Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Automated Check-In

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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.

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NOTICE

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16. Abstract

This report summarizes the research results in the Automated Check-in Activity Area. Situations in AHS where transition from manual to automated control takes place are analyzed. In particular, vehicle fitness testing to ensure safe and smooth automated operation has been emphasized. The check-in procedures presented here and an effective malfunction management system, together with a reliable control system, would ensure a safe, smoothly operating AHS system. It is concluded that on-board built-in diagnostic tests are practical for sensor testing since crucial sensor tests can be performed via consistency checks on the redundant paths; on-board built-in tests of control actuators and electronics is also practical, *provided the systems are designed for testability*. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site tests are expected to be needed. Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.

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Executive Summary

The research team for Automated Check-in consisted of the University of Southern California (USC), Ford and Daimler Benz. The Center for Advanced Transportation Technologies at USC led the research effort. Professors Levent Turan, Petros Ioannou, and Michael G. Safonov were the researchers in this group. Professors David Smith and Diane Damos from the Department of Human Factors at USC have assisted with the human factors aspects of the study, and Ford and Daimler Benz provided consulting in various areas of automotive technology.

The underlying framework in this research is an evolutionary approach to vehicle and highway automation. This evolutionary deployment of AHS starts with the current traffic configuration at the lower end of automation, and goes all the way to a fully automated, synchronized configuration where human intervention is minimal. Hence, longitudinal and lateral control, lane changing, collision avoidance, route planning, etc. are all automated in a certain sequence, and slowly over a period of time. This leads to five intermediate, evolutionary levels of automation, which are called Evolutionary Representative System Configurations (ERSCs). In particular, ERSC1 involves automated headway and speed maintenance, ERSC2 introduces steering assist and rear-end collision avoidance, ERSC3 is the first level where we have hands-off/feet-off operation, ERSC4 has full collision avoidance, and the roadway provides direct control commands to each vehicle at ERSC5.

We have analyzed situations in AHS where transition from manual to automated control takes place. In particular, vehicle fitness testing to ensure safe and smooth automated operation has been emphasized. The check-in procedures presented here and an effective malfunction management system, together with a reliable control system, would ensure a safe, smoothly operating AHS system.

In order to analyze the check-in procedures, we need certain assumptions about the roadway configurations. With the purpose of keeping the treatment general, we introduced three conceptual representative entry configurations: (1)Designated Entry with a Dedicated Entry Ramp; (2)Designated Entry without a Dedicated Entry Ramp; (3)Continuous Entry.

We identified four different categories of check-in tests that could be used to test the fitness of the vehicle to enter an AHS facility:

1. *Initial Testing and Certification:* When the automated function vehicle components are manufactured, these will be tested and certified at the factory. If vehicles are retrofitted with these components, the facility performing the retrofit will be responsible for initial testing and certification.

2. *Periodic Off-site Testing:* In addition to the initial testing, periodic (e.g., once a year) testing will be performed at certain testing facilities to certify the fitness of the vehicle for automated lane driving. The certification may also be coded into the nonvolatile memory of the microprocessor of the vehicle. All automated components will be tested in the periodic tests. Required driver qualifications, if any, may be certified via periodic driver's license examinations for automated vehicle operators.

3. *On-board Built-in Diagnostic Testing:* On-board diagnostics and self tests performed continuously whenever the vehicle is operating under manual or automated control. These tests start at ignition time, and are performed continuously as long as the vehicle is operating. After the vehicles are admitted into the automated lane, continuous diagnostic checks will be performed to ensure continuous vehicle fitness. Standard fault detection algorithms can be used for On-board Built-in Diagnostic Tests.

4. *On-site Testing at Check-in Point:* Tests performed just before the vehicle joins the automatic lane, possibly while the vehicle is in motion, or at a check-in station.

For each Evolutionary Representative System Configuration (ERSC), alternative scenarios have been developed, and relevant functions to be tested are determined. Each function is then evaluated for its criticality with respect to safety. Criticality and feasibility considerations lead to a subset of functions to be tested for each of the ERSCs. Test procedures for each function in these subsets are also discussed. The main goal is to accomplish all tests while the vehicle is driven under manual control as on-board built-in diagnostic tests. This minimizes the check-in procedures at the check-in site, is transparent to the driver and the traffic flow, and allows smooth transition between manual and automated lane.

Since the driver is ultimately responsible for the overall control of the vehicle at ERSC1 and ERSC2, check-in testing of automated equipment is not essential, and on-board built-in diagnostic testing procedures are required primarily for efficient and reliable operation. The reliability functional requirement imposed on the control system is that, under no circumstances, a single-point failure will cause a catastrophic system failure. Hence, double (or even triple) redundancy is absolutely necessary for a fail-safe design for higher ERSCs (see figure 1). Hence, on-board built-in diagnostic tests are practical for sensor testing since crucial sensor tests can be performed via consistency checks on the redundant paths; on-board built-in tests of control actuators and electronics is also practical, *provided the systems are designed for testability*. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site tests are expected to be needed. Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.

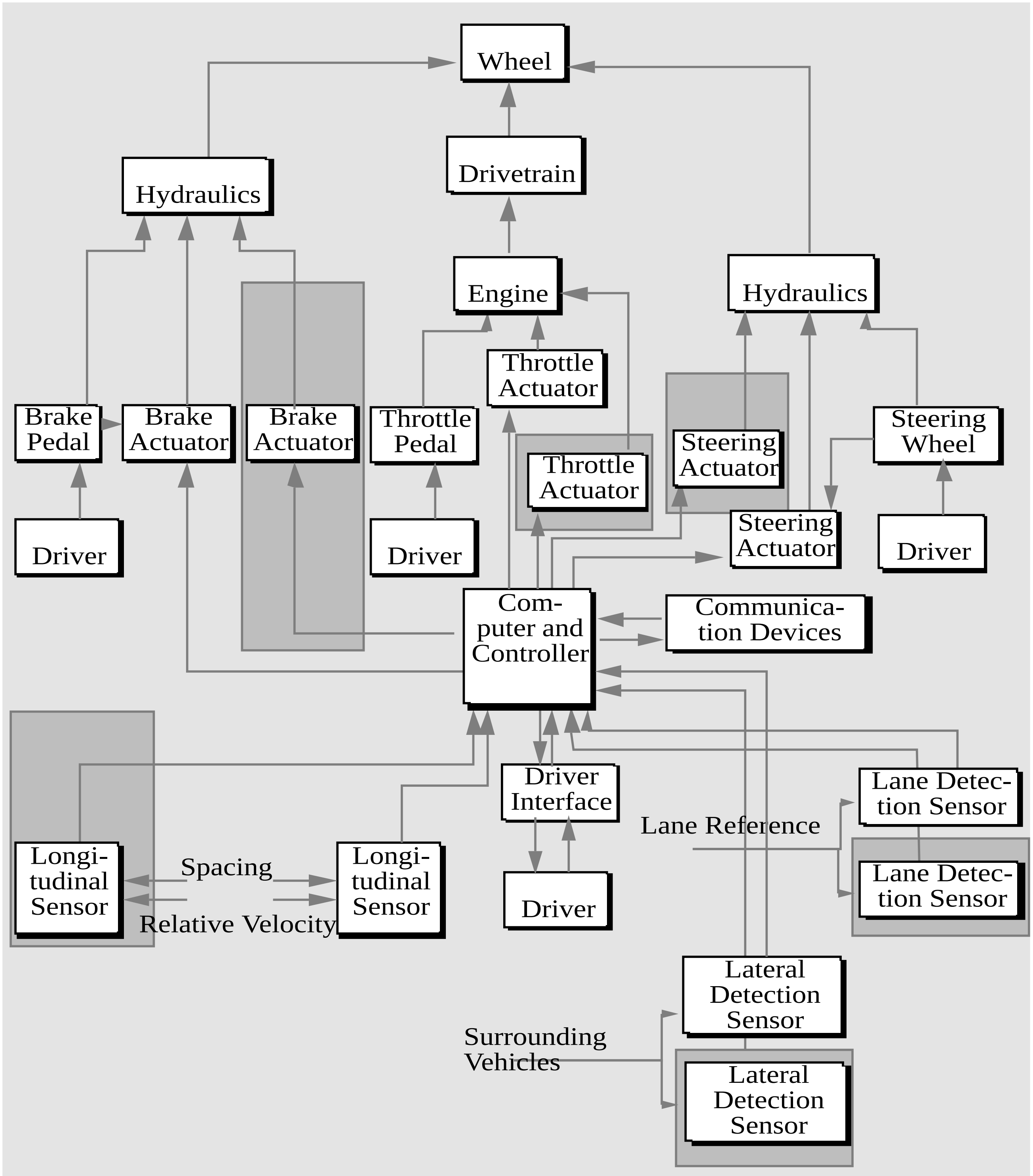

Figure 1: Conceptual Diagram of the AHS Vehicle (hatched rectangles indicate redundant components, the computer has built-in redundancy)

The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

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Introduction

Check-in refers to the situations where transition from manual to automated control takes place. Check-in involves three major elements: the vehicle, the driver, and the roadway. The activity area “Entry/Exit” deals with roadway issues. Hence, driver and vehicle issues will dominate the Automated Check-in activity area research efforts. In particular, the emphasis will be on vehicle fitness testing to ensure safe and smooth automated operation. Currently, vehicle malfunctions cause considerable amount of travel interruptions [1] . In addition, there are some AHS specific components that may fail, and the check-in procedures have to be designed such that most of the malfunctions are predicted or detected before the vehicle enters the dedicated lane. The check-in procedure and an effective malfunction management system, together with a reliable control system, would ensure a safe, smoothly operating AHS system.

For each Evolutionary Representative System Configuration (ERSC), alternative scenarios are developed, and relevant functions to be tested are determined. Each function is then evaluated for its criticality with respect to safety. Criticality and feasibility considerations lead to a subset of functions to be tested for each of the ERSCs. Test procedures for each function in these subsets are also discussed. The main goal is to accomplish all tests while the vehicle is driven under manual control as on-board built-in diagnostic tests. This minimizes the check-in procedures at the check-in site, is transparent to the driver and the traffic flow, and allows smooth transition between manual and automated lane. Issues, risks, recommendations, and key findings are also discussed for each ERSC. In particular, human factors issues, infrastructure requirements, safety and liability issues, and design issues are analyzed.

The discussion for each ERSC is intended to be as self-contained as possible. Hence, applicable material from earlier ERSCs are repeated, rather than being referred to, in the text. Even though this inevitably leads to repetition, we believe that it enhances the readability of each ERSC section as an independent unit.

Representative Entry/Exit Configurations

Before we go into the analysis of check-in we will need an analysis framework. The Representative Entry/Exit Configurations presented in this section provides this framework along with the Evolutionary Representative System Configurations.

In order to analyze the check-in procedures, we need certain assumptions about the roadway configurations. With the purpose of keeping the treatment general, we introduce three representative entry/exit configurations (see figure 2):

(1) Designated Entry/Exit with a Dedicated Entry/Exit Ramp

(2) Designated Entry/Exit without a Dedicated Entry/Exit Ramp

(3) Continuous Entry/Exit

These configurations are only conceptual. For a more detailed description of various entry/exit configurations, see [2] . The continuous entry/exit configuration requires the least amount of infrastructure changes, and therefore may be a good candidate for the early ERSCs. Designated entry/exit configurations provide a setting where the roadway may have more control over the entry/exit maneuvers. Designated entry/exit configuration also allows the auto lanes to be separated with barriers from the manual lanes although this is not necessarily an inherent feature of the configuration. Dedicated ramps increase safety, and allow more control such as ramp metering, gate installation at entry points, etc., albeit with an increase in cost.

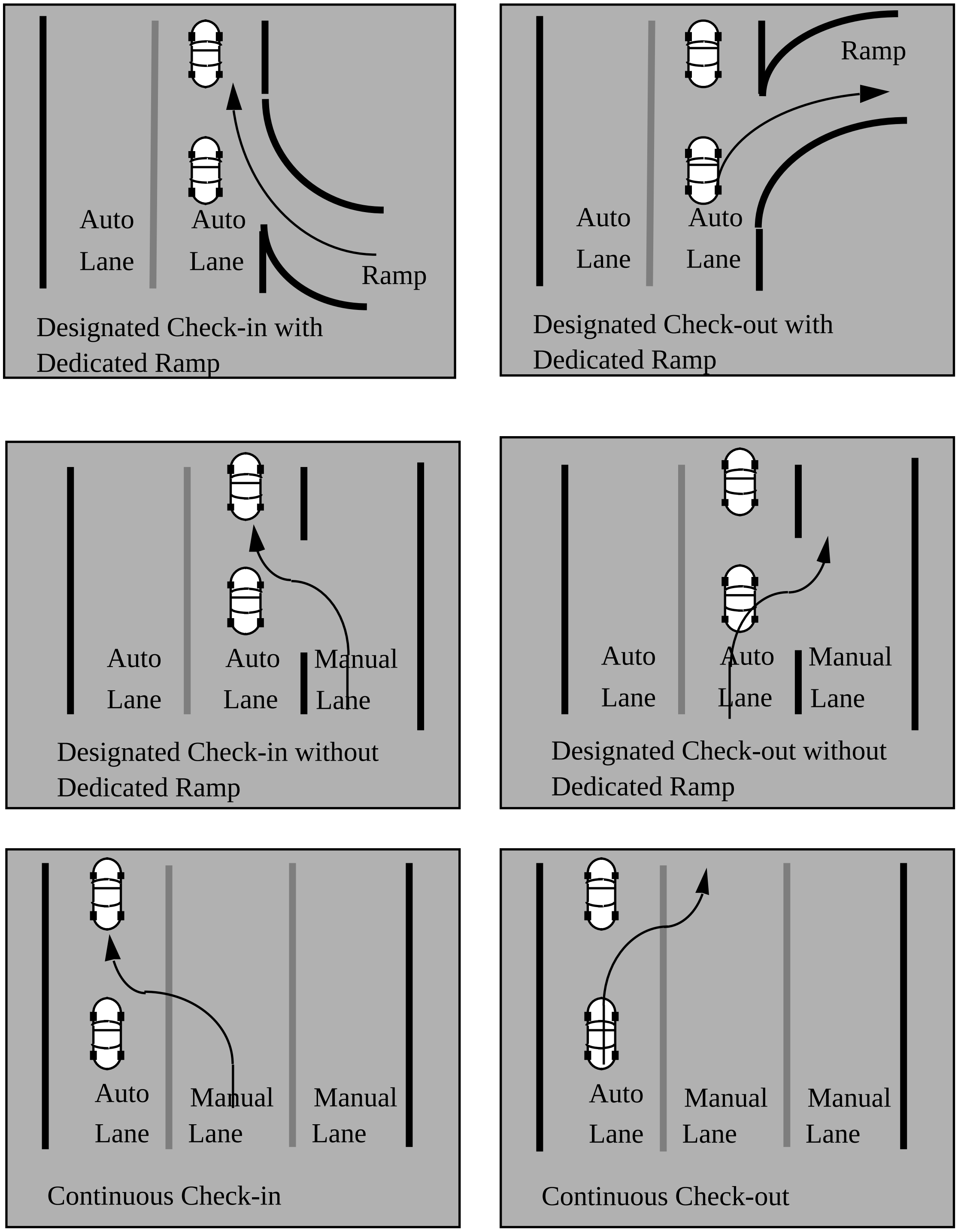

Figure 2: Entry Configurations Exit Configurations

Check-in Testing Categories

In our approach, we identify four different categories of check-in tests that could be used to test the fitness of the vehicle to enter an AHS facility.

