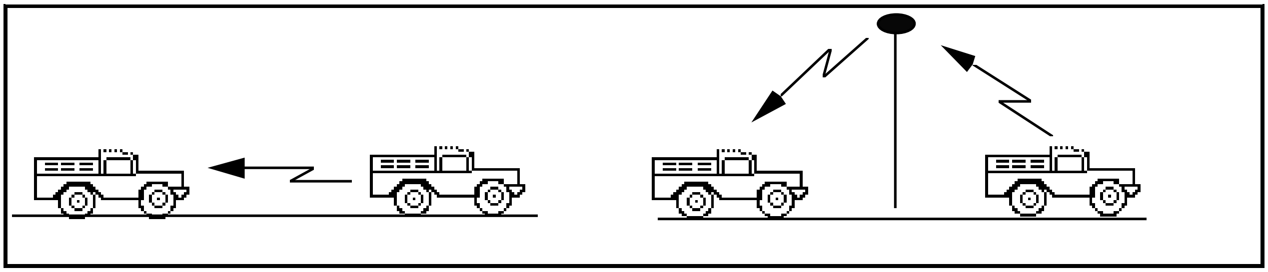
L_t and L_r are the losses at the transmitter and receiver. G_t and G_r are the gains at the transmit and receive antennas. P_t is the transmitted power. L_p is the path loss. The path loss models the propagation environment, range, and conditions.

Types of communication: The communication links can be acknowledged or unacknowledged. Important links for maneuver coordination require acknowledgments that the message has been received correctly. The security of the data link must also be specified. Certain types of vehicle to roadway communications such as vehicle identification and location must be secure to prevent unauthorized use of the data. The type of addressing tells if the communication link is one-to-one between vehicles or one-to-many such as between the roadway and other vehicles.

Directional Line-of-Sight

Vehicle-vehicle communications assist in real-time longitudinal and lateral control and maneuver coordination. There are two approaches to vehicle-to-vehicle communications. The first is the directional line-of-sight system shown in figure 97 a. These systems have a directional beam that only works when one vehicle sees another. Examples of this technology are ultrasound, microwave, and infrared. Both ultrasound and infrared have short ranges and tight power budgets. They have very high path losses in rainy or snowy conditions as well. For lower speed data networks the infrared can operate over longer ranges. This type of infrared link has been tested in the California PATH project and in the PROMETHEUS project. (31; 33)

The directivity of the link is an advantage when it reduces interference between vehicles. The directivity also requires precise alignment between the receiver and transmitter. This may require more accurate lateral control to work on the highway. This technology may be best suited for longitudinal control problems where one vehicle follows the other.



(a) (b)

Figure 97. Possible architectures for vehicle to vehicle communications systems. (a) shows a direct point-to-point link between vehicles. (b) shows a system where the roadway acts as a relay between the two systems.

Broadcast Systems

Broadcast technology such as radio can perform communications between vehicles and vehicles and the roadway. In this system a vehicle or the roadway sends a signal out in all directions at a given bandwidth. This signal tends to have a long range. This can cause interference if more than one car talks at once in the same frequency band. Broadcast systems use coding in time, frequency, or both to avoid interference and allow multiple users to share the same channel as shown in figure 98. This shared usage can increase channel capacity. [97]

The roadway may communicate with the automated vehicles with a cellular system along the roadway or with subcarriers on existing FM or TV signals. [16] Cellular systems break the transmission area down into smaller broadcast "cells." Each base station is in the center of a cell. Figure 99 shows the architecture of this cellular system. Adjacent cells operate at different frequency bands. Physically separated cells reuse frequencies. Cell size ranges from tens of meters to 1-2 kilometers. Efficient use of spectrum is needed since there are many competing usages for wireless communications.[104] The vehicles and roadway communicate with each other through a base station. For example vehicles in an adjacent lane may send messages to one another through the base station. The destination address may designate vehicles on certain sections of roadway by lane number.

The technology for simple vehicle to roadside communications exists in some of today's automatic toll collection systems.[38; 53] An interrogator sends out a pulse. The vehicle transponder responds with the vehicle identification number and some data from a variable register. Future systems must allow for longer and more frequent messages.

TDMA and CDMA systems conserve frequency bandwidth. A typical TDMA protocol has a fixed frame length (T_f) during which the interrogators and transponders communicate. [97] The frame has three active segments. In the first segment the reader sends a control message to activate the transponders within transmission range and send them instructions. The second segment is for data exchange. This segment has a variable number of slots for messages (n_s). The third segment the transponders respond to the interrogation pulse by sending their identification randomly placed in one of n_{ID} slots. The reader then selects which transponders can send messages. The number of frames offered to a vehicle in a cell is:

$$n_f = \frac{T_c}{T_f}$$

The number of vehicles in the interrogator range determine how often each vehicle can successfully request a message slot P_c:

$$P_c = \left(\frac{n_{ID} - 1}{n_{ID}} \right)^{n_v - 1}$$

The average number of frames that it takes to successfully send a message request is $N_{ave}=1/P_c$.[85] This gives an upper bound on system capacity since each transponder times out for a time interval after transmitting its data.

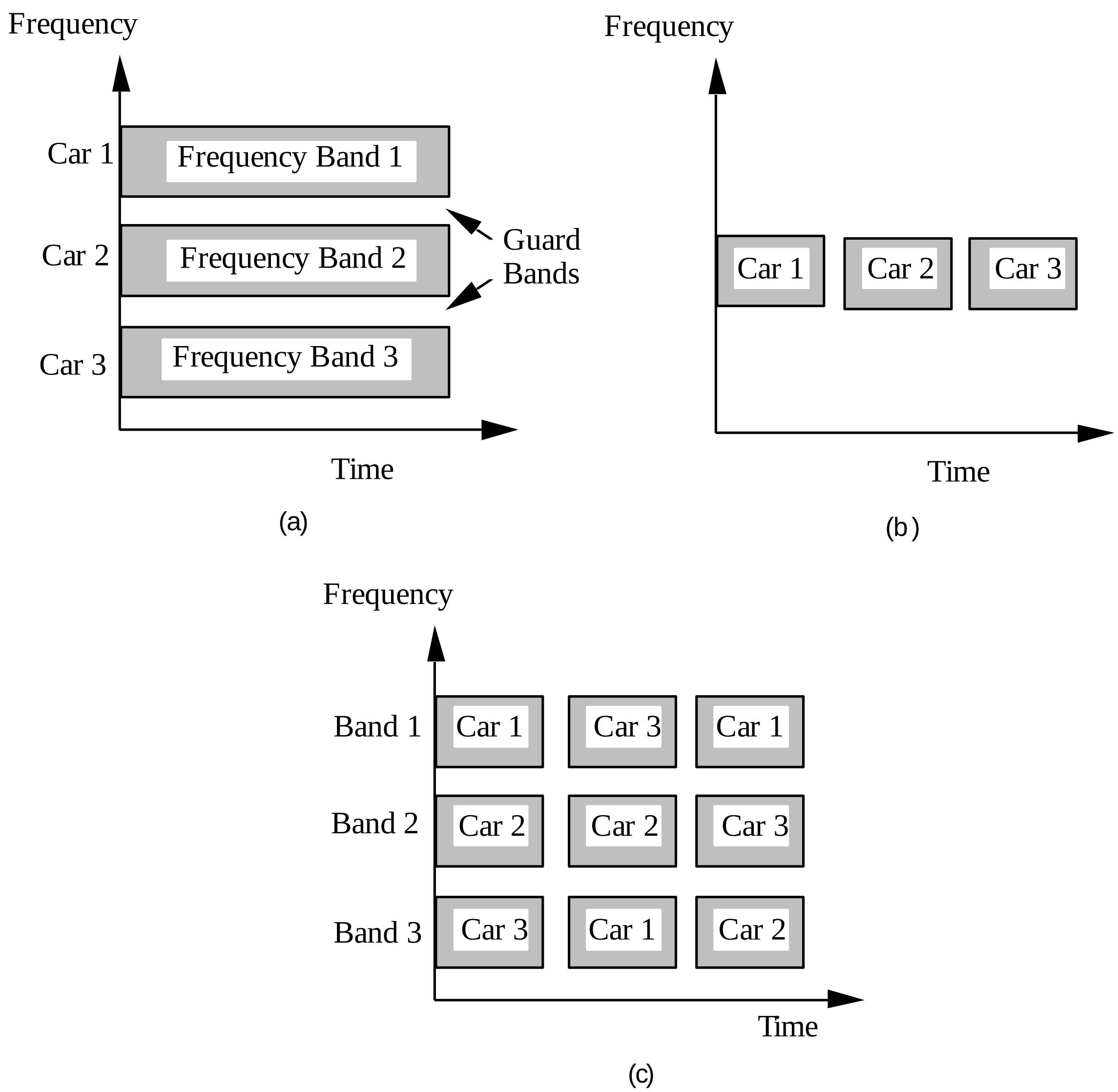


Figure 98. Different types of signal coding to avoid interference. (a) Frequency division multiplexing (FDMA'b) Time division multiplexing (TDMA'c) Code division multiplexing (CDMA).

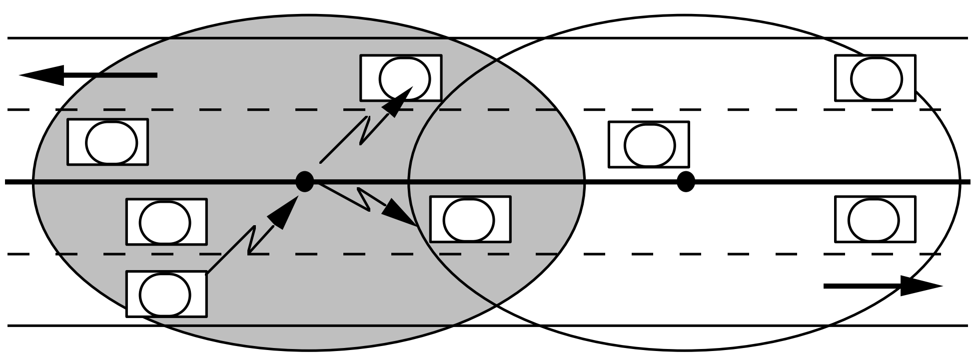


Figure 99. Cellular communication system for VRC. Each cell has a base station (black dot) that communicates with the vehicles within its range.

CDMA has parallel bands of TDMA time slots. Each user follows a coded sequence to choose which time and frequency slot to use. This system provides security and interference resistance since the signal moves in time and frequency. It also requires more complex hardware and switching.

Communications and Detection Theory

Collision warning systems and emergency maneuvers require that fast and accurate decisions be made about what to do and what to tell the driver. Sensors alone can detect the direction and speed of other vehicles but the vehicle can only guess at the intent of the other vehicles. With communications between vehicles this need of guessing may disappear.

The rear-end collision warning and avoidance systems demonstrate this problem. In a system with no vehicle to vehicle communications the following vehicle must detect if the vehicle ahead is braking and how much it is braking. The rear-end collision warning system in the vehicle warns the driver that a rear-end collision may occur. The driver then brakes. The collision warning system must warn the driver when a collision may occur without false alarms. High rates of false alarms can cause the driver to ignore the warnings or turn off the system. If vehicle to vehicle communications is present then the vehicle ahead sends its braking data to the vehicle behind. This data serves as an electronic brake light for the vehicle behind.

For example, if there is no communication between vehicles then the follower vehicle must wait until the lead car begins to brake and slow down before it can detect an emergency stop Æ t_d:

$$\Delta t_d = \ {}_b + t_{det}$$

τ_b is the braking actuation delay for the preceding vehicle. t_{det} is how long the vehicle behind needs to measure the closing rate until it can decide that the vehicle ahead is slowing. The figure below illustrates this problem. The dashed line shows the actual deceleration curve of the lead vehicle relative to the following vehicle. The solid line shows the actual sensor measurements taken by the following vehicle. The measurement noise is due to sensor and controller errors. Due to this noise the rear-end collision warning or avoidance system cannot decide that a collision will occur until it is sure that it is measuring an actual deceleration, not noise. If communication between vehicles is present, the detector only needs to confirm the information sent by the vehicle ahead. This takes less time than a detector working alone.