1. ***Initial Testing and Certification:*** When the automated function vehicle components are manufactured, these will be tested and certified at the factory. If vehicles are retrofitted with these components, the facility performing the retrofit will be responsible for initial testing and certification.
2. ***Periodic Off-site Testing:*** In addition to the initial testing, periodic (e.g. once a year) testing will be performed at certain testing facilities to certify the fitness of the vehicle for automated lane driving. The certification may also be coded into the nonvolatile memory of the microprocessor of the vehicle. All automated components will be tested in the periodic tests. Required driver qualifications, if any, may be certified via periodic driver's license examinations for automated vehicle operators.
3. ***On-board Built-in Diagnostic Tests:*** On-board diagnostics and self tests performed continuously whenever the vehicle is operating under manual or automated control. These tests start at ignition time, and are performed continuously as long as the vehicle is operating. After the vehicles are admitted into the automated lane, continuous diagnostic checks will be performed to ensure continuous vehicle fitness. Standard fault detection algorithms can be used for On-board Built-in Diagnostic Tests [3] .
4. ***On-site Testing at Check-in Point:*** Tests performed just before the vehicle joins the automatic lane, possibly while the vehicle is in motion, or at a check-in station.

In the following, we will discuss these testing categories for each evolutionary representative system configuration, pointing out the categories that are essential for ensuring smooth and safe operation.

Evolutionary Representative System Configuration One (ERSC1)
In this ERSC, the vehicle is responsible for headway and speed maintenance, and there is communication between the roadway and the vehicle. A blind spot detector assists the driver in lane changing maneuvers by providing warnings, and rear-end collision warnings alert the driver whenever there is a potential for a rear-end collision. The driver is responsible for steering and emergencies.

Vehicle and Driver Functions to Be Tested for Check-in
The functions needed to be tested for ERSC1, and the required components for each function are shown in table 1.

Table 1: Functions to Be Tested at Check-in for ERSC1

FUNCTION TO BE TESTED	REQUIRED COMPONENTS
Speed and Headway Maintenance	Sensors: Speed sensor; headway and relative speed sensor Actuators: Brake; throttle Computer control system
Rear-end Collision Warning	Sensors: Headway and relative speed sensor Vehicle-vehicle communication devices Computer control system
Blind Spot Warning	Sensors: Blind spot detection sensor
Receive Speed, Headway, and Traffic Information from Roadway	Roadway-vehicle communication devices
Vehicle to Roadway Communication (option)	Vehicle-roadway communication devices
Driver Interface	Driver interface controls and displays
Other Vehicle Functions	Critical fluids level and pressure, engine temperature, brake pad condition, tire pressure and condition, wipers, headlights, etc.

Specific testing procedures for these components will be discussed in the following subsections. Before analyzing the test procedures, however, we will describe alternative scenarios for each entry/exit configuration.

Designated Check-in with a Dedicated Ramp

Check-in Scenario I
This scenario is the closest to a current driving situation where the driver is responsible for verification of component status. Figure 3 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

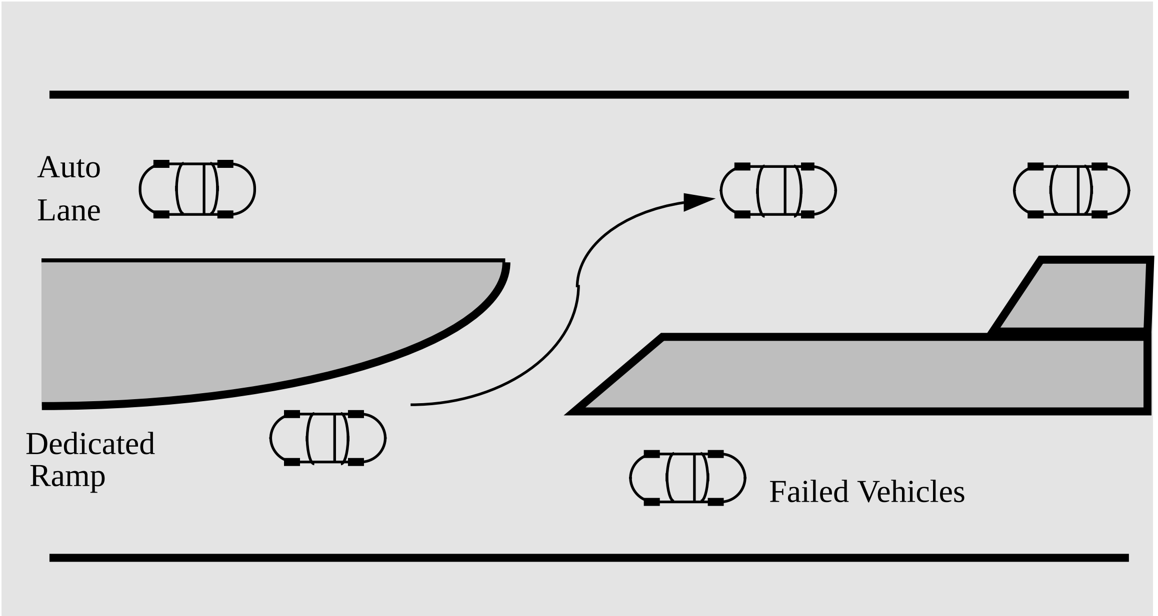

Figure 3: Designated Check-in with a Dedicated Ramp, Check-in Scenario I

Driver Functions: The driver guides the vehicle through the ramp into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

***Vehicle Functions*:** The vehicle has all diagnostics on board to enable it verify fitness of the vehicle. Any malfunction is brought to the driver's attention. Once in the automated lane, the vehicle establishes communication with the preceding and following vehicles in order to transmit and receive braking level signals for the rear-end collision warning generation. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information.

Roadway Functions: Apart from providing the dedicated ramp, the roadway provides headway and speed recommendations, and traffic information to the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps. Also, toll paying and outstanding ticket checking could be accomplished on the ramp, albeit at the expense of additional delay.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 4 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

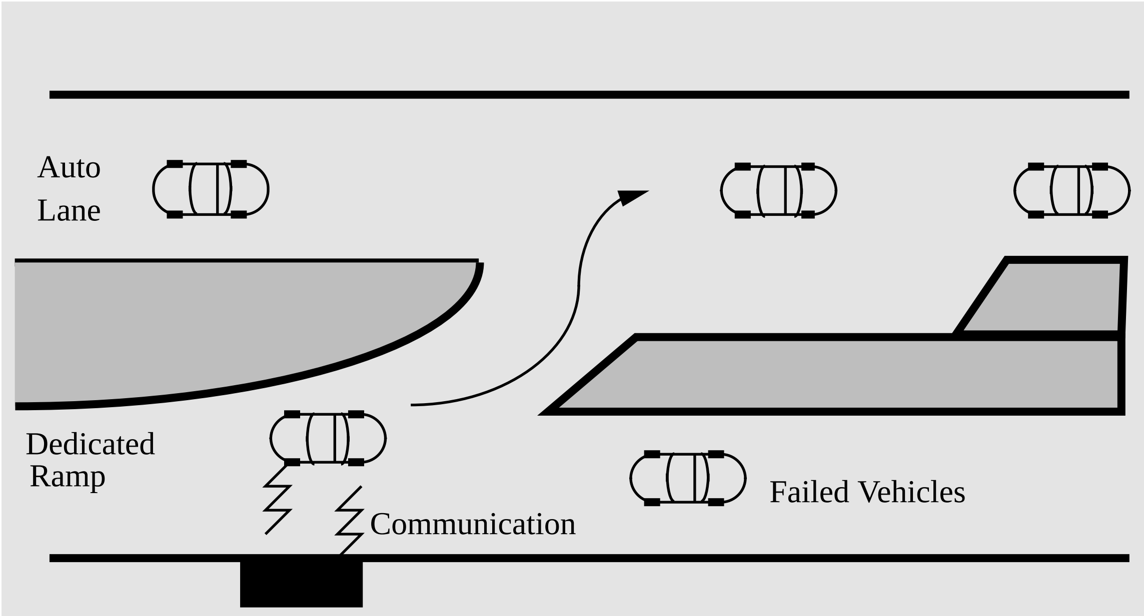

Figure 4: Designated Check-in with a Dedicated Ramp, Check-in Scenario II

Driver Functions: The driver guides the vehicle through the ramp into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane, and assumes longitudinal control of the vehicle. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated ramp, the roadway provides headway and speed recommendations, and traffic information to the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying and outstanding ticket checking may be accomplished on the ramp.

Check-in Scenario III

In this scenario, a gate is used to allow vehicles determined to be fit into the automated lane. Figure 5 illustrates this scenario conceptually.

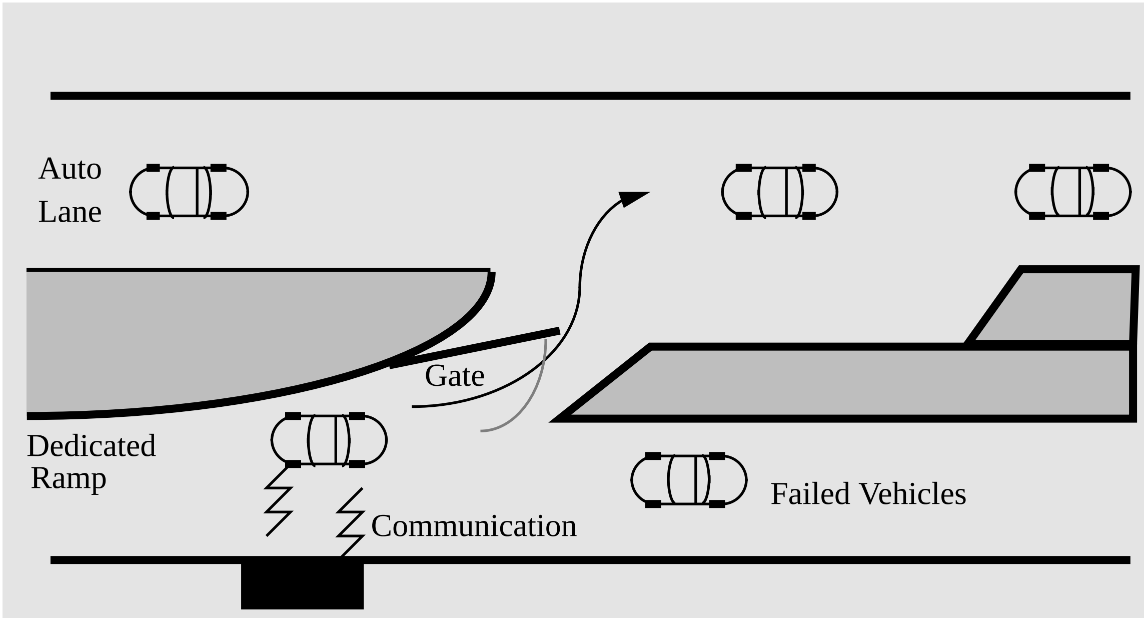

Figure 5: Designated Check-in with a Dedicated Ramp, Check-in Scenario III

Driver Functions: The driver guides the vehicle to the ramp, and into the automated lane if the vehicle is determined to be fit for automated operation causing the gate to be opened. The driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. The vehicle may establish communication with other vehicles in the automated lane, and assumes longitudinal control of the vehicle. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information.
Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. The roadway opens the gate if the vehicle is determined to be fit to operate in the automated lane. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. The roadway also sends headway and speed recommendations, and traffic information to the vehicles.

Designated Check-in without a Dedicated Ramp

Check-in Scenario I

This scenario is the closest to current driving situation where the driver is responsible for verification of component status. Figure 6 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

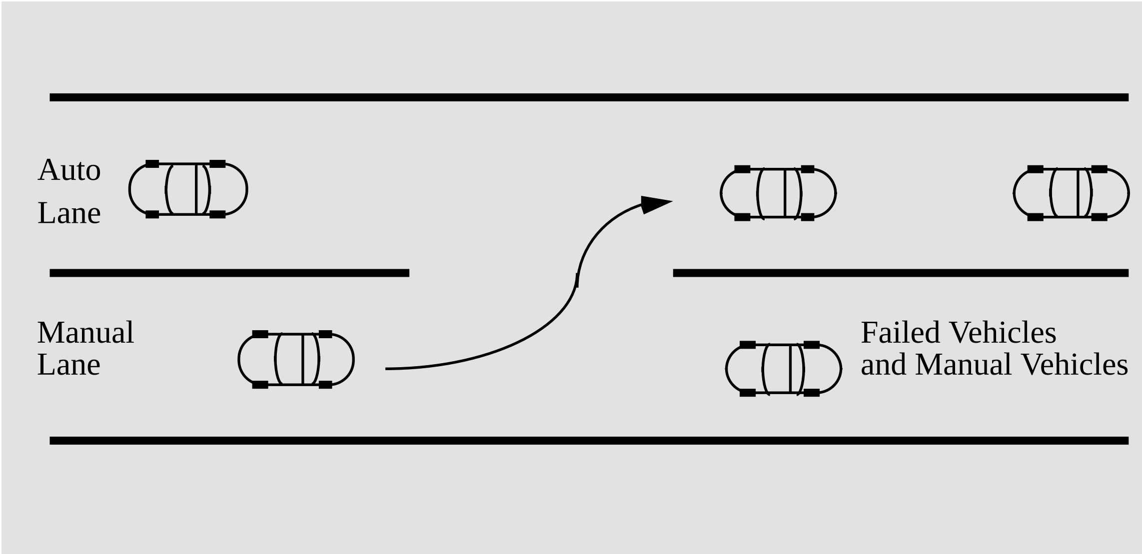

Figure 6: Designated Check-in without a Dedicated Ramp, Check-in Scenario I

Driver Functions: The driver guides the vehicle through the designated opening into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.
***Vehicle Functions*:** The vehicle has all diagnostics on board to enable it verify fitness of the vehicle. Any malfunction is brought to the driver's attention. Once in the automated lane, the vehicle may establish communication with the preceding and following vehicles in order to transmit and receive braking level signals. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information.
Roadway Functions: The roadway provides headway and speed recommendations, and traffic information to the vehicles.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 7 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

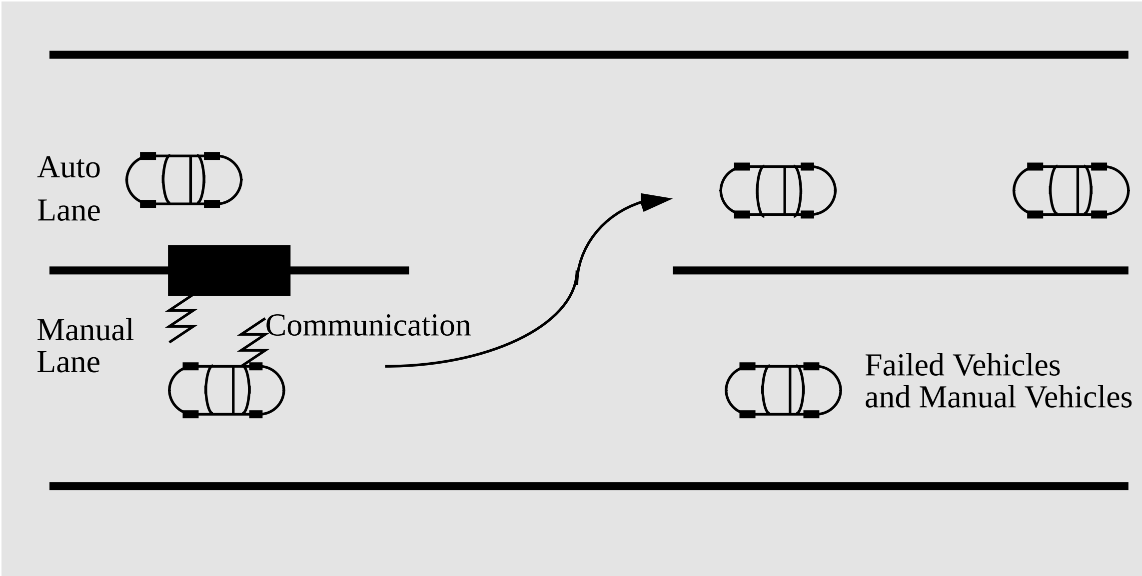

Figure 7: Designated Check-in without a Dedicated Ramp, Check-in Scenario II

Driver Functions: The driver guides the vehicle through the designated opening into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane, and assumes longitudinal control of the vehicle. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information.
Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the designated opening, the roadway provides headway and speed recommendations, and traffic information to the vehicles. Also, toll paying and outstanding ticket checking can be accomplished at the designated entry point.

Continuous Check-in

Check-in Scenario I

This scenario is the closest to current driving situation where the driver is responsible for verification of component status. Figure 8 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

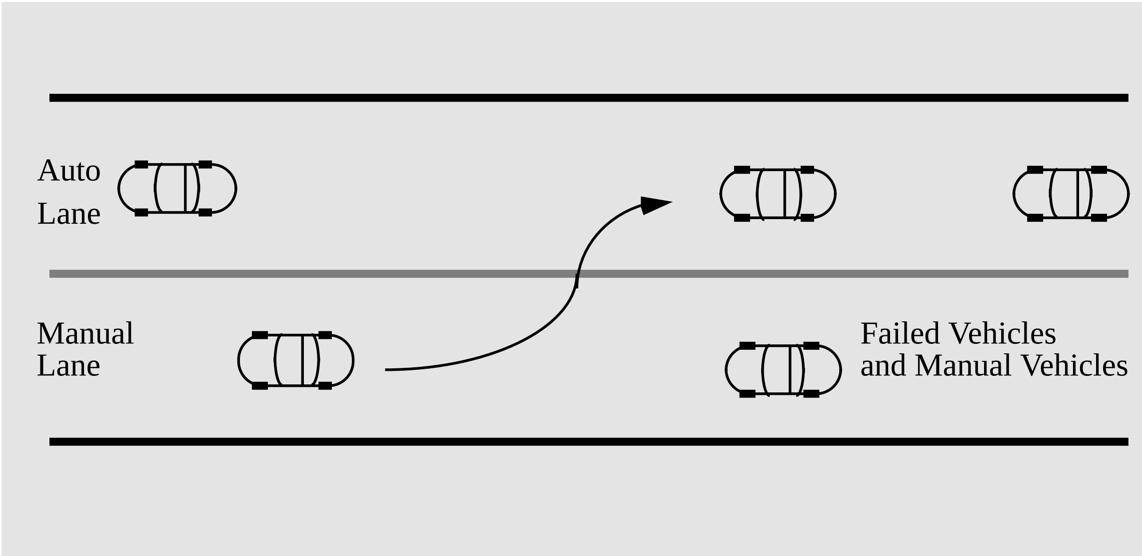

Figure 8: Continuous Check-in, Check-in Scenario I

Driver Functions: The driver guides the vehicle into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.
***Vehicle Functions*:** The vehicle has all diagnostics on board to enable it verify fitness of the vehicle. Any malfunction is brought to the driver's attention. Once in the automated lane, the vehicle may establish communication with the preceding and following vehicles in order to transmit and receive braking level signals. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information.
Roadway Functions: The roadway provides headway and speed recommendations, and traffic information to the vehicles.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 9 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

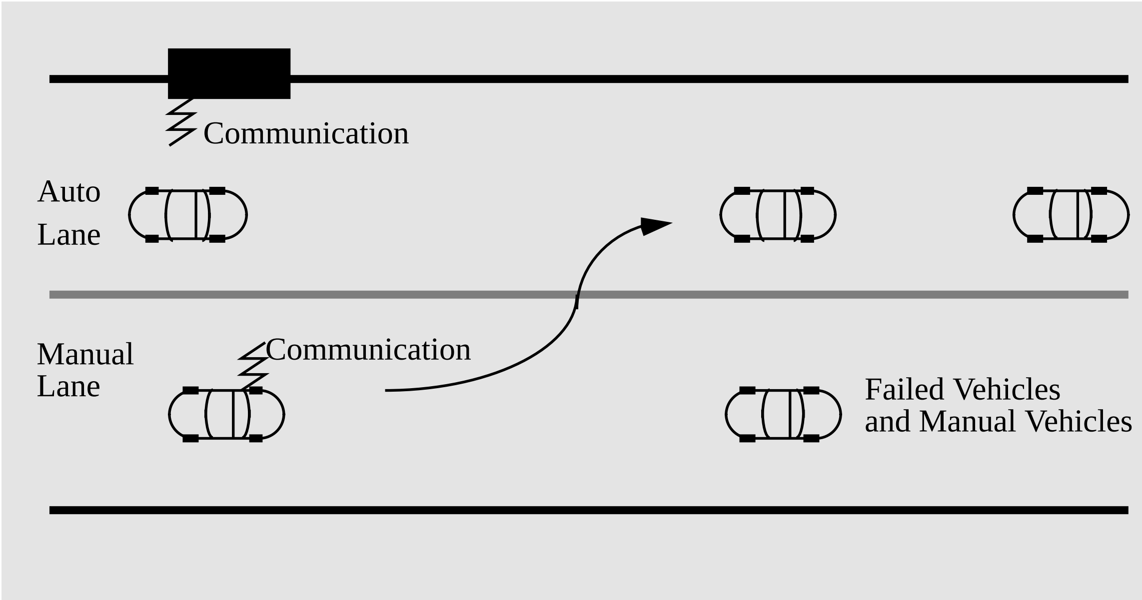

Figure 9: Continuous Check-in, Check-in Scenario II

Driver Functions: The driver guides the vehicle into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane, and assumes longitudinal control of the vehicle. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information.
Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. The roadway provides headway and speed recommendations, and traffic information to the vehicles. Also, toll paying and outstanding ticket checking can be accomplished before entry.

Check-in Testing Procedures

In this subsection, we will discuss the actual testing procedures for the various vehicle components identified in table .1. We believe that the check-in tests will have to be predominantly in the form of on-board diagnostics and self tests. We will also briefly discuss alternative on-site testing procedures, but these kinds of tests are not emphasized because they may create disturbance on smooth and safe operations, may be time consuming, and are not transparent to the user. Figure 10 shows a conceptual diagram of the AHS vehicle components at this level of ERSC. Various components discussed in table .1 are identified on this diagram. The check-in tests should cover all these components, and all the paths between the components.
As discussed earlier, check-in tests are classified into four groups. For the scenario described above, these testing categories are discussed in the following.

1. ***Initial Testing and Certification:*** For ERSC1, automated features are expected to be manufactured independent of AHS, and this type of testing would just involve certification at

the factory. If the vehicle is retrofitted with automated features, initial testing and certification would be performed at the retrofit garage.

2. ***Periodic Off-site Testing:*** Due to the current “low maintenance vehicle” trends in the automotive industry, no additional periodic testing beyond the normal maintenance procedures is expected to be needed at this level of ERSC.

3. ***On-board Built-in Diagnostic Tests:*** Since most of the automated components on the vehicles are expected to be developed independent of AHS at ERSC1, all these components are expected to have on-board self tests and diagnostics for continuously monitoring their fitness. These diagnostics should include testing of the following components described below:
   Speed Sensor:
   Since the ABS systems perform extensive diagnostics of the wheel speed sensor, the diagnostic tests currently used will be utilized. The vehicle speed is computed from the wheel speed in software. Since vehicle speed is not a crucial variable in control algorithms, using the existing speed sensors is expected to yield satisfactory results. If the achievable accuracy of the existing speed sensors is determined to be insufficient, additional methods of velocity sensing can be used.

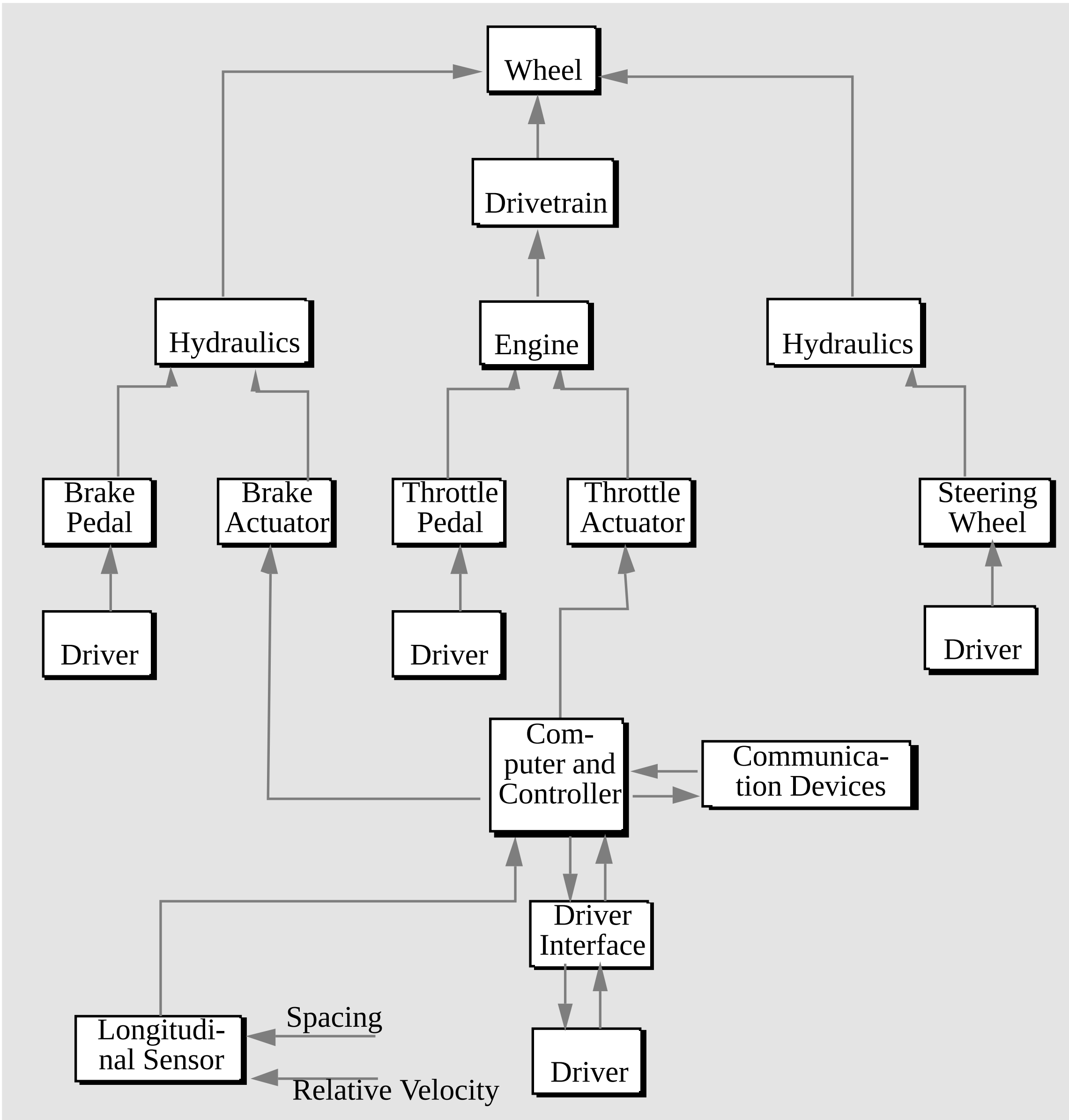

Figure 10: Conceptual Diagram of the AHS Vehicle for ERSC1

Longitudinal (Headway and Relative Velocity) Sensor(s):
A loop-back test can be performed to test the longitudinal sensor. For the example of a longitudinal sensor using radar technology, this can be accomplished by injecting a signal at the antenna input (perhaps on a second pulsed carrier signal to distinguish it from a signal coming from an actual target) emulating an imaginary target, and checking the sensor output. In fact, this test will probably be closely related to the built-in sensor diagnostic test and calibration procedure. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers. The only path this test would not be able to test is the path from the actual gap to the signal generated by the antenna (see the shaded area in figure 11). An antenna misalignment, for example, could not be detected directly by such a test. To deal with this issue, consistency checks on the antenna outputs could be performed. This would involve comparing the antenna output with the output

of a vehicle model. If the antenna signal falls outside the expected values indicated by the model, a malfunction would be indicated. Also, a sensor in front of (or around) the antenna could be used to indicate a body damage that would cause misalignment. Designing the longitudinal control system to be robust with respect to antenna misalignments and enclosing the antenna within a plastic cover as in aircraft radars may be other design options. Since the driver is considered to be a backup controller at this ERSC, such solutions to the problem of testing the path from the actual measurement variable to the signal generated by the antenna are acceptable. These arguments apply, mutatis mutandis, to other candidate longitudinal sensor technologies.

Since the driver is considered to be a backup controller at this ERSC, the reliability improvement gained by redundant sensor system design can probably not justify the associated additional cost. If there is hardware redundancy, however, a complete sensor test can be accomplished as an on-board diagnostic and self test. Each redundant path would produce some outputs and the results would be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously whenever there is a vehicle in the sensor's range.

Brakes:

At this level of ERSC, the brakes are actuated only in cases where throttle control is not sufficient to achieve desired decelerations. The driver is responsible for emergency braking, including the situation where the automated brake actuation function fails. Current diagnostic tests check the components involved in manual braking. Additionally, since automatic longitudinal control is expected to be introduced independent of AHS, some diagnostic tests for automated braking functions are expected to be already in place. The ultimate responsibility to take control over via manual braking capabilities is on the driver, therefore no additional testing of the automated braking components are recommended to be tested. Although it seems unlikely, if on-board diagnostics and self tests of automated components of brake actuation are determined to be required for ERSC1, this could be achieved with some modifications in the brake system design. These design modifications will be elaborated on in the sections where we will discuss higher levels of ERSCs.