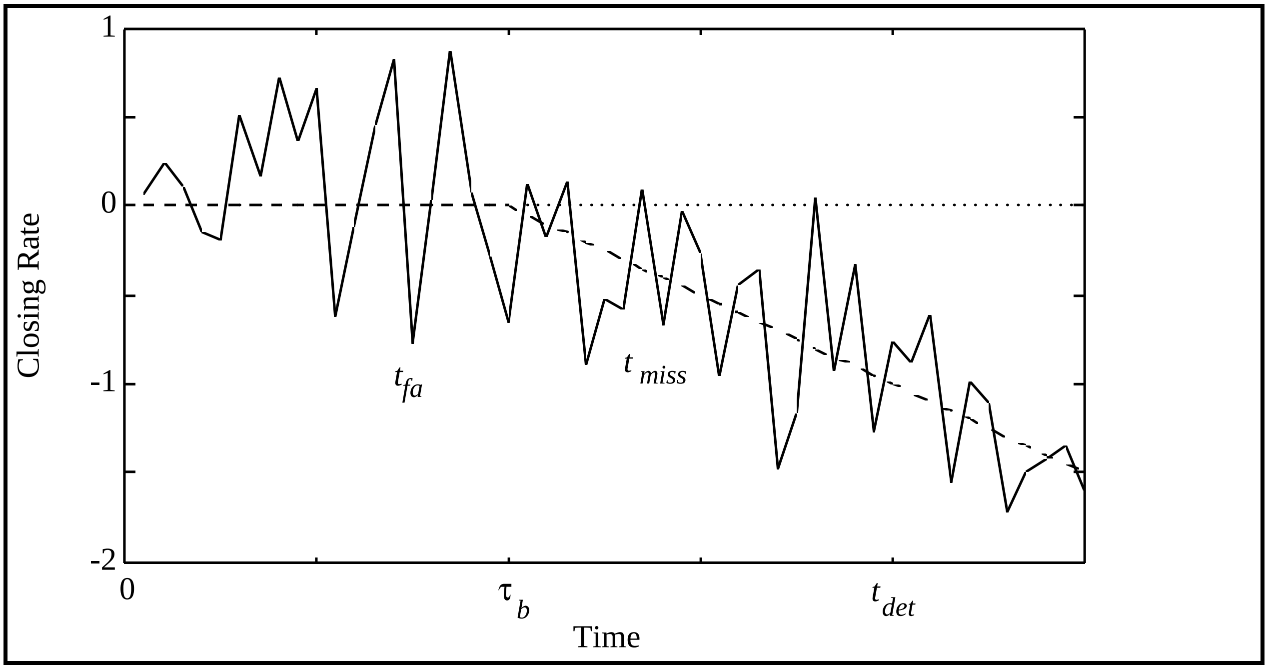


Figure 100. The dashed line shows the actual deceleration curve of the lead vehicle relative to the following vehicle. The solid line shows the actual sensor measurements taken by the following vehicle. The measurement noise is due to sensor and controller errors. t_{fa} shows a false alarm situation. t_{miss} shows a case where the detector misses the emergency braking condition. t_{det} shows when the detector can safely decide that the vehicle is braking with a low probability of false alarm.

This is equivalent to a binary detection problem between two hypotheses: S_0 and S_1. S_0 is the case where the car ahead is not decelerating. S_1 is the case where the vehicle ahead brakes at an acceleration a_{bmax}. This gives the detection problem: (110)

S_0: Æv + n

S_1: Æv + a_{bmax} t + n

Æv is the closing rate between the vehicles. t (t is the time since the beginning of the lead vehicle stopping maneuver. n is the noise of the sensor measurements and the vehicle speed controller. As with any binary decision problem there are four possible outcomes that are summarized in the table below. The goal is to minimize the number of false alarms and maximize the number of correct detections. These parameters determine the performance of the detector.

Table 41. Possible decisions of a binary detector.

True Condition	Decision by Detector	Cost of Decision	Description
S_0: Vehicle ahead not braking	S_0: Vehicle ahead not braking	C_{00}	Correct Decision, null condition
S_0: Vehicle ahead not braking	S_1: Vehicle ahead braking	C_{10}	Incorrect decision; false alarm
S_1: Vehicle ahead braking	S_0: Vehicle ahead not braking	C_{01}	Incorrect decision; missed detection
S_1: Vehicle ahead braking	S_1: Vehicle ahead braking	C_{11}	Correct Decision, braking detected when the vehicle ahead brakes, Detection Rate

For this analysis, we assume that the noise is Gaussian with zero mean and a variance $_n$. The probability of correctly deciding to brake P_D is (110)

$$P_D = \mathrm{erfc}\left(\frac{\ln}{d} - \frac{d}{2}\right)$$

The probability of deciding to brake when the car ahead is not decelerating P_{FA} is (110)