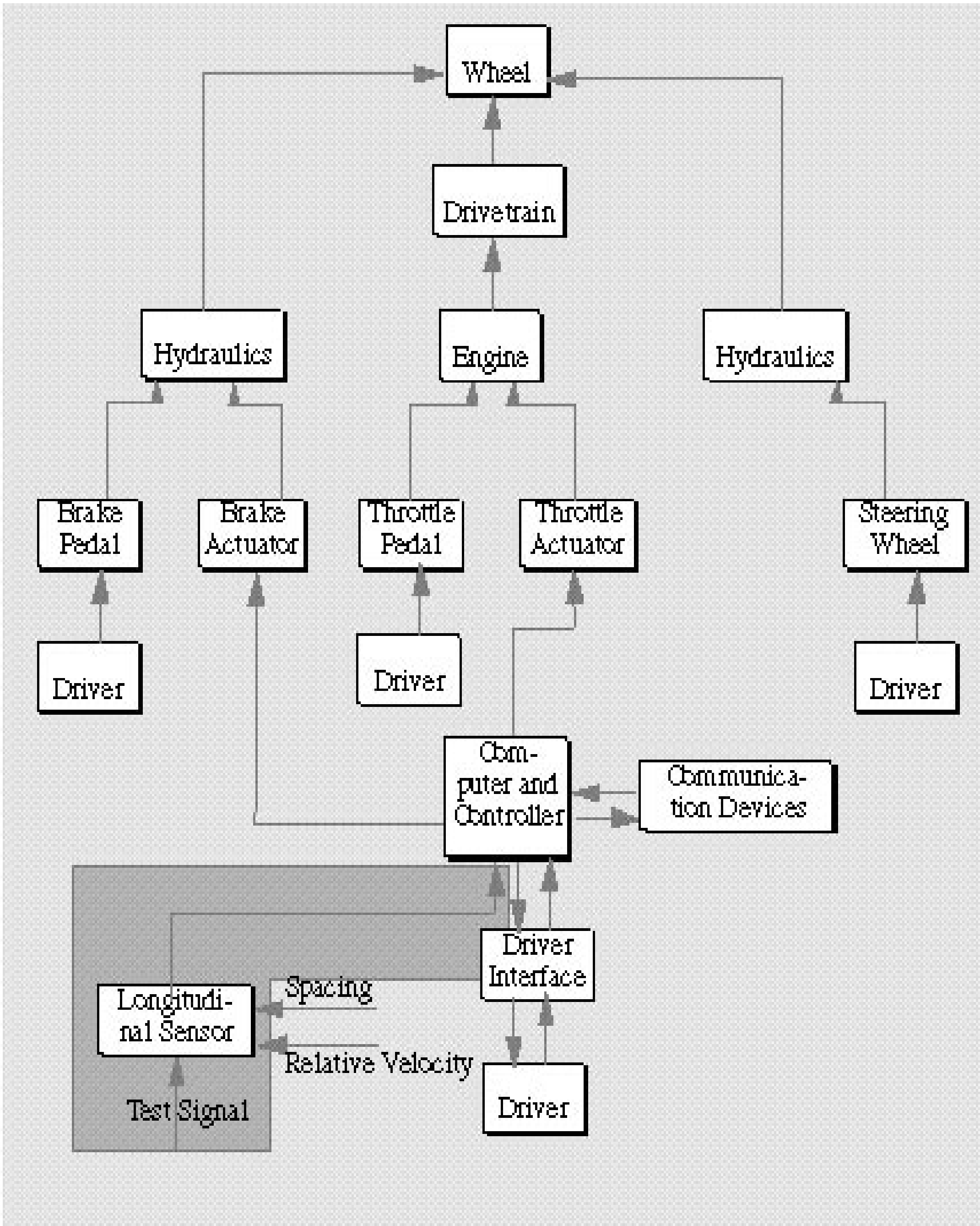

Figure 11: Loop-Back Test Coverage Area for Longitudinal (Headway and Relative Velocity) Sensor for ERSC1

Throttle:
At this level of ERSC, the driver is responsible for taking over the longitudinal control of the vehicle in situations where the automated throttle actuation function fails. Current diagnostic tests check the components involved in manual throttle operations. Additionally, since automatic longitudinal control is expected to be introduced independent of AHS, some diagnostic tests for automated throttle functions are expected to be already in place. The

ultimate responsibility to take control over via manual throttle capabilities is on the driver, therefore no additional testing of the automated throttle actuation components are recommended to be tested.

Although it seems unlikely, if on-board diagnostics and self tests of automated components of throttle actuation are determined to be required for ERSC1, this could be achieved with some modifications in the throttle system design. These design modifications will be elaborated on in the sections where we will discuss higher levels of ERSCs.

Controller:

Controller tests can be performed as a software diagnostic test. This test could be performed via consistency checks on the outputs using known input sets, and validated vehicle models.

Blind-spot Sensor(s):

A loop-back test similar to the one discussed for the longitudinal sensor can be used for testing purposes.

If there is hardware redundancy, in spite of unjustified cost at this ERSC, a complete sensor test can be accomplished as an on-board diagnostics and self test. Each redundant path would detect objects in their field of view independently and the results would be compared for consistency. This procedure can be performed continuously whenever there is a vehicle in the sensor's view.

Other Vehicle Functions:

Tire pressure and condition, brake pad condition, engine temperature, pressure and level of critical fluids (engine oil, brake fluid, fuel, etc.), lights, horn, wipers, etc., can be tested as an on-board diagnostic and self test. Most of these tests are either already available (e.g. Engine Control Management System) or the technology to implement them is already developed.

- Tire Pressure: Can be monitored via on-board diagnostics equipment.
- Brake Pad Condition: Brake pad thickness measurement may be included to increase the reliability of the system.
- Engine Temperature: Currently available diagnostics will be sufficient.
- Pressure And Level Of Critical Fluids: Currently available diagnostics will be sufficient.
- Headlights and Wipers: Currently available diagnostics will be sufficient.
- Turn Signals: Currently available diagnostics will be sufficient.
- Emergency Flashers: Currently available diagnostics will be sufficient.

System-Level Testing of the Vehicle:

The vehicle functions can also be monitored for fitness using a validated vehicle model. This would involve comparing the actual vehicle output (e.g. speed) for a given input (e.g. brake or throttle actuation) with the output of a vehicle model implemented in the software for the same inputs (Figure 12). Such validated vehicle models are generated as part of the vehicle design process, and hence are easily available.

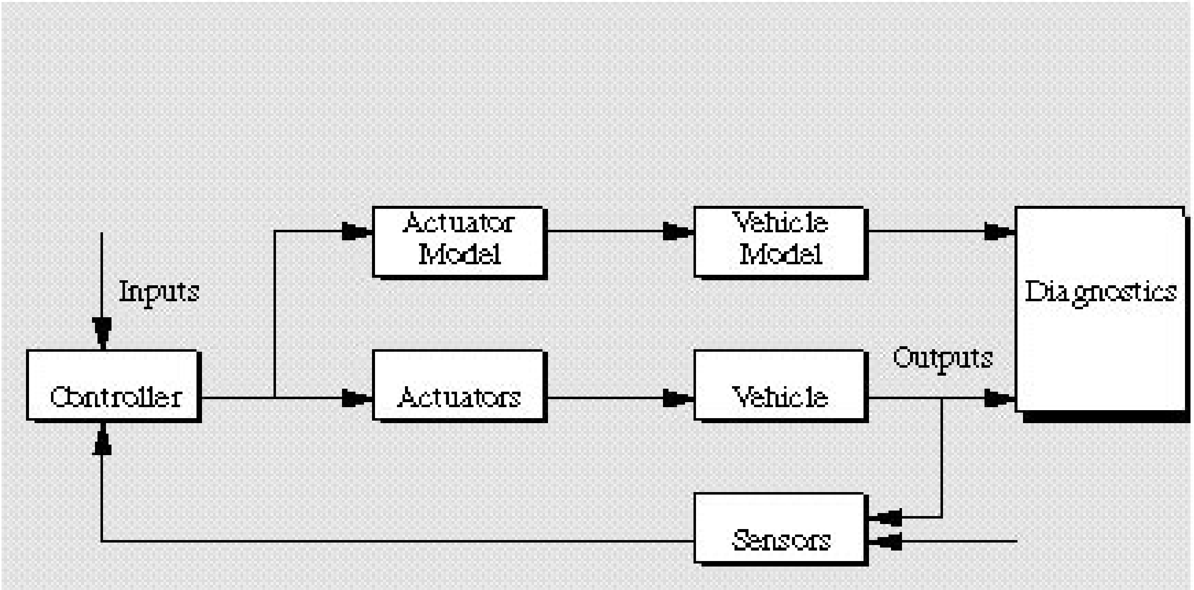

Figure 12: Software Diagnostic Test for the Controller

Vehicle-Roadway Communication:
The vehicle-roadway communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. The communication link will then operate under continuous error checking to ensure non-faulty communication.
Driver Interface:
The driver interface is expected to be developed mostly independent of AHS, and it is expected to have built-in diagnostics and tests accomplished via testing signals at various locations of the diagnostic system. Depending on the display technology used, resistance measurements may be used to detect faulty displays. Alternatively, the operator can check the displays at power-on. Audio signals may be redundant to displays for critical information. The controls can be designed to have redundant paths and contacts, and audio and/or visual feedback signals, so that the driver can monitor the operational status of controls.

4. ***On-site Testing at Check-in Point:***
Because the system is continuously tested by on-board diagnostics, on-site check-in tests are not expected to be needed at ERSC1, with the exception of testing the communications. Nevertheless, on-site testing is an alternative to on-board diagnostics, albeit a time consuming and hence disruptive one. We briefly discuss alternative on-site test procedures below for the sake of completeness.
Longitudinal Sensor(s):
The longitudinal sensor could also be tested via calibration checks at the check-in points. When the vehicle is at a predetermined position at the entry point, the on-board computer will instruct the sensor(s) to measure the distance from the vehicle to the stationary test target. If the sensor is designed such that it can pick up signals emitted from a source imbedded into the highway surface, this source can be used as a test target. The relative velocity measurement could be verified via the vehicle speedometer. This procedure, however, will require roadway modifications. Therefore, it is not recommended.
Brakes:

The brake path can be tested on-site. This test would require the driver to perform a standard braking maneuver just before the entry point. The resulting velocity profile would then be required to lie in a certain region. If maximum braking capability needs to be determined, a more desirable, but still somewhat disturbing to the passengers, procedure would be to apply the brakes to the wheels until they lock up. When ABS kicks in, maximum braking capability for that wheel has been reached, and the brakes can be released. This procedure, however, will still be disturbing and time consuming, and is not recommended.

Throttle:

The throttle path can be tested on-site. This test would require the driver to perform a standard acceleration maneuver The resulting velocity profile would then be required to lie in a certain region. This procedure, however, will be time consuming and may disturb traffic flow.

Blind-spot Sensor(s):

The blind-spot sensor(s) could be tested on-site. This procedure, however, will require installation of special stationary test targets and a procedure to be followed at pre-defined entrance locations. This kind of testing is unnecessary since on-board built-in diagnostic testing can be used as discussed above. Therefore the details of such an approach will not be discussed here.

Vehicle-Roadway Communication:

If communication is not established by the time on-site tests begin, these tests will be part of the on-site testing procedure.

Vehicle-to-vehicle Communication:

The vehicle-to-vehicle communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. If the link is not established by the time the vehicle reaches the entry point, the communication will be established either on-site or in the automated lane.

System-Level Tests:

As discussed earlier, system-level tests can be performed continuously as built-in diagnostic tests. System-level tests can also be performed as on-site tests by briefly activating automatic control, while the driver is alerted to be ready to manually override. This procedure, however, is complicated and therefore not recommended.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

Table 2 summarizes the criticality and practicality of performing each type of test for each function. The criticality measure indicates how crucial that particular test is. In this table, “essential” means the test is crucial to safe and reliable operation of the system, and failure to test may lead to serious accidents; “required” means the test is required in order to guarantee smooth operation providing the expected performance benefits; and “desired” means it would be nice if the test could be performed to provide additional system reliability, but the lack of such a test would not by itself indicate serious reliability problems. To decide whether the test designated as “desired” should be performed, another measure is devised that designates the practicality of the test. If a particular test is practical (i.e. cost and time efficient, transparent and undisturbing to the users and traffic flow, etc.), and the test is designated as being desired, then we may recommend the test to be performed.

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within couple of seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as “essential” or “required”, the test is also determined to be practical (see table 2).

Human Factors Issues:

There are various studies and guidelines for the operator interface. (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous, or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue, and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

Table 2: Criticality and Practicality of Check-in Test Categories for Each Function for ERSC1 (essential - required - desired; practical - not practical)

FUNCTION TO BE TESTED	Initial Testing and Certification	Periodic Off-site Testing	On-board Built-in Diagnostic Tests	On-site Testing
Speed and Headway Maintenance	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Rear-end Collision Warning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Blind Spot Warning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Receive Speed, Headway, and Traffic Information from Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Vehicle to Roadway Communication (option)	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Driver Interface	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Other Vehicle Functions	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
System-Level Vehicle Testing	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical

User acceptance is an important human factors issue [15,16] . Since many functions at this ERSC are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. Since the driver is responsible for emergencies and lateral control at this level of ERSC, most of the liability is still with the driver. Law enforcement efforts may be needed to ensure compliance for the scenarios where the driver is responsible for the fitness of the vehicle and himself/herself. Automation could help the law enforcement by identifying unauthorized vehicles in the dedicated lane.

Another major issue for implementation of AHS is dedicating a lane to AHS operations. Construction of a new lane will be costly, and taking away an existing lane from manual traffic may provoke major political turbulence [18,19] . It may therefore be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions at this ERSC are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software, and working out details of dedicating a lane will be major activities required. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:
There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles at ERSC1 beyond the ones discussed above.

Key Findings

- Since the driver is ultimately responsible for the overall control of the vehicle at ERSC1, check-in testing of automated equipment is not essential, and on-board built-in diagnostic testing procedures are required primarily for efficient and reliable operation.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

Evolutionary Representative System Configuration Two (ERSC2)

In this ERSC, full longitudinal collision avoidance providing emergency braking is introduced. Also, there is more communication between the vehicles to allow transmission of braking, velocity, and acceleration profiles and capabilities. Steering assist/stability augmentation and lane departure warnings are added to help the driver in lateral control.

Vehicle and Driver Functions to Be Tested for Check-in

The functions needed to be tested for ERSC2, and the required components for each function are shown in table 3.

Specific testing procedures for these components will be discussed in the following subsections. Before analyzing the test procedures, however, we will describe alternative scenarios for each entry/exit configuration.

Designated Check-in with a Dedicated Ramp

Check-in Scenario I

This scenario is the closest to current driving situation where the driver is responsible for verification of component status. Figure 3 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the ramp into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

***Vehicle Functions*:** The vehicle has all diagnostics on board to enable it to verify the fitness of the vehicle. Any malfunction is brought to the driver's attention. Once in the automated lane, the vehicle will establish communication with the preceding and following vehicles in order to transmit and receive braking, velocity, and acceleration profiles and capabilities. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle using the headway and speed information received from the vehicles. Also, toll paying and outstanding ticket checking may be accomplished on the ramp.

Table 3: Functions to Be Tested at Check-in for ERSC2

FUNCTION TO BE TESTED	REQUIRED COMPONENTS
Speed and Headway Maintenance	Sensors: Speed sensor; headway and relative speed sensor Actuators: Brake; throttle Computer control system
Rear-end Collision Avoidance	Sensors: Speed sensor; headway and relative speed sensor Vehicle-vehicle communication Actuators: Brake; throttle Computer control system
Blind Spot Warning	Sensors: Blind spot detection sensor
Receive Speed, Headway, and Traffic Information from Roadway	Roadway-vehicle communication devices
Driver Interface	Driver interface controls and displays
Transmit Vehicle Status and Speed to Roadway	Vehicle-roadway communication devices
Lane Departure Warning	Sensors: Lane detection sensor
Steering Assist	Sensors: Lane detection sensor Actuators: Steering Controller
Other Vehicle Functions	Critical fluids level and pressure, engine temperature, brake pad condition, tire pressure and condition, wipers, headlights, etc.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 4 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the ramp into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into the automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying and outstanding ticket checking may be accomplished on the ramp.

Check-in Scenario III

In this scenario, a gate is used to allow vehicles determined to be fit into the automated lane. Figure 5 illustrates this scenario conceptually.

Driver Functions: The driver guides the vehicle to the ramp, and into the automated lane if the vehicle is determined to be fit for automated operation causing the gate to be opened. The driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. The vehicle establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. The roadway opens the gate if the vehicle is determined to be fit to operate in the automated lane. Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying and outstanding ticket checking may be accomplished on the ramp.

Designated Check-in without a Dedicated Ramp

Check-in Scenario I

This scenario is the closest to current driving situation where the driver is responsible for verification of component status. Figure 6 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the designated opening into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.