$$P_{FA} = \mathrm{erfc}\left(\frac{\ln}{d} + \frac{d}{2}\right)$$

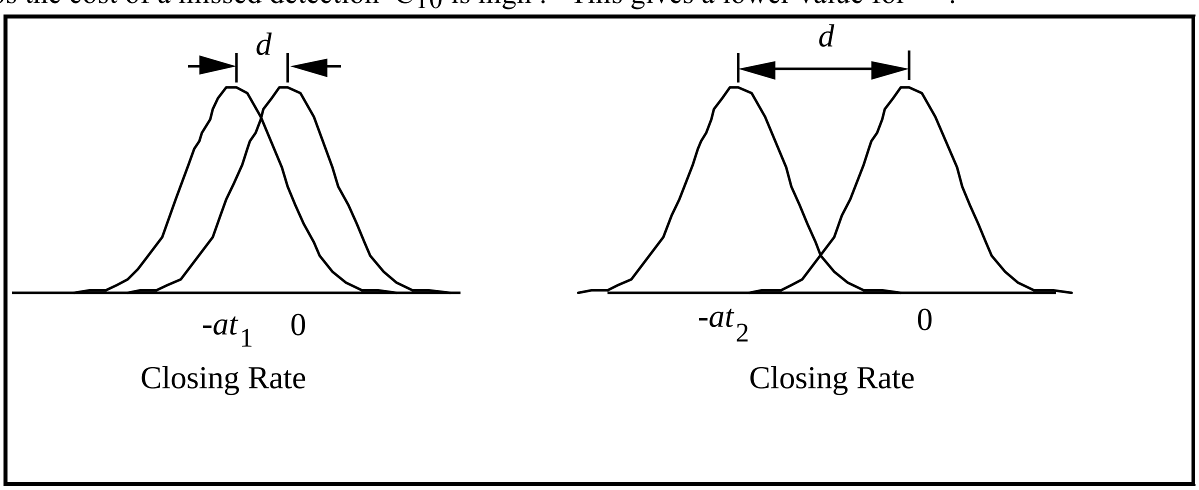
d is the normalized distance between hypothesis S_0 and S_1: $d = at/ \; _n$. Figure 101 shows the geometric interpretation of d. erfc is the complementary error function:

$$erfc(x) = \frac{1}{\sqrt{2}} \int_x^{\infty} \exp\left(-\frac{x^2}{2}\right) dx$$

is the Bayes cost function that gives the cost for false alarms, correct and missed detections (110):

$$\triangleq \frac{P_0(C_{10} - C_{00})}{P_1(C_{01} - C_{11})}$$

P_0 and P_1 are the a priori probabilities that the vehicle ahead is braking or not braking. In most cases these probabilities are unknown and set to 1/2. The terms C_{00}, C_{10}, C_{01},C_{11} are the costs of each possible decision listed in table 41. For example in a collision warning system the cost of a false alarm C_{10} is high since humans will quickly learn to ignore repeated false alarms. This gives a higher value for . In a collision avoidance system where the vehicle is responsible for emergency stops the cost of a missed detection C_{10} is high . This gives a lower value for .



(a) (b)

Figure 101. The curve centered at 0 is the null hypothesis that assumes that the vehicle ahead is not executing an emergency stop. (a) In this case, the vehicle has just begun to brake, the hypotheses are not far enough away (i.e. *d* is small) to make a good decision. (b) The vehicle has been braking for some time(i.e. *d* is large) and the detector can make a correct decision with a low probability of false alarm.

Figure 102 shows the relationship for P_D and P_{FA} with respect to d. The curves change with . = ∞ corresponds to the case where the receiver always decides no acceleration. = 0 corresponds to the case where the receiver always decides that acceleration is present. This shows that as t increases for constant noise and accelerations the performance of the detector improves. A good rear-end collision detection system needs a low false alarm rate and a high probability of detection. [64] This may require a d on the order of 4 or higher. For example if the maximum deceleration of the lead vehicle is 8 m/s^2 and the noise deviation is 0.5 m/s then t = 0.25 s gives d=4. d=5 gives t=0.31 s.

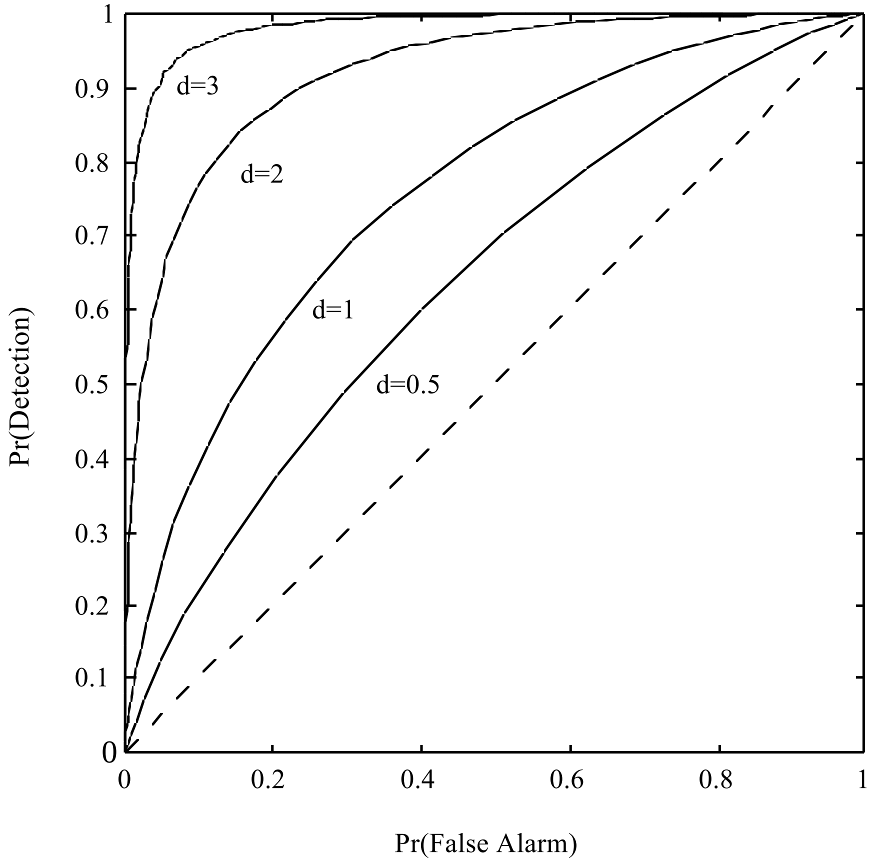


Figure 102. The probability of correctly deciding that the vehicle ahead is decelerating depends on the space between the two signals *d*. As *d* increases the detection-false alarm trade-off improves.

Appendix B: Roadway Traffic Controller

For manual driving, the traffic flow is often irregular and unstable. This leads to congestion and to low traffic flow rate during minor incidents. These irregularities are due to variation of vehicle speeds and headways that are selected by the individual drivers. Congestion could be reduced and traffic flow rate could be increased, if the speed and density of the vehicles along a lane can be properly controlled by a roadway controller. In this paper we propose a roadway controller and investigate the benefits of controlling the density and speed of the vehicles along a lane by using the roadway controller. The roadway controller sends the appropriate speed commands to vehicles in each section of the lane. The vehicles are equipped to follow each other automatically and respond to the roadway commands without any driver intervention. A macroscopic traffic flow model is used for analysis and simulations. Our results demonstrate significant benefits in terms of smooth and stable traffic flow that reduce congestion considerably.

Introduction

Congestion is nowadays one of the main problems in urban transportation all over the world. Reduction of congestion is an important objective not only for ensuring shorter and more reliable travel times, but also in reducing its indirect consequences on pollution and fuel consumption, thus improving the quality of life.

Traditionally, on-ramp metering control strategies are employed to improve overall freeway operation by limiting, regulating and timing the entrance of vehicles from one or more ramps onto the main line Variable message signs are also an alternative way adopted at road side to set speed limits and to advise drivers of conditions on the road ahead or to advise them on the best route to follow and reach their destination. The recently developed concepts of automated highway system provide a direct control of overall freeway operation through microscopic vehicle following or platoon control laws and macroscopic traffic control laws. Research results on microscopic vehicle following or platoon control laws can be found in many papers [18,42,50,95,130]. In this paper, we concentrate on the design of roadway controllers for traffic control on the macroscopic level.

An important function of macroscopic roadway controllers is to generate the appropriate speed commands to be received by the vehicles at the various sections of a highway system. It is well known that the inhomogeneity of the traffic density distribution is the main cause of the formation of congestion and congestion amplification. Therefore, in normal traffic condition, the command should be generated so that the density distribution along the highway is uniform leading to higher and smoother traffic flow. In case of incidents the roadway controller should be able to control the traffic density distribution in an effort to minimize the effect of the incident on traffic flow.

Current research conducted in macroscopic traffic control emphasize the design of macroscopic control strategies to operate overall systems with homogeneous traffic density [89]. (The purpose of these macroscopic control laws is to avoid the formation of congestion or to avoid congestion amplification which are mainly caused by the traffic inhomogeneity.) strongly coupling nature of traffic models, the macroscopic traffic controllers proposed in the literature are still remained in the category of {\bf strategy planning} approach. No theoretical support is offered by these controllers. The efficiency of these controllers are either demonstrated by simulation results or by experimental results conducted in some particular highways. In other words, the validity of these controllers is still based on case-by-case experience. The design of a theoretic based macroscopic controller is still an open problem in this field which needs further research effort.

Seeing these problems and in order to provide more reliable solution, we propose a roadway traffic density controller. The proposed roadway traffic density controller is capable of operating the overall highway system not only with a uniform traffic density distribution (in normal traffic condition), but also with a proper (which may not be uniform) density distribution (in case of incidents) determined by a higher level network controller based on overall network considerations.

This appendix is organized as follows. Firstly, a discrete traffic flow model is reviewed and the problem statement is given. Secondly, a roadway traffic controller is proposed. The implementation issue is then discussed and simulation results are presented.

Traffic Flow Model

Traffic models describe traffic behavior in terms of appropriate aggregated traffic variables. Due to the analogy between the mathematical description of traffic flow and fluid dynamics, the first traffic flow model was proposed by Lighthill and Withal [122] based on kinematic wave theory. In this model traffic density is the only state variable which results in poor transient behavior. Payne [126,127], Cremer and May [119] proposed several modifications to overcome this problem. A much more sophisticated model was proposed by Papageorgiou [123,124] which has been tested, validated and reported with excellent results in the Boulevard Peripherique in Paris [123,124]. However, Papageorgiou's model exhibits several unrealistic phenomena. Due to these concerns, Karaaslan, Varaiya and Walrand [56] proposed a modified model to eliminate these unrealistic phenomena. In the following, a more detail description about this modified model is given.

Consider a freeway system which is subdivided into N sections with lengths L_i, (i = 1, ···, N). For a discrete time KT, where T is the sampling time interval, we define the following space-time discretized traffic variables: $k_i(n)$ is the number of vehicles in the freeway section i at time nT divided by the length L_i of the section; $v_i(n)$ is the space mean speed of vehicle in the freeway section i at time nT; $q_i(n)$ is the number of vehicles leaving sections i during the time period [nT,(n+1)T], dividing by T; and $r_i(n)$ and $s_i(n)$ (No. vehicles/hour) are on-ramp and off-ramp volumes of section i respectively.

The modified freeway traffic flow model was in the following form:

$$q_i(n) = \quad k_i(n)v_i(n) + (1 - \quad)k_{i+1}(n)v_{i+1}(n) \qquad \text{(B.1)}$$

$$k_i(n+1) = k_i(n) + \frac{T}{L_i}[q_{i-1}(n) + r_i(n) - s_i(n)] \qquad \text{(B.2)}$$

$$
\begin{aligned}
v_i(n+1) = v_i(n) + \frac{T}{\ }\{V_e[k_i(n)] - v_i(n)\} \\
+\frac{T}{L_i}\frac{k_{i-1}(n)}{k_i(n)+}v_i(n)[\sqrt{v_{i-1}(n)v_i(n)} \\
-v_i(n)] - \frac{(n)T}{L_i}w_i(n)
\end{aligned}
\qquad \text{(B.3)}
$$

where

$$
(n) = \begin{cases} {}_1 \dfrac{\ }{k_{jam} - k_{i+1}(n) +} & \text{if } k_{i+1}(n) > k_i(n) \\ {}_2 & \text{otherwise} \end{cases}
$$

and α, ρ, σ, κ', τ, μ_1, μ_2 are positive constants; $V_e[k_i(\cdot)]$ represents the steady-state speed-density characteristics; $w_i(\cdot)$ represents the average influence of vehicles' response on the mean speed evolution at sampling time nT in section i.