***Vehicle Functions*:** The vehicle has all the diagnostics on board to enable it to verify the fitness of the vehicle. Any malfunction is brought to the driver's attention. Once in the automated lane, the vehicle establishes communication with the preceding and following vehicles in order to transmit and receive braking level signals. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 7 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the designated opening into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to control the vehicle manually in the manual lane.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. Also, toll paying and outstanding ticket checking can be accomplished at the designated entry point.

Continuous Check-in

Check-in Scenario I

This scenario is the closest to current driving situation where the driver is responsible for verification of component status. Figure 8 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle into the automated lane. The driver is responsible for the fitness of the vehicle and himself/herself, and for switching on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.

***Vehicle Functions*:** The vehicle has all diagnostics on board to enable it verify fitness of the vehicle. Any malfunction is brought to the driver’s attention. Once in the automated lane, the vehicle establishes communication with the preceding and following vehicles in order to transmit and receive braking level signals. Additionally, the vehicle establishes communication with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. Figure 9 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle into the automated lane. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues to manually control the vehicle in the manual lane.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane departure warning, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles.

Check-in Testing Procedures:

In this subsection, we will discuss the actual testing procedures for the various vehicle components identified in table 3. We believe that the check-in tests will have to be predominantly in the form of on-board diagnostics and self tests. We will also briefly discuss alternative on-site testing procedures, but these kinds of tests are not emphasized because they may disturb smooth and safe operations, may be time consuming, and are not transparent to the user. Figure 13 shows a conceptual diagram of the AHS vehicle components at this level of ERSC. Various components discussed in table 3 are identified on this diagram. The check-in tests should cover all these components, and all the paths between the components.

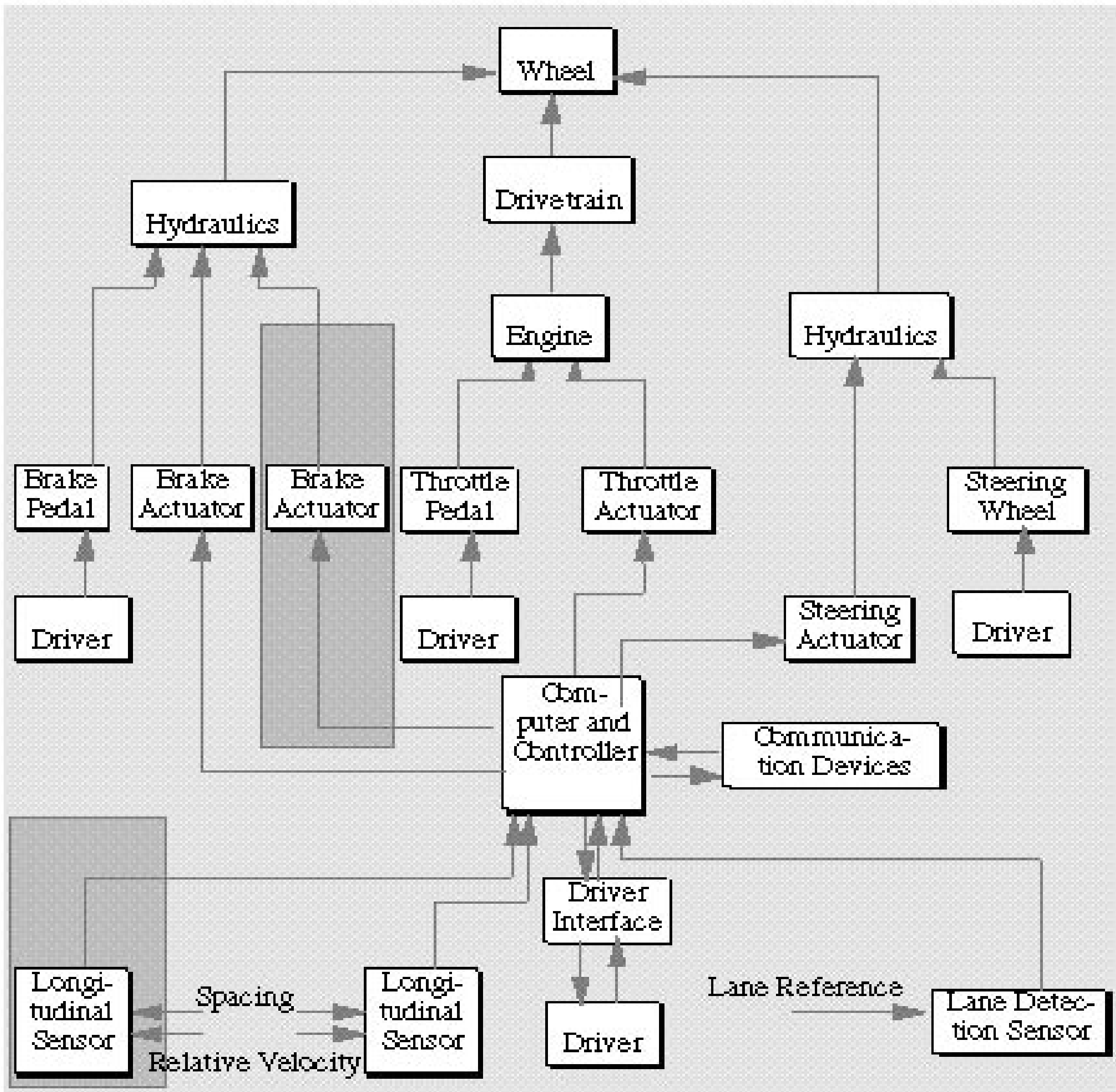

Figure 13: Conceptual Diagram of the AHS Vehicle for ERSC2 (hatched rectangles indicate redundant components, the computer has built-in redundancy)

As discussed earlier, check-in tests are classified into four groups. For the scenario described above, these testing categories are discussed in the following.

1. ***Initial Testing and Certification:*** For ERSC2, many automated features are expected to be manufactured independent of AHS, and this type of testing would involve certification at the factory. If the vehicle is retrofitted with automated features, initial testing and certification would be performed at the retrofit garage.
2. ***Periodic Off-site Testing:*** Due to the current “low maintenance vehicle” trends in the automotive industry, no additional periodic testing beyond the normal maintenance procedures is expected to be needed for ERSC2.
3. ***On-board Built-in Diagnostic Tests:*** Since most of the automated components on the vehicles are expected to be developed independent of AHS at ERSC2, all these components are expected to have on-board self tests and diagnostics for continuously monitoring their

fitness. Additionally, the vehicle computer must have software to test the system as a whole, verifying its fitness via comparison with an internal simulator model of the vehicle. The diagnostics should include testing of the following components described below:

Speed Sensor:

Since the ABS systems perform extensive diagnostics of the wheel speed sensor, the diagnostic tests currently used will be utilized. The vehicle speed is computed from the wheel speed in software. Since vehicle speed is not a crucial variable in control algorithms, using the existing speed sensors is expected to yield satisfactory results. If the achievable accuracy of the existing speed sensors is determined to be insufficient, additional methods of velocity sensing can be used.

Longitudinal (Headway and Relative Velocity) Sensor(s):

Since we introduce full longitudinal collision avoidance at this ERSC, the vehicle spacing could be made much smaller compared to ERSC1 in order to obtain higher capacity. This would mean that we no longer can rely on the driver as a backup controller, simply because the human delay will make it impossible at these headway values for the operator to interfere in case of system failure. The reliability functional requirement imposed on the control system is that, under no circumstances, a single-point failure will cause a catastrophic system failure. Hence, double (or even triple) redundancy is absolutely necessary for a fail-safe design. This situation is depicted in figure 13 for the longitudinal sensor and the brake actuator.

Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs and the results would simply be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously whenever there is a vehicle in the sensor’s range. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Additionally, a loop-back test similar to the one discussed for ERSC1 can be performed to test the longitudinal sensor. For the example of a longitudinal sensor using radar technology, this can be accomplished by injecting a signal at the antenna input (perhaps on a second pulsed carrier signal to distinguish it from a signal coming from an actual target) emulating an imaginary target, and checking the sensor output. In fact, this test will probably be closely related to the built-in sensor diagnostic test and calibration procedure.

Once the vehicle is in the dedicated lane, vehicle-to-vehicle communications will provide an additional redundant path since braking, velocity, and acceleration profiles are communicated between vehicles.

Brakes:

To perform the on-board built-in diagnostic brake tests, some modifications in the brake system design are indicated, since most of the current brake actuators designed to be used with automatic longitudinal control are not activated in manual driving mode. As soon as the brake actuator becomes part of the manual braking loop, the brake loop test can be accomplished as an on-board built-in diagnostic test. This would mean that the driver commands will activate the brake actuator, as shown in figure 14 (a) (ABS mechanism is not included in this diagram). Although most current brake systems are like the one shown in figure 14 (b), the technology for the type shown in figure 14 (a) of a system is currently available. The test can be accomplished anytime the driver brakes. Actuation of the brake pedal will send a signal to the brake actuator, which in turn will increase the brake line pressure, and the vehicle will decelerate. Using the speed sensor, the deceleration can be estimated. This deceleration will then be compared with the deceleration expected due to the brake line pressure observed. Due to the condition of the brake pads, weather, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the brake system performance might be deteriorating. If the problem is not taken care of, the braking performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the brake pedal to the brake line pressure needs to be checked to determine if the brake line pressure buildup correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range of the braking system will have to be better than a predetermined standard as required by the control system designers.

As discussed earlier, safety considerations mandate redundancy in the longitudinal control system due to the introduction of longitudinal collision avoidance. Therefore, we need to test all redundant paths of brake actuation. This could be achieved by a design modification where both actuators are activated when the brake is activated either by the driver or by the longitudinal control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing braking performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC1 is activated.

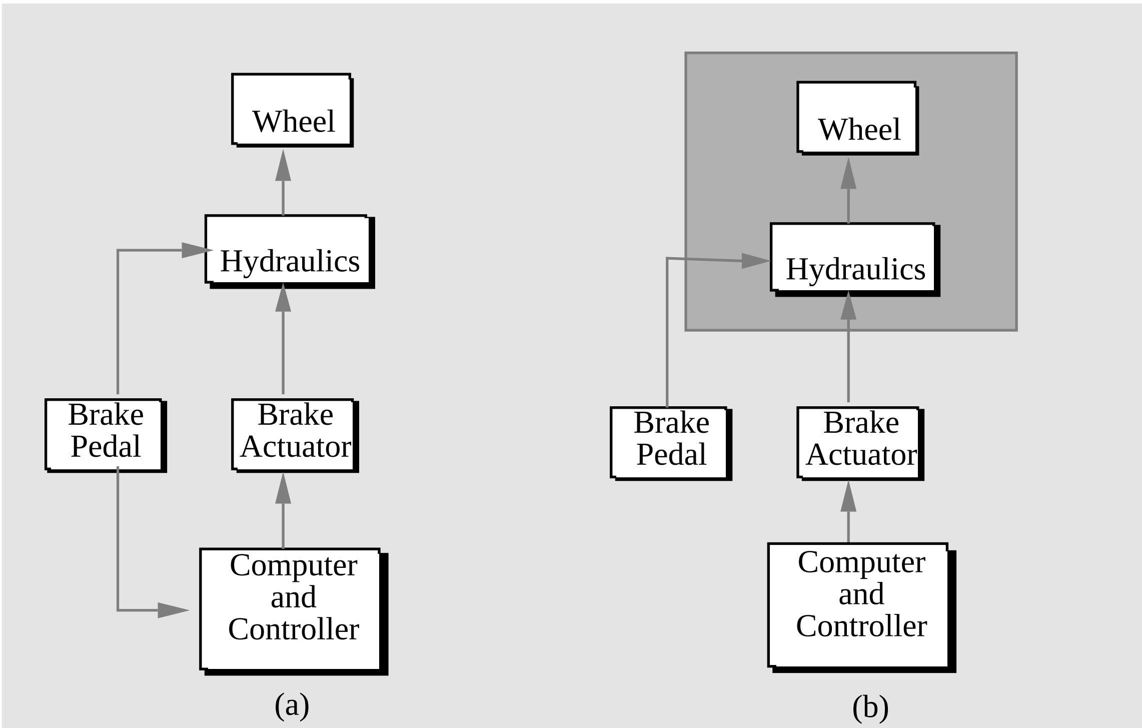

Figure 14: Two Types of Brake Systems: (a) Brake Pedal Actuates the Brake Actuator; (b) Brake Pedal Actuates the Hydraulics (current systems). (The booster mechanism is considered to be part of the hydraulics.)

A test to determine the coefficient of friction at the tire-road interface could be used to enable prediction of deceleration values. These kinds of tests are currently available [20,21,22,23] .

Throttle:

The throttle tests are conceptually very similar to the brake tests discussed above. The throttle path can be tested continuously in manual driving mode if the throttle actuator is involved in manual throttle operation (see the discussion for the brake testing procedure above). The test can be accomplished any time the driver steps on the accelerator. Actuation of the pedal will send a signal to the throttle actuator, which in turn will increase the throttle angle, and the vehicle will accelerate. Using the speed sensor, the acceleration can be estimated. This acceleration will then be compared with the acceleration expected due to the throttle angle observed. Due to the condition of the drivetrain, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the throttle system performance might be deteriorating. If the problem is not taken care of, the acceleration performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the accelerator pedal to the throttle angle needs to be checked to determine if the observed throttle angle correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Controller:

Controller tests can be performed as a software diagnostic test. This test could be performed via consistency checks on the redundant outputs.

Blind Spot Warning Sensor(s):

A loop-back test similar to the one discussed for the longitudinal sensor can be used for testing purposes.

If there is hardware redundancy, in spite of unjustified cost at this ERSC, a complete sensor test can be accomplished as an on-board diagnostic and self test. Each redundant path would detect objects in their field of view independently, and the results would be compared for consistency. This procedure can be performed continuously whenever there is a vehicle in the sensor's view.

Other Vehicle Functions:

Tire pressure and condition, brake pad condition, engine temperature, pressure and level of critical fluids (engine oil, brake fluid, fuel, etc.), lights, horn, wipers, etc., can be tested as an on-board diagnostic and self test. Most of these tests are either already available (e.g. Engine Control Management System) or the technology to implement them is already developed.

- Tire Pressure: Can be monitored via on-board diagnostics equipment.
- Brake Pad Condition: Brake pad thickness measurement may be included to increase the reliability of the system.
- Engine Temperature: Currently available diagnostics will be sufficient.
- Pressure And Level Of Critical Fluids: Currently available diagnostics will be sufficient.
- Headlights and Wipers: Currently available diagnostics will be sufficient.
- Turn Signals: Currently available diagnostics will be sufficient.
- Emergency Flashers: Currently available diagnostics will be sufficient.

System-Level Testing of the Vehicle:

The system-level interactions of vehicle functions must also be monitored to verify the correct response and fitness of the overall system using a validated vehicle simulation model residing as software in the vehicle computer. This would involve comparing the actual vehicle output (e.g. speed) for a given input (e.g. brake, throttle, or steering actuation) with the output of the vehicle model implemented in the software for the same inputs (Figure 15). Such validated vehicle models are generated as part of the vehicle design process, and hence are easily available.