Typical parameter values are:

$$
\left.
\begin{aligned}
v_f = 93.1km/h; k_j = 110veh/km/lane; l = 1.86; m = 4.05; \\
= 0.95; \quad = 40veh/km/lane; \quad ' = 4veh/km/lane; \\
{}_1 = 12km^2/h; \quad {}_2 = 6km^2/h; \quad = 120veh/km/lane; \\
= 35veh/km/lane; and \quad = 20.4\sec.
\end{aligned}
\right\}
\qquad \text{(B.4)}
$$

The physical meaning of each term of equation (B.3) which influences the mean speed of a section can be interpreted as follows The term $\frac{T}{\ }\{V_e[k_i(n)] - v_i(n)\}$ is the relaxation term which includes the speed-density characteristics as a desired value according to the current density $k_i(n)$. $V_e(k_i)$ denotes the steady-state speed-density characteristics. For homogeneous traffic condition on todays freeway, a fairly general formula for the steady-state speed-density relationship is given by

$$
V_e(k_i) = v_f(1 - (\frac{k_i}{k_{jam}})^l)^m \qquad \text{(B.5)}
$$

where l>0 and m>1 are real-valued parameters; v_f is the free speed; and k_{jam} denotes the traffic density at traffic jam. The free speed v_f represents the human driving characteristic of the particular road under consideration and its value can be estimated by calibrating with real traffic data. For a fully automated highway system under homogeneous heavy traffic conditions, the steady-state speed-density characteristic depends on the specified safety policy between two consecutive vehicles. For example, if the specified safety policy is a function of speed, i.e.

$$
S_d = S(v)
$$

(where S_d is the designated safety distance to be kept for two consecutive vehicles), then the steady-state speed-density relationship corresponding to this safety policy is

$$V_e(k_i) = S^{-1}(\frac{1}{k_i}) \tag{B.6}$$

where $S^{-1}(\cdot)$ is the inverse function of $S(\,.\,)$, i.e., $x=S^{-1}(y)$ satisfies the equation $S(x)=y$. The term $\frac{T}{L_i}\,{}_i(n)[v_{i-1}(n) - v_i(n)]$ is the convection term. It represents the influence of the incoming traffic on the mean speed evolution in segment i. The term $--\frac{T}{L_i} w_i(n)$ is the anticipation term. It describes the driver response to the down stream density. For example, if the density downstream is lower, drivers tend to speed up and vice versa. For today's freeway system, $w_i(n)$ can be approximately represented by

$$w_i(n) = \frac{k_{i+1}(n) - k_i(n)}{k_i(n) +};$$

It represents the influence of the traffic density downstream on the mean speed evolution. For an automated highway system, where the human driver has been replaced by an automatic control system, the anticipation term will be greatly affected by the adopted automatic control strategy and automated highway architecture. A suitable control strategy to determine the anticipation term is important for achieving high capacity and smooth traffic flow.

We use equations (B.1), (B.2), (B.3), (B.5) with

$$w_i(n) = \frac{k_{i+1}(n) - k_i(n)}{k_i(n) +};$$

to represent the traffic dynamics of current highway system. The traffic dynamics of automated highway system was represented by (B.1), (B.2), (B.3), (B.6) with a properly designed $w_i(n)$.

Problem Statement

To reduce congestion, the traffic management center of the automated highway system should be capable of providing the strategy to properly guide and organize vehicles. One of the possible strategies is to directly control the density and speed of the vehicles along a lane by sending the appropriate speed commands to each vehicle of the lane.

Assume that the roadway has the capability of measuring mean speeds and traffic densities at each section of a lane. The tasks of the traffic management center should be able to assess the status of the traffic and provide the appropriate speed commands to the vehicles at the various sections of the lane. For this purpose, a roadway controller should be designed to perform these tasks. The roadway controller should generate the appropriate speed commands to be received by the vehicles at the various sections of the lane. The command should be generated so that the density distribution along the lane is uniform leading to higher and smoother traffic flow. In case of incidents the roadway should be able to control the traffic density distribution in an effort to minimize the effect of the incident on traffic flow. Therefore, to be able to address the situations described above, a roadway traffic density controller is proposed in this section. The proposed roadway traffic density controller is designed to provide proper speed command to each vehicle of the lane such that the density distribution of the lane is able to track a desired distribution determined based on overall traffic considerations.

Consider a lane which is subdivided into N sections with lengths L_i, ($i = 1, \cdots, N$). The traffic flow volume entering section 1 at sampling time nT is $q_0(n)$ No. vehicles/hr. Based on overall traffic considerations, the desired traffic density distribution of the freeway is assumed to be determined by a higher level controller. (For example, it is known that inhomogeneous traffic density distribution is the main cause of the traffic congestion. Therefore, the higher level controller may assign a homogeneous density distribution for the dedicated lane to avoid the formation of congestion.) Let us denote the desired or optimal traffic density of section i at sampling time n as $k_{di}(n)$.

We assume that the following condition is satisfied for each section at any sampling time.

Assumption

- The traffic flow controllability is satisfi ed, i.e.,
  There exists a positive constant δ^* such that the following holds:

$$
\begin{aligned}
& k_i(n+1) = k_i(n) + \frac{T}{L_i}[\quad k_i(n) v_{i-1}(n) \\
& +(1-2\quad)k_i(n)v_i(n) - (1-\quad)k_{i+1}(n)v_{i+1}(n)] \\
& \geq \quad ^* > 0 \qquad \forall i, n,
\end{aligned}
$$

The above condition is referred to as the condition of traffic flow controllability. If this condition is violated at sampling time n in section i, the traffic density at sampling time n+1 in section i will be less than δ. This situation can be interpreted as not enough vehicle/traffic will be in this section at sampling time n+1; and hence, there is not enough vehicles/traffic to be controlled in this section. In this situation, we say that the traffic is loss of control and "traffic control" is meaningless in this section; and hence, the control law at this section can be switched off. Therefore, the assumption of traffic flow controllability is physically reasonable and acceptable.

Our objective is to choose a proper value of $w_i(n)$ for section i at sampling time n such that the traffic density at section i converges to the desired traffic density k_{di} exponentially, i.e.,

$$k_i \to k_{d_i} \text{ as } n \to \infty$$

exponentially fast.

Roadway Traffic Density Controller

In this section, we propose a macroscopic roadway traffic density controller for a single lane without on-ramp and off-ramp traffic.

Let the on-ramp and off-ramp traffic flow rates are zero, i.e., $r_i(n)=s_i(n)=0$, and define

$$_i(n) = k_i(n) - k_{d_i}(n)$$
$$_i(n) = \frac{T}{L_i}[q_{i-1}(n) - q_i(n)] - k_{d_i}(n+1) + k_i(n) - c \quad _i(n)$$

From (B.1)-(B.3), we have

$$_i(n+1) = c \quad _i(n) + \quad _i(n)$$
$$_i(n+1) = c \quad _i(n) + \quad _i(n)$$

where

$$_i(n) = e_i(n) + \frac{(n)T}{L_i}[\bar{a}_i(n)w_{i-1}(n) + \bar{b}_i(n)w_i(n) + \bar{c}_i(n)w_{i+1}(n)]$$
$$a_i(n) = \frac{T}{L_i} \quad k_i(n)$$
$$b_i(n) = \frac{T}{L_i}(1-2 \quad)k_i(n)$$
$$c_i(n) = \frac{-T}{L_i}(1- \quad)k_{i+1}(n)$$
$$d_i(n) = k_i(n) - c \quad _i(n) - k_{d_i}(n+1)$$
$$\bar{a}_i(n) = a_i(n+1), \bar{b}_i(n) = b_i(n+1)$$
$$\bar{c}_i(n) = c_i(n+1), \bar{d}_i(n) = d_i(n+1)$$
$$f_i(n) = v_i(n) + \frac{T}{\ }\{V_e[k_i(n)] - v_i(n)\}$$
$$+\frac{T}{L_i}\frac{k_{i-1}(n)}{k_i(n)+}, v_i(n)[\sqrt{v_{j-1}(n)v_i(n)} - v_i(n)]$$
$$e_1(n) = -c \quad _1(n) + \bar{b}_1(n)f_1 + \bar{c}_1(n)f_2 + \bar{d}_1(n)$$
$$e_i(n) = -c \quad _i(n) - \bar{a}_i(n)f_{i-1}(n) + \bar{b}_i(n)f_i$$
$$+\bar{c}_i(n)f_{i+1} + \bar{d}_i(n) \quad \forall i = 2, 3, \cdots, N-1$$
$$e_N(n) = -c \quad _N(n) - \bar{a}_N(n)f_{N-1}(n) + \bar{b}_N(n)f_N + \bar{d}_N(n)$$
$$c_\eta > 0, \quad c_\xi > 0, \quad |c_\eta| < 1, \quad |c_\xi| < 1$$

Lemma 1

Consider the following discrete time system

$$z(n+1) = cz(n) + u(n), \quad z(0) = z_0$$

where c is a constant and $|c| < 1$, then,

$$u(n) \rightarrow 0 \text{ exponentially implies } z(n) \rightarrow 0 \text{ exponentially.}$$

Proof: The proof is trivial and is omitted.

For section i, at sampling time nT, if $w_i(n)$ is designed such that

$$\kappa_i(n) = 0 \quad \forall \ i, n,$$

then, from Lemma 1, since $\kappa_i(n) = 0$ and $|c_\eta|<1$, we have $\eta_i(n) \rightarrow 0$ as $n \rightarrow \propto$. Moreover, since $|c_\xi|<1$ and $\eta_i(n) \rightarrow 0$ as $n \rightarrow \propto$, we have $\xi_i(n) = k_i(n) - k_{di}(n) \rightarrow 0$ as $n \rightarrow \propto$. In other words, the control objective is achieved.

Based on this, we have the following theorem.

Theorem 2 Assume that the traffic flow controllability is satisfied for each section at any sampling time. There exists a $w_i(n)$ at sampling time n, section i

$$w_i(n) = -\frac{L_i}{(n)T} u_i(n),$$

where $u_i(n)$ satisfies

$$P(n)\, U(n) = E(n)$$

and

$$P(n) =$$

$$\begin{bmatrix} \bar{b}_1 & {}_1\bar{b}_2 & 0 & \cdot & \cdot & \cdot & 0 \\ {}_2\bar{b}_1 & \bar{b}_2 & {}_2\bar{b}_3 & 0 & \cdot & \cdot & 0 \\ & {}_3\bar{b}_2 & \bar{b}_3 & {}_3\bar{b}_3 & 0 & \cdot & 0 \\ 0 & 0 & \cdot & \cdot & \cdot & 0 & 0 \\ 0 & \cdot & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & \cdot & \cdot & 0 & \cdot & \cdot & {}_{N-1}\bar{b}_N \\ 0 & 0 & \cdot & \cdot & 0 & {}_N\bar{b}_{N-1} & \bar{b}_N \end{bmatrix}$$

$$U(n)=\begin{bmatrix} u_1(n) \\ u_2(n) \\ u_3(n) \\ \cdot \\ \cdot \\ \cdot \\ u_N(n) \end{bmatrix}, \quad E(n)=\begin{bmatrix} e_1(n) \\ e_2(n) \\ e_3(n) \\ \cdot \\ \cdot \\ \cdot \\ e_N(n) \end{bmatrix}$$

$$_i = \frac{L_i}{L_{i+1}} \frac{}{1-2} < 0$$

$$_i = \frac{-L_i}{L_{i-1}} \frac{1-}{1-2} > 0$$

that drives the traffic density at section i converges to the desired traffic density k_{di} exponentially, i.e.,

$$k_i \rightarrow k_{di}$$

exponentially.

Proof: The control w_i can be obtained by solving $_i(n) = 0$. For a detail derivation, please see Chien [(17)].

If the velocity command, which is to be send to vehicles in each section of the lane to achieve at sampling time n+1, is chosen as

$$v_{command} = v_i(n) + \frac{T}{} \{V_e[k_i(n)] - v_i(n)\}$$

$$+ \frac{T}{L_i} \frac{k_{i-1}(n)}{k_i(n)+} , v_i(n)[\sqrt{v_{i-1}(n)v_i(n)} - v_i(n)]$$

$$- \frac{(n)T}{L_i} w_i(n)$$

then the traffic density at section i converges to the desired traffic density k_{di} exponentially.