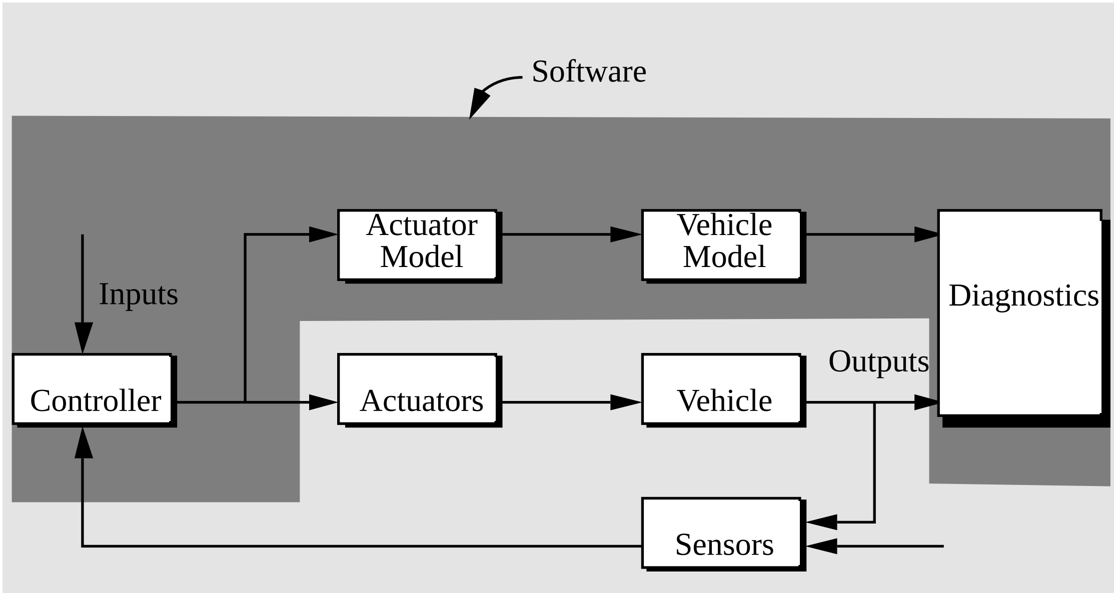

Figure 15: Software Diagnostic for the Controller

Vehicle-Roadway Communication:
The vehicle-roadway communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. The communication link will then operate under continuous error checking to ensure non-faulty communication.
Driver Interface:
The driver interface is expected to be developed mostly independent of AHS, and it is expected to have built-in diagnostics and tests accomplished via testing signals at various locations of the diagnostic system. Depending on the display technology used, resistance measurements may be used to detect faulty displays. Alternatively, the operator can check the displays at power-on. Audio signals may be redundant to displays for critical information. The controls can be designed to have redundant paths and contacts, and audio and/or visual feedback signals, so that the driver can monitor the operational status of controls.
Lane Detection Sensor(s):
If there is no redundancy in the sensor, then a loop-back test similar to the one discussed for the longitudinal sensor can be used to as a built-in test. The issues with such a procedure discussed for the longitudinal sensor are also valid for this sensor. If there is redundancy and the manual lane is modified to enable the sensing of its lanes, the test can be accomplished by comparing redundant path outputs.
Steering Actuator:
At this level of ERSC, the steering actuator is used to assist the driver in keeping the vehicle in the lane. The driver is responsible for the steering task, automation only makes it easier for the driver to perform the task. The built-in diagnostic tests for the steering actuator are expected to be sufficient at this level of ERSC.
Although it seems unlikely, if more elaborate on-board diagnostics and self tests of automated components of steering actuation are determined to be required for ERSC2, this could be achieved with some modifications in the steering system design. These design modifications will be elaborated on in the sections where we will discuss higher levels of ERSCs.

4. ***On-site Testing at Check-in Point:***
Because the system is continuously tested by on-board diagnostics, on-site check-in tests are not expected to be needed at ERSC2, with the exception of testing the communications.

Nevertheless, on-site testing is an alternative to on-board diagnostics, albeit a time consuming and hence disruptive one. We briefly discuss alternative on-site test procedures below for the sake of completeness.

Longitudinal Sensor(s):

The longitudinal sensor could also be tested via calibration checks at the designated check-in points. When the vehicle is at a predetermined position, the on-board computer will instruct the sensor(s) to measure the distance from the vehicle to the stationary test target. If the sensor is designed such that it can pick up signals emitted from a source imbedded into the highway surface, this source can be used as a test target. The relative velocity measurement could be verified via the vehicle speedometer. This procedure, however, will require roadway modifications. Therefore, it is not recommended.

Brakes:

The brake paths can be tested on-site. This test would require the driver to perform a standard braking maneuver before the entry point. The resulting velocity profile would then be required to lie in a certain region. If maximum braking capability needs to be determined, a more desirable, but still somewhat disturbing to the passengers, procedure would be to apply the brakes to the wheels until they lock up. When ABS kicks in, maximum braking capability for that wheel has been reached, and the brakes can be released. This procedure, however, will still be disturbing and time consuming, and is not recommended.

Throttle:

The throttle path can be tested on-site. This test would require the driver to perform a standard acceleration maneuver. The resulting velocity profile would then be required to lie in a certain region. This procedure, however, will be time consuming and may disturb traffic flow.

Blind-spot Sensor(s):

The blind-spot sensor(s) could be tested on-site. This procedure, however, will require installation of special stationary test targets and a procedure to be followed at pre-defined entrance locations. This kind of testing is unnecessary since on-board built-in diagnostic testing can be used as discussed above. Therefore the details of such an approach will not be discussed here.

Vehicle-Roadway Communication:

If communication is not established by the time on-site tests begin, these tests will be part of the on-site testing procedure.

Vehicle-to-vehicle Communication:

The vehicle-to-vehicle communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. If the link is not established by the time the vehicle reaches the entry point, the communication will be established either on-site or in the automated lane.

System-Level Tests:

As discussed earlier, system-level tests can be performed continuously as built-in diagnostic tests. System-level tests can also be performed as on-site tests by briefly activating automatic control, while the driver is alerted to be ready to manually override. This procedure, however, is complicated and therefore not recommended.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

Table 4 summarizes the criticality and practicality of performing each type of test for each function. The criticality measure indicates how crucial that particular test is. In this table, “essential” means the test is crucial to safe and reliable operation of the system, and failure to test may lead to serious accidents; “required” means the test is required in order to guarantee a smooth operation providing the expected performance benefits; and “desired” means it would be nice if the test could be performed to provide additional system reliability, but the lack of such a test would not by itself indicate serious reliability problems. In order to decide whether the test designated as “desired” should be performed, another measure is devised that designates the practicality of the test. If a particular test is practical (i.e. cost and time efficient, transparent and undisturbing to the users and traffic flow, etc.), and the test is designated as being desired, then we may recommend the test to be performed.

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within a few seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as “essential” or “required”, the test is also determined to be practical (see table 4).

Table 4: Criticality and Practicality of Check-in Test Categories for Each Function for ERSC2 (essential - required - desired; practical - not practical)

FUNCTION TO BE TESTED	Initial Testing and Certification	Periodic Off-site Testing	On-board Built-in Diagnostic Tests	On-site Testing
Speed and Headway Maintenance	Essential/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Rear-end Collision Warning	Essential/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Blind Spot Warning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Receive Speed, Headway, and Traffic Information from Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Driver Interface	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Transmit Vehicle Status and Speed to Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Lane Departure Warning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Steering Assist	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Other Vehicle Functions	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
System-Level Vehicle Testing	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical

Human Factors Issues:

There are various studies and guidelines for the operator interface (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous, or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue, and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

User acceptance is an important human factors issue [15,16] . Since many functions at this ERSC are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. Since the driver is responsible for lateral control at this level of ERSC, most of the liability is still with the driver.

When the driver is responsible for the fitness of the vehicle and himself/herself, law enforcement efforts may be needed to ensure compliance. Automation could help the law enforcement by identifying unauthorized vehicles in the dedicated lane.

Another major issue for implementation of AHS is dedicating a lane to AHS operations. Construction of a new lane will be costly, and taking away an existing lane from manual traffic may provoke major political turbulence [18,19] . It may therefore be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions at this ERSC are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software will be an activity of major importance. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:

There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles at ERSC2 beyond the ones discussed above.

Key Findings

- For ERSC2, on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical since crucial sensor tests can be performed via consistency checks on the redundant paths introduced to implement longitudinal collision avoidance. Furthermore, the design modifications for the brake system discussed earlier allow on-board built-in diagnostic testing of brakes. Therefore, no on-site tests are expected to be needed.
- Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

Evolutionary Representative System Configuration Three (ERSC3)

In this ERSC, lane keeping is introduced and the blind spot sensor is improved to provide extensive lateral collision warnings. Also, there is maneuver coordination between vehicles via communications.

Vehicle and Driver Functions to Be Tested for Check-in

The functions needed to be tested for ERSC3, and the required components for each function are shown in table 5.
Specific testing procedures for these components will be discussed in the following subsections. Before analyzing the test procedures, however, we will describe alternative scenarios for each entry/exit configuration.

Designated Check-in with a Dedicated Ramp

Check-in Scenario I

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle and the driver guides the vehicle into the automated lane. Figure 4 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:
Driver Functions: The driver guides the vehicle through the ramp into the automated lane with help from the maneuver coordination and lateral collision warning functions. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles, provides lateral collision warnings, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Table 5 : Functions to Be Tested at Check-in for ERSC3

FUNCTION TO BE TESTED	REQUIRED COMPONENTS
Speed and Headway Maintenance	Sensors: Speed sensor; headway and relative speed sensor Actuators: Brake; throttle Computer control system
Rear-end Collision Avoidance	Sensors: Speed sensor; headway and relative speed sensor Vehicle-vehicle communication devices Actuators: Brake; throttle Computer control system
Lateral Collision Warning	Sensors: Blind spot detection sensor
Receive Speed, Headway, and Traffic Information from Roadway	Roadway-vehicle communication devices
Driver Interface	Driver interface controls and displays
Transmit Vehicle Status and Speed to Roadway	Vehicle-roadway communication devices
Maneuver Coordination	Vehicle-vehicle communication devices
Lane Keeping	Sensors: Lane detection and preview sensor Actuators: Steering Computer control system
Other Vehicle Functions	Critical fluids level and pressure, engine temperature, brake pad condition, tire pressure and condition, wipers, headlights, etc.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying, registration status and outstanding ticket checking may be accomplished on the ramp.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle, as a result of which the entry gate opens to allow the vehicle into the automated lane, and the driver guides the vehicle into the automated lane. Figure 5 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the ramp into the automated lane with help from the maneuver coordination and lateral collision warning functions and, provided that the vehicle is verified to be fit, the gate opens. The driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. The vehicle coordinates entry maneuvers with other vehicles, provides lateral collision warnings, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. If check-in tests are passed, the gate is opened to allow the vehicle into the automated lane. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, synchronizing a gap in the automated lane for the entering vehicle, and helping in maneuver coordination. Also, toll paying and outstanding ticket checking may be accomplished on the ramp.

Check-in Scenario III

In this scenario, the lane keeping and maneuver coordination functions are used to guide the vehicle automatically into the automated lane. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle to the ramp, and switches on the automated mode. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver guides the vehicle out of the ramp.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified by the roadway, the vehicle coordinates entry maneuvers with other vehicles, guides itself into the automated lane, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps, and synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying and outstanding ticket and registration status checking may be accomplished on the ramp.

Designated Check-in without a Dedicated Ramp

Check-in Scenario I

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle and the driver guides the vehicle into the automated lane. Figure 7 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle through the designated opening into the automated lane with help from the maneuver coordination and lateral collision warning functions. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into the automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues manual operation in the manual lane.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles, provides lateral collision warnings, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway using communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is synchronizing a gap in the automated lane for the entering vehicle. Also, toll paying and registration status and outstanding ticket checking may be accomplished at the designated entry point.

Check-in Scenario II

In this scenario, the lane keeping and maneuver coordination functions are used to guide the vehicle automatically into the automated lane. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle on the manual lane to the designated opening, and switches on the automated mode. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues manual operations in the manual lanes.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification using a standard protocol. If vehicle fitness is verified by the roadway, the vehicle coordinates entry maneuvers with other vehicles, guides itself into the automated lane, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway using communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles and receives vehicle status and speed information from the vehicles. A possible roadway passive role is to synchronize a gap in the automated lane for the entering vehicle and to help maneuver coordination. Also, toll paying and registration status and outstanding ticket checking may be accomplished at the designated entry point.

Continuous Check-in

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle into the automated lane with help from the maneuver coordination and lateral collision warning functions. The driver is responsible for obeying the roadway signal prohibiting the vehicle to go into automated lane in case of failed check-in tests. If vehicle fitness is verified, the driver switches on the automated mode once the vehicle is in the dedicated lane. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set. If the check-in tests are failed, the driver continues manual operations in the manual lanes.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles, provides lateral collision warnings, and establishes communication with other vehicles in the automated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. A possible roadway passive role is synchronizing a gap in the automated lane for the entering vehicle and helping the maneuver coordination.

Check-in Testing Procedures:

In this subsection, we will discuss the actual testing procedures for the various vehicle components identified in table 5. We believe that the check-in tests will have to be predominantly in the form of on-board diagnostics and self tests. We will also briefly discuss alternative on-site testing procedures, but these kinds of tests are not emphasized because they may disturb traffic flow. Figure 16 shows a conceptual diagram of the AHS vehicle components at this level of ERSC. Various components discussed in table 5 are identified on this diagram. The check-in tests should cover all these components, and all the paths between the components.

As discussed earlier, check-in tests are classified into four groups. For the scenario described above, these testing categories are discussed in the following.

1. ***Initial Testing and Certification:*** For ERSC3, many automated features are expected to be manufactured independent of AHS, and this type of testing would involve certification at the factory. If the vehicle is retrofitted with automated features, initial testing and certification would be performed at the retrofit garage.
2. ***Periodic Off-site Testing:*** Due to the current “low maintenance vehicle” trends in the automotive industry, no additional periodic testing beyond the normal maintenance procedures is expected to be needed for ERSC3.