Implementation algorithm

In this section, a computation algorithm for the purpose of simplifying implementation is proposed. To obtain the control law for each section, the computation involves solving a tridiagonal matrix equality.

$$P(n)\ U(n) = E(n)$$

Since traffic flow controllability is assumed, the non-singularity of the matrix P(n) is guaranteed. Therefore, it is trivial that the solution of the control law for each section can be computed through the obtaining of the matrix inversion.

$$U(n) = P^{-1}(n)\ E(n)$$

However, high computational effort is required to obtain the inversion of the N x N matrix P(n) if the number of sections N is large. Hence, more efficient method should be employed. Several iterative methods can be adopted to obtain the solution. However, these iterative methods have several drawbacks:

- Iterative methods require recursive computations. The computation rate may turn out to be slow when the numbers of sections N is large. Moreover, during the recursive computation stage, numerical error might accumulate and the solution may be highly distorted.

- Most recursive iterative methods require all information about the element of the matrix to be available during the recursive computing stage. Hence, to apply these recursive iterative methods to our problem, information from all sections should be combined and be passed to a central computer center. And then, based on all information from each section, the central computer decides the control action to be taken for each section and then passes the decision back to each section.

To avoid slow computation rate due to a large number of sections, large accumulated numerical error due to recursive computation, and extremely complex and high cost communication network between sections and central computer, we propose an approximation algorithm with the following features:

- Non-recursive algorithm. (This avoids the slow computation rate and large accumulated numerical error due to recursive computation.)

- No central computer center is needed. The control action is determined by a local computer center based only on the information passed from its adjacent sections in a series way. (This eliminates the need of extremely complex and high cost communication network.)

We described the approximation algorithm below: For section i, at sampling time n, the control law $w_i(n)$ is replaced with

$$\hat{w}_{l_i}(n) = -\frac{L_i}{(n)T}\hat{u}_{l_i}(n)$$

where $\hat{u}_{l_i}(n)$ is a component of $\hat{U}_l$, and

$$\hat{U}_l(n) = \sum_{m=0}^{l}(-1)^m Z_m(n)$$

$Z_m(n) = [T^{-1}(n)\,\Delta(n)]\,Z_{m-1}(n)$ m = 1, 2, 3, ...

$Z_0(n) = T^{-1}(n)\,E(n)$

$T(n) =$

$$\begin{bmatrix} \bar{b}_1(n) & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ {}_2\bar{b}_1(n) & \bar{b}_2(n) & 0 & 0 & \cdot & \cdot & 0 \\ 0 & {}_3\bar{b}_2(n) & \bar{b}_3(n) & 0 & 0 & \cdot & 0 \\ 0 & 0 & \cdot & \cdot & \cdot & 0 & 0 \\ 0 & \cdot & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & \cdot & \cdot & 0 & \cdot & \cdot & 0 \\ 0 & 0 & \cdot & \cdot & 0 & {}_N\bar{b}_{N-1}(n) & \bar{b}_N(n) \end{bmatrix}$$

$\Delta(n) =$

$$\begin{bmatrix} 0 & {}_1\bar{b}_2(n) & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & {}_2\bar{b}_3(n) & 0 & \cdot & \cdot & 0 \\ 0 & 0 & 0 & {}_3\bar{b}_3(n) & 0 & \cdot & 0 \\ 0 & 0 & \cdot & \cdot & \cdot & 0 & 0 \\ 0 & \cdot & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & \cdot & \cdot & 0 & \cdot & 0 & {}_{N-1}\bar{b}_N(n) \\ 0 & 0 & \cdot & \cdot & 0 & 0 & 0 \end{bmatrix}$$

The on-line implementation of this approximation is summarized in the following:

Step 1: Determination of Z_0

Since $Z_0 = T^{-1} E$, it implies $TZ_0 = E$. Let $z_0^1, z_0^2, z_0^3, \ldots, z_0^N$ are components of Z_0. Therefore, they should satisfy the following equations:

$$\bar{b}_1 z_0^1 = e_1$$
$${}_2\bar{b}_1 z_0^1 + \bar{b}_2 z_0^2 = e_2$$
$${}_3\bar{b}_2 z_0^2 + \bar{b}_3 z_0^3 = e_3$$
$$\cdots\cdots\cdots\cdots\cdots$$
$${}_N\bar{b}_{N-1} z_0^{N-1} + \bar{b}_N z_0^N = e_N$$

In other words, all components of Z_0 can be determined by a series way.

Step 2: Determination of Z_i ($i = 2, 3, 4, \ldots l$)

Since $Z_i = T^{-1} \Delta Z_{i-1}$, it implies $TZ_i = \Delta Z_{i-1}$. Let $z_i^1, z_i^2, z_i^3, \ldots, z_i^N$ are components of Z_i. Therefore, they should satisfy the following equations:

$$\bar{b}_1 z_i^1 = {}_1\bar{b}_2 z_{i-1}^2$$
$${}_2\bar{b}_1 z_i^1 + \bar{b}_2 z_i^2 = {}_2\bar{b}_3 z_{i-1}^3$$
$${}_3\bar{b}_2 z_i^2 + \bar{b}_3 z_i^3 = {}_3\bar{b}_4 z_{i-1}^4$$
$$\cdots\cdots\cdots\cdots\cdots$$
$${}_N\bar{b}_{N-1} z_i^{N-1} + \bar{b}_N z_i^N = 0$$

In other words, all components of Z_i can be determined by a series way.

Remark It can be shown that, with the parameter set (B.4),

$$\lim_{l\to\infty} \left\| \frac{U(n) - \hat{U}_l}{U(n)} \right\| = 0$$

for some natural norm $\|\cdot\|$. It implies that $\hat{U}_l(n)$ can be served as a good approximation of $U(n)$; and hence, $\hat{w}_i(n)$ can be served as a good approximation of $w_i(n)$. Furthermore, it can also be shown that, even the zero-order approximation, i.e., $w_{0i}(n)$, provides a good approximation of $w_i(n)$. In other words, the computation effort can be greatly reduced by the proposed algorithm when zero-order approximation is adopted.

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