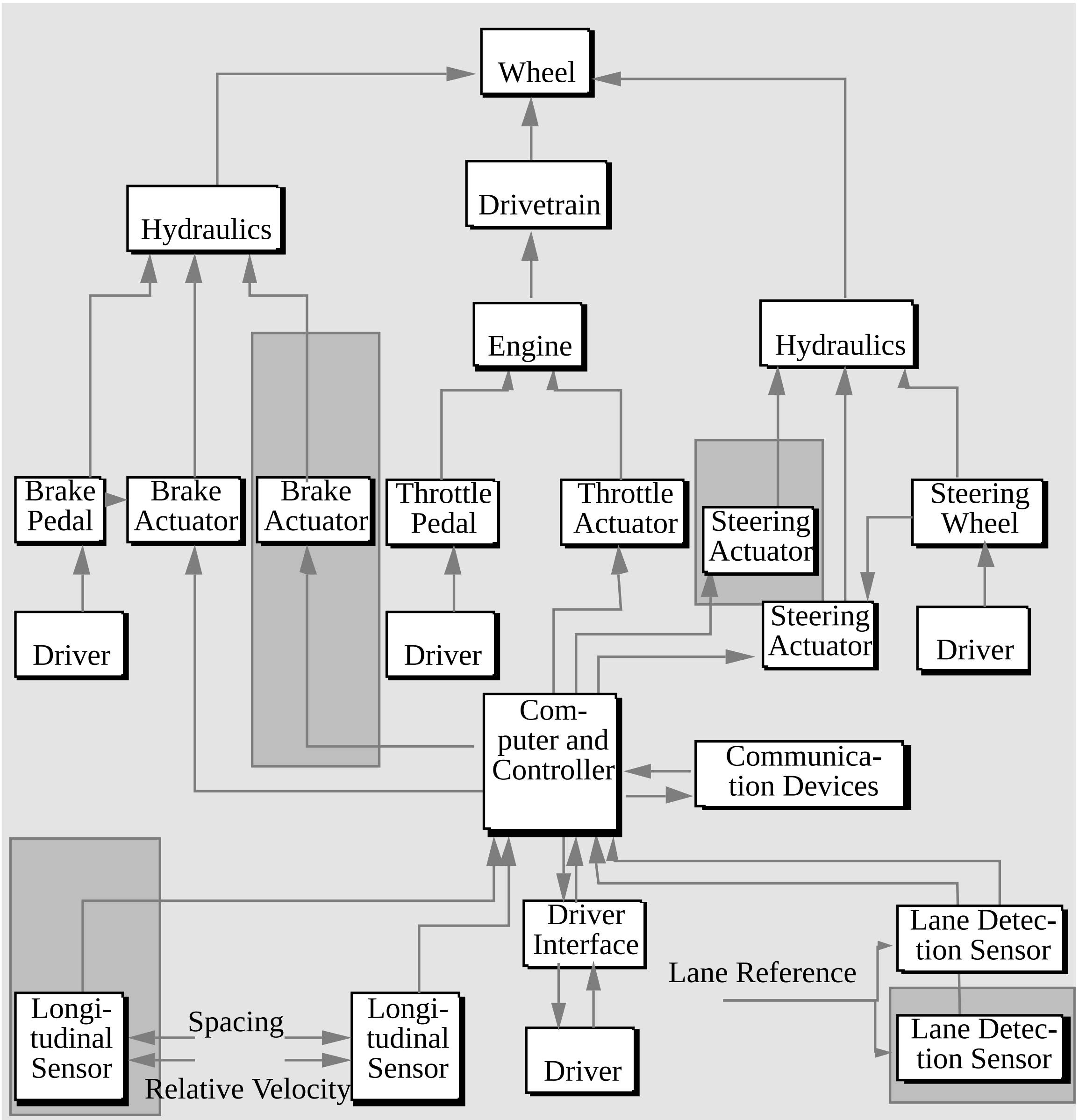

Figure 16: Conceptual Diagram of the AHS Vehicle for ERSC3 (hatched rectangles indicate redundant components, the computer has built-in redundancy)

3. ***On-board Built-in Diagnostic Tests:*** Since many components on the vehicles are expected to be developed independent of AHS at ERSC3, all these components are expected to have on-board self tests and diagnostics for continuously monitoring their fitness. Additionally, the vehicle computer must have software to test the system as a whole, verifying its fitness via comparison with an internal simulator model of the vehicle. The diagnostics should include testing of the following components described below:
   Speed Sensor:
   Since the ABS systems perform extensive diagnostics of the wheel speed sensor, the diagnostic tests currently used will be utilized. The vehicle speed is computed from the wheel speed in software. Since vehicle speed is not a crucial variable in control algorithms, using the existing speed sensors is expected to yield satisfactory results. If the achievable accuracy of the existing speed sensors is determined to be insufficient, additional methods of velocity sensing can be used.

Longitudinal (Headway and Relative Velocity) Sensor(s):
As discussed for ERSC2, we need multiple redundancies in the longitudinal control system. Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs and the results would simply be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously whenever there is a vehicle in the sensor's range. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.
Additionally, a loop-back test similar to the one discussed for ERSC1 can be performed to test the longitudinal sensor. For the example of a longitudinal sensor using radar technology, this can be accomplished by injecting a signal at the antenna input (perhaps on a second pulsed carrier signal to distinguish it from a signal coming from an actual target) emulating an imaginary target, and checking the sensor output. In fact, this test will probably be closely related to the built-in sensor diagnostic test and calibration procedure.
Once the vehicle is in the dedicated lane, vehicle-to-vehicle communications will provide an additional redundant path since braking, velocity, and acceleration profiles are communicated between vehicles.
Brakes:
In order to perform the on-board built-in diagnostic brake tests, some modifications in the brake system design are indicated, since most of the current brake actuators designed to be used with automatic longitudinal control are not activated in manual driving mode. As soon as the brake actuator becomes part of the manual braking loop, the brake loop test can be accomplished as an on-board built-in diagnostic test. This would mean that the driver commands will activate the brake actuator, as shown in figure 14 (a) (ABS mechanism is not included in this diagram). Although most current brake systems are like the one shown in figure 14 (b), the technology for this type of a system is currently available. The test can be accomplished anytime the driver brakes. Actuation of the brake pedal will send a signal to the brake actuator, which in turn will increase the brake line pressure, and the vehicle will decelerate. Using the speed sensor, the deceleration can be estimated. This deceleration will then be compared with the deceleration expected due to the brake line pressure observed. Due to the condition of the brake pads, weather, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the brake system performance might be deteriorating. If the problem is not taken care of, the braking performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the brake pedal to the brake line pressure needs to be checked to determine if the brake line pressure buildup correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range of the braking system will have to be better than a predetermined standard as required by the control system designers.
As discussed earlier, safety considerations mandate redundancy in the longitudinal control system due to the introduction of longitudinal collision avoidance. Therefore, we need to test all redundant paths of brake actuation. This could be achieved by a design modification where both actuators are activated when the brake is activated either by the driver or by the longitudinal control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing braking performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC1 level of longitudinal control is activated.
A test to determine the coefficient of friction at the tire-road interface could be used to enable prediction of deceleration values. These kinds of tests are currently available [20,21,22,23] .
Throttle:

The throttle tests are conceptually very similar to the brake tests discussed above. The throttle path can be tested continuously in manual driving mode if the throttle actuator is involved in manual throttle operation (see the discussion for the brake testing procedure above). The test can be accomplished any time the driver steps on the accelerator. Actuation of the pedal will send a signal to the throttle actuator, which in turn will increase the throttle angle, and the vehicle will accelerate. Using the speed sensor, the acceleration can be estimated. This acceleration will then be compared with the acceleration expected due to the throttle angle observed. Due to the condition of the drivetrain, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the throttle system performance might be deteriorating, If the problem is not taken care of, the acceleration performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the accelerator pedal to the throttle angle needs to be checked to determine if the observed throttle angle correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Controller:

Controller tests can be performed as a software diagnostic test. This test could be performed via consistency checks on the redundant outputs.

Lateral Collision Detection Sensor(s):

A loop-back test similar to the one discussed for the longitudinal sensor can be used for testing purposes.

If the vehicle guides itself automatically into the automated lane, as required in some of the scenarios described above, there needs to be hardware redundancy, and a complete sensor test can be accomplished as an on-board built-in diagnostic and self test. Each redundant path would detect objects in their field of view independently and the results would be compared for consistency. This procedure can be performed continuously whenever there is a vehicle in the sensor’s view.

Other Vehicle Functions:

Tire pressure and condition, brake pad condition, engine temperature, pressure and level of critical fluids (engine oil, brake fluid, fuel, etc.), lights, horn, wipers, etc., can be tested as an on-board diagnostic and self test. Most of these tests are either already available (e.g. Engine Control Management System) or the technology to implement them is already developed.

- Tire Pressure: Can be monitored via on-board diagnostics equipment.
- Brake Pad Condition: Brake pad thickness measurement may be included to increase the reliability of the system.
- Engine Temperature: Currently available diagnostics will be sufficient.
- Pressure And Level Of Critical Fluids: Currently available diagnostics will be sufficient.
- Headlights and Wipers: Currently available diagnostics will be sufficient.
- Turn Signals: Currently available diagnostics will be sufficient.
- Emergency Flashers: Currently available diagnostics will be sufficient.

System-Level Testing of the Vehicle:

The system-level interactions of vehicle functions must also be monitored to verify the correct response and fitness of the overall system using a validated vehicle simulation model residing as software in the vehicle computer. This would involve comparing the actual vehicle output (e.g. speed) for a given input (e.g. brake, throttle, or steering actuation) with the output of the vehicle model implemented in the software for the same inputs (Figure 15). Such validated vehicle models are generated as part of the vehicle design process, and hence are easily available.

Vehicle-Roadway Communication:

The vehicle-roadway communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. The communication link will then operate under continuous error checking to ensure non-faulty communication.

Driver Interface:

The driver interface is expected to be developed mostly independent of AHS, and it is expected to have built-in diagnostics and tests accomplished using testing signals at various locations of the diagnostic system. Depending on the display technology used, resistance measurements may be used to detect faulty displays. Alternatively, the operator can check the displays at power-on. Audio signals may be redundant to displays for critical information. The controls can be designed to have redundant paths and contacts, and audio and/or visual feedback signals, so that the driver can monitor the operational status of controls.

Lane Detection Sensor(s):

The lane keeping controller is a higher bandwidth (i.e. faster responding) controller than the longitudinal controller. Therefore, it would not be very long before the vehicle leaves the lane after a malfunction in the lane keeping control system. Hence, we cannot rely on the operator to be the backup controller for lane keeping. This makes it essential to introduce redundancies. Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs and the results would simply be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously wherever the road is modified to allow sensing of its lanes. It is recommended that access ramps and roads be so fitted to allow pre-entry checks of lane keeping sensors. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers. Additionally, a loop-back test similar to the one discussed for the longitudinal sensor can be performed to test the lane detection sensor.

Steering Actuator:

In order to perform the on-board built-in diagnostic steering actuator tests, some modifications in the steering system design may be indicated, since the steering actuators may not be activated in manual driving mode. As soon as the steering actuator becomes part of the manual steering loop, the steering loop test can be accomplished as an on-board built-in diagnostic test. This would mean that the driver commands will activate the steering actuator directly; the technology for this type of a system is currently available. The test can be accomplished anytime the driver steers the vehicle. A steering wheel motion will send a signal to the steering actuator, which in turn will increase the pressure in the hydraulic system, and the vehicle will turn. Using a rate gyro, the angular velocity of the vehicle can be measured, which is then compared with the expected angular velocity. This expected value is computed using the steering wheel input and a mathematical model of the vehicle. Due to the condition of the steering links, weather, highway levelness, tire condition etc., there will be some variation from the expected results. Therefore, some region will have to be established outside of which the driver would be given a warning that the steering system performance might be deteriorating. If the problem is not taken care of, the steering performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. Both accuracy and dynamic range of the steering system will have to be better than a predetermined standard as required by the control system designers.

As discussed earlier, safety considerations mandate redundancy in the lateral control system. Therefore, we need to test all redundant paths of steering actuation. This could be achieved by a design modification where both actuators are activated when steering is activated either by the driver or by the lateral control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing steering performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC2 is activated.

Vehicle-to-vehicle Communication:

Once vehicle-to-vehicle communication is established, a built-in error checking protocol will be used to test the link.

Driver Alertness:

Once all sensors and actuators are tested, the driver's response to the traffic conditions can be evaluated to determine the driving capabilities of the driver. This will not only enable the detection of non-alert (e.g. drunk) drivers, but also will be useful in the driver readiness testing during the check-out phase.

4. ***On-site Testing at Check-in Point:***

Because the system is continuously tested by on-board diagnostics, on-site check-in tests are not expected to be needed at ERSC3, with the exception of testing the communications and the lane keeping sensors. Nevertheless, on-site testing is an alternative to on-board diagnostics, albeit a time consuming and hence disruptive one. We briefly discuss alternative on-site test procedures below for the sake of completeness.

Longitudinal Sensor(s):

The longitudinal sensor could also be tested using calibration checks at the designated check-in points. When the vehicle is at a predetermined position, the on-board computer will instruct the sensor(s) to measure the distance from the vehicle to the stationary test target. If the sensor is designed such that it can pick up signals emitted from a source imbedded into the highway surface, this source can be used as a test target. The relative velocity measurement could be verified using the vehicle speedometer or possibly by lane detection sensors. This procedure, however, will require roadway modifications. Therefore, it is not recommended.

Brakes:

The brake paths can be tested on-site. This test would require the driver to perform a standard braking maneuver before the entry point. The resulting velocity profile would then be required to lie in a certain region. If maximum braking capability needs to be determined, a more desirable, but still somewhat disturbing to the passengers, procedure would be to apply the brakes to the wheels until they lock up. When ABS kicks in, maximum braking capability for that wheel has been reached, and the brakes can be released. This procedure, however, will still be disturbing and time consuming, and is not recommended.

Throttle:

The throttle path can be tested on-site. This test would require the driver to perform a standard acceleration maneuver. The resulting velocity profile would then be required to lie in a certain region. This procedure, however, will be time consuming and may disturb traffic flow.

Lateral Collision Detection Sensor(s):

The lateral collision detection sensor(s) could be tested on-site using stationary test targets at predetermined locations. This procedure, however, will be complex, offers no clear advantages over built-in on-board diagnostic tests, and is not recommended.

Vehicle-Roadway Communication:

If communication is not established by the time on-site tests begin, these tests will be part of the on-site testing procedure.

Lane Detection Sensor:

The lane detection sensors could be tested by checking that the vehicle is in the middle of the lane while the driver is steering the vehicle manually. This procedure, however, will not be as conclusive.

Steering Actuator:

Once the lane detection sensor and the controller are tested, the automated lane keeping controller can be turned on to test the actuator. If the controller performance is satisfactory, the steering actuator performance can be deduced to be satisfactory.

System-Level Tests:
As discussed earlier, system-level tests can be performed continuously as built-in diagnostic tests. System-level tests can also be performed as on-site tests by briefly activating automatic control while the driver is alerted to be ready to manually override. This procedure, however, is complicated and therefore not recommended.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

Table 6 summarizes the criticality and practicality of performing each type of test for each function. The criticality measure indicates how crucial that particular test is. In this table, “essential” means the test is crucial to safe and reliable operation of the system, and failure to test may lead to serious accidents; “required” means the test is required in order to guarantee smooth operation providing the expected performance benefits; and “desired” means it would be nice if the test could be performed to provide additional system reliability, but the lack of such a test would not by itself indicate serious reliability problems. In order to decide whether the test designated as “desired” should be performed, another measure is devised which designates the practicality of the test. If a particular test is practical (i.e. cost and time efficient, transparent and undisturbing to the users and traffic flow, etc.), and the test is designated as being desired, then we may recommend the test to be performed.

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within couple of seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as “essential” or “required”, the test is also determined to be practical (see table 6).

Human Factors Issues:

There are various studies and guidelines for the operator interface (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

User acceptance is an important human factors issue [15,16] . Since many functions at this ERSC are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. The driver is only responsible for lane changing and lateral collision avoidance at ERSC3. Hence, there is already potentially a major shift in liability from the driver to the system.

Table 6: Criticality and Practicality of Check-in Test Categories for Each Function for ERSC3 (essential - required - desired; practical - not practical)

FUNCTION TO BE TESTED	Initial Testing and Certification	Periodic Off-site Testing	On-board Built-in Diagnostic Tests	On-site Testing
Speed and Headway Maintenance	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Rear-end Collision Warning	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Lateral Collision Warning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Receive Speed, Headway, and Traffic Information from Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Driver Interface	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Transmit Vehicle Status and Speed to Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Maneuver Coordination	Required[1]/ Practical	Desirable/ Practical	Required[1] / Practical	Required [1]/ Practical
Lane Keeping	Required/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Other Vehicle Functions	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
System-Level Vehicle Testing	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical

[1] In the scenarios where the vehicle guides itself into the automated lane automatically, this function becomes essential.

In the scenarios where the driver is responsible for not entering the automated lane when the roadway does not give authorization, law enforcement efforts may be needed to ensure compliance. Automation could help the law enforcement by identifying unauthorized vehicles in the dedicated lane. Traffic signals and law enforcement may also be used to ensure that drivers of failed vehicles do not cause additional delays, and clear the AHS entrance area promptly.

Another major issue for implementation of AHS is dedicating a lane to AHS operations. Construction of a new lane will be costly and taking away an existing lane from manual traffic may provoke major political turbulence [18,19]. It may, therefore, be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions at this ERSC are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software will be an activity of major importance. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:

There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles at ERSC3 beyond the ones discussed above.

Key Findings

- For ERSC3, on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical since crucial sensor tests can be performed using consistency checks on the redundant paths. Furthermore, the design modifications for the brake and steering systems discussed earlier allow on-board built-in diagnostic testing of brake and steering actuators. Therefore, no on-site tests are expected to be needed.
- Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.
- On-board built-in diagnostic testing of the lane keeping sensor can be accomplished in the manual lanes only if portions of the manual lanes are modified to include lane keeping reference aids. This is easily accomplished on the entry ramps and at designated entry points, but the portions of the manual lane next to the automated lane would need to be modified for the continuous entry case.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

Evolutionary Representative System Configuration Four (ERSC4)

At ERSC4, automated lane changing and lateral collision avoidance are introduced. In order to accomplish this, maneuver coordination is improved. Also, the vehicle can now perform route planning.

Vehicle and Driver Functions to Be Tested for Check-in

The functions needed to be tested for ERSC4, and the required components for each function are shown in table 7.

Specific testing procedures for these components will be discussed in the following subsections. Before analyzing the test procedures, however, we will describe alternative scenarios for each entry/exit configuration.

Designated Check-in with a Dedicated Ramp

Check-in Scenario I

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle and the vehicle guides itself automatically into the automated lane. Figure 4 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle onto the ramp. The driver is responsible for not entering the dedicated lane if the roadway does not verify fitness of the vehicle. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification using a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles and executes a merge operation into the dedicated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information and to transmit vehicle status and speed. The vehicle also does route planning and changes lanes as necessary in the dedicated lanes.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles and receives vehicle status and speed information from the vehicles. The roadway participates in maneuver coordination and helps in synchronizing a gap in the automated lane for the entering vehicle. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps. Also, toll paying, registration status and outstanding ticket checking may be accomplished on the ramp.

Table 7: Functions to Be Tested at Check-in for ERSC4

FUNCTION TO BE TESTED	REQUIRED COMPONENTS
Speed and Headway Maintenance	Sensors: Speed sensor; headway and relative speed sensor Actuators: Brake; throttle Computer control system
Rear-end Collision Avoidance	Sensors: Speed sensor; headway and relative speed sensor Vehicle-vehicle communication devices Actuators: Brake; throttle Computer control system
Lateral Collision Avoidance	Sensors: Lateral detection sensor Vehicle-vehicle communication devices Actuators: Steering Computer control system
Receive Speed, Headway, and Traffic Information from Roadway	Roadway-vehicle communication devices
Driver Interface	Driver interface controls and displays
Transmit Vehicle Status and Speed to Roadway	Vehicle-roadway communication devices
Maneuver Coordination	Vehicle-vehicle communication devices Lateral detection sensor
Lane Keeping	Sensors: Lane detection and preview sensor Actuators: Steering Computer control system
Lane Changing	Sensors: Lane detection sensor Vehicle-vehicle communication devices Actuators: Steering Computer control system
Route Planning	Roadway-vehicle communication devices Sensors: Lateral detection sensor Vehicle-vehicle communication devices
Other Vehicle Functions	Critical fluids level and pressure, engine temperature, brake pad condition, tire pressure and condition, wipers, headlights, etc.

Check-in Scenario II

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle, as a result of which the entry gate opens to allow the vehicle into the automated lane, and the vehicle guides itself automatically into the automated lane. Figure 5 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle onto the ramp. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry

maneuvers with other vehicles and executes a merge operation into the dedicated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information and to transmit vehicle status and speed. The vehicle also does route planning and changes lanes as necessary in the dedicated lanes.
Roadway Functions: Results of all tests are verified by the roadway using communication with the vehicle. If check-in tests are passed, the gate is opened to allow the vehicle into the automated lane. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles and receives vehicle status and speed information from the vehicles. The roadway participates in maneuver coordination and helps in synchronizing a gap in the automated lane for the entering vehicle. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps. Also, toll paying, registration status, and outstanding ticket checking may be accomplished on the ramp.

Designated Check-in without a Dedicated Ramp

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle and the vehicle guides itself automatically into the automated lane. Figure 7 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:
Driver Functions: The driver is responsible for not entering the dedicated lane if the roadway does not verify fitness of the vehicle. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles, and executes a merge operation into the dedicated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed. The vehicle also does route planning and changes lanes as necessary in the dedicated lanes.
Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. The roadway participates in maneuver coordination and helps in synchronizing a gap in the automated lane for the entering vehicle. Toll paying, registration status, and outstanding ticket checking may be accomplished at the entry point.

Continuous Check-in

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle. The functions of the driver, roadway, and vehicle in this scenario are described as follows:
Driver Functions: The driver is responsible for not entering the dedicated lane if the roadway does not verify fitness of the vehicle. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set.
Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. The vehicle coordinates entry maneuvers with other vehicles, and executes a merge operation into the dedicated lane. Additionally, the vehicle communicates with the roadway to receive headway and speed recommendations, and traffic information, and to transmit vehicle status and speed. The vehicle also does route planning, and changes lanes as necessary in the dedicated lanes.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides headway and speed recommendations, and traffic information to the vehicles, and receives vehicle status and speed information from the vehicles. The roadway participates in maneuver coordination and helps in synchronizing a gap in the automated lane for the entering vehicle. Toll paying, registration status and outstanding ticket checking may be accomplished at the entry point.

Check-in Testing Procedures:

In this subsection, we will discuss the actual testing procedures for the various vehicle components identified in table 7. We believe that the check-in tests will have to be predominantly in the form of on-board diagnostics and self tests. We will also briefly discuss alternative on-site testing procedures, but these kinds of tests are not emphasized because they may disturb traffic flow. Figure 17 shows a conceptual diagram of the AHS vehicle components ERSC4. Various components discussed in table 7 are identified on this diagram. The check-in tests should cover all these components, and all the paths between the components.

As discussed earlier, check-in tests are classified into four groups. For the scenario described above, these testing categories are discussed in the following.

1. ***Initial Testing and Certification:*** For ERSC4, many automated features are expected to be manufactured independent of AHS, and this type of testing would involve certification at the factory. If the vehicle is retrofitted with automated features, initial testing and certification would be performed at the retrofit garage.
2. ***Periodic Off-site Testing:*** Due to the current “low maintenance vehicle” trends in the automotive industry, no additional periodic testing beyond the normal maintenance procedures is expected to be needed for ERSC4.
3. ***On-board Built-in Diagnostic Tests:*** Since many components on the vehicles are expected to be developed independent of AHS at ERSC4, all these components are expected to have on-board self tests and diagnostics for continuously monitoring their fitness. Additionally, the vehicle computer must have software to test the system as a whole, verifying its fitness via comparison with an internal simulator model of the vehicle. The diagnostics should include testing of the following components described below:

   Speed Sensor:

   Since the ABS systems perform extensive diagnostics of the wheel speed sensor, the diagnostic tests currently used will be utilized. The vehicle speed is computed from the wheel speed. In the automated lanes this information could be corroborated with speed data derived from roadway lane markings and intervehicle communications. Since vehicle speed is not a crucial variable in control algorithms, using the existing speed sensors is expected to yield satisfactory results. If the achievable accuracy of the existing speed sensors is determined to be insufficient, additional methods of velocity sensing can be used.

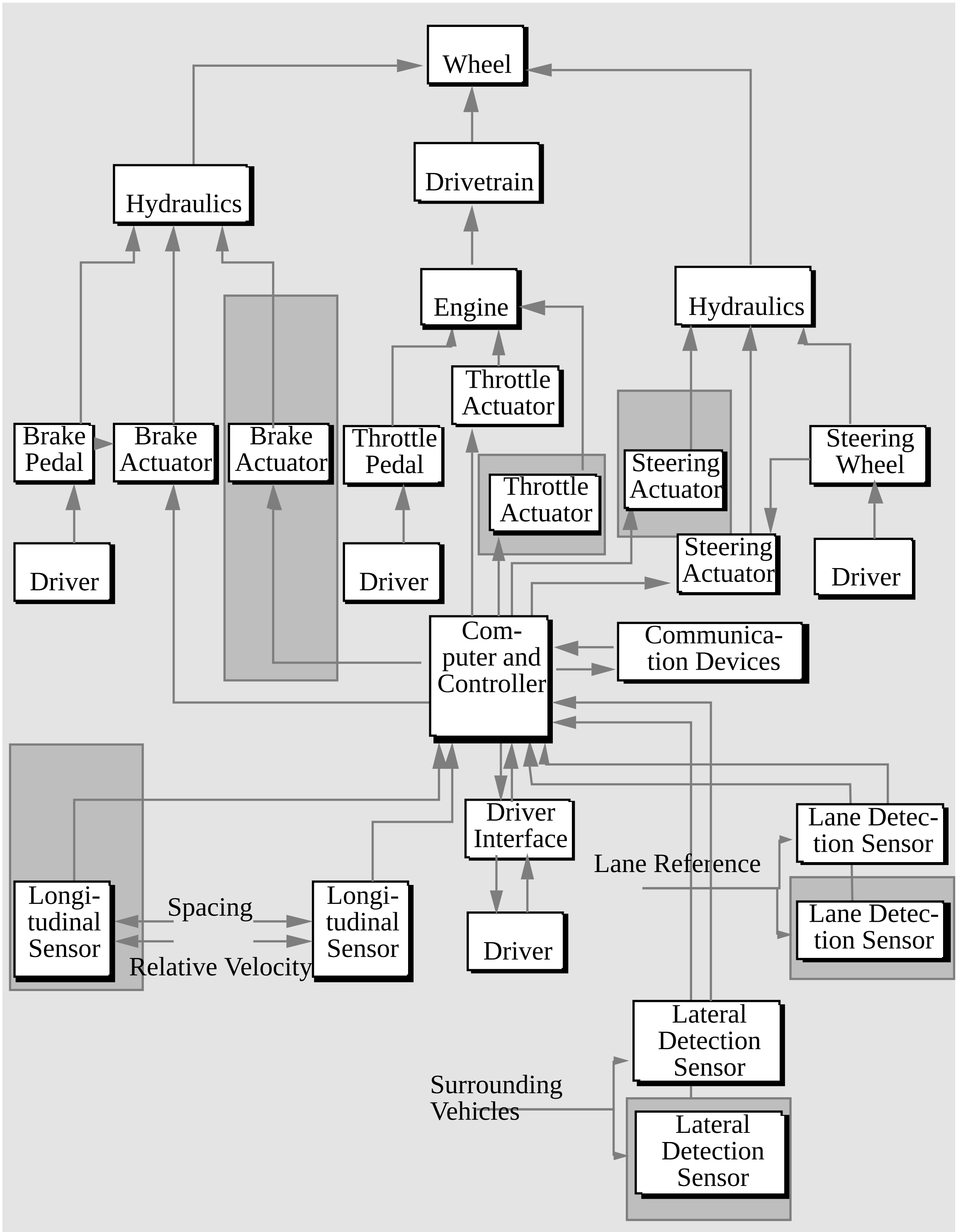

Figure 17: Conceptual Diagram of the AHS Vehicle for ERSC4 (hatched rectangles indicate redundant components, the computer has built-in redundancy)

Longitudinal (Headway and Relative Velocity) Sensor(s):
As discussed for ERSC3, safety considerations mandate multiple redundancies in the longitudinal control system. Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs, and the results would simply be compared for consistency. A voting

system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously whenever there is a vehicle in the sensor's range. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Additionally, a loop-back test similar to the one discussed for ERSC1 can be performed to test the longitudinal sensor. For the example of a longitudinal sensor using radar technology, this can be accomplished by injecting a signal at the antenna input (perhaps on a second pulsed carrier signal to distinguish it from a signal coming from an actual target) emulating an imaginary target, and checking the sensor output. In fact, this test will probably be closely related to the built-in sensor diagnostic test and calibration procedure.

Once the vehicle is in the dedicated lane, vehicle-to-vehicle communications will provide an additional redundant path since braking, velocity, and acceleration profiles are communicated between vehicles.

Brakes:

In order to perform the on-board built-in diagnostic brake tests, some modifications in the brake system design are indicated, since most of the current brake actuators designed to be used with automatic longitudinal control are not activated in manual driving mode. As soon as the brake actuator becomes part of the manual braking loop, the brake loop test can be accomplished as an on-board built-in diagnostic test. This would mean that the driver commands will activate the brake actuator, as shown in figure 14 (a) (ABS mechanism is not included in this diagram). Although most current brake systems are like the one shown in figure 14 (b), the technology for this type of a system is currently available. The test can be accomplished anytime the driver brakes. Actuation of the brake pedal will send a signal to the brake actuator, which in turn will increase the brake line pressure, and the vehicle will decelerate. Using the speed sensor, the deceleration can be estimated. This deceleration will then be compared with the deceleration expected due to the brake line pressure observed. Due to the condition of the brake pads, weather, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the brake system performance might be deteriorating. If the problem is not taken care of, the braking performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the brake pedal to the brake line pressure needs to be checked to determine if the brake line pressure buildup correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range of the braking system will have to be better than a predetermined standard as required by the control system designers.

As discussed earlier, safety considerations mandate redundancy in the longitudinal control system due to the introduction of longitudinal collision avoidance. Therefore, we need to test all redundant paths of brake actuation. This could be achieved by a design modification where both actuators are activated when the brake is activated either by the driver or by the longitudinal control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing braking performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC1 level of longitudinal control is activated.

A test to determine the coefficient of friction at the tire-road interface could be used to enable prediction of deceleration values. These kinds of tests are currently available [20,21,22,23] .

Throttle:

The throttle tests are conceptually very similar to the brake tests discussed above. The throttle path can be tested continuously in manual driving mode if the throttle actuator is involved in manual throttle operation (see the discussion for the brake testing procedure above). The test can be accomplished any time the driver steps on the accelerator. Actuation of the pedal will send a signal to the throttle actuator, which in turn will increase the throttle angle, and the vehicle will accelerate. Using the speed sensor, the acceleration can be estimated. This acceleration will then be compared with the acceleration expected due to the throttle angle observed. Due to the condition of the drivetrain, highway grade, etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the throttle system performance might be deteriorating, If the problem is not taken care of, the acceleration performance will eventually fall below the minimum acceptable limit, and the vehicle will fail the check-in test. In addition, the path from the accelerator pedal to the throttle angle needs to be checked to determine if the observed throttle angle correlates as expected to the duration and displacement observed at the pedal. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Safety considerations mandate redundancy in the throttle actuator due to the introduction of full collision avoidance. Therefore, we need to test all redundant paths of throttle actuation. This could be achieved by a design modification where both actuators are activated when the throttle is activated either by the driver or by the longitudinal control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing acceleration performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC3 level of longitudinal control is activated.

Controller:

Controller tests can be performed as a software diagnostic test. This test could be performed via consistency checks on the redundant outputs.

Lateral Collision Detection Sensor(s):

Safety considerations mandate multiple redundancies in the lateral control system due to the introduction of lane changing and lateral collision avoidance. Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs and the results would simply be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously whenever there is a vehicle in the sensor's range. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers.

Additionally, a loop-back test similar to the one discussed for the longitudinal sensor at ERSC1 can be performed.

Once the vehicle is in the dedicated lane, vehicle-to-vehicle communications will provide an additional redundant path since maneuver coordination requires communication between vehicles.

Other Vehicle Functions:

Tire pressure and condition, brake pad condition, engine temperature, pressure and level of critical fluids (engine oil, brake fluid, fuel, etc.), lights, horn, wipers, etc., can be tested as an on-board diagnostic and self test. Most of these tests are either already available (e.g. Engine Control Management System) or the technology to implement them is already developed.

- Tire Pressure: Can be monitored via on-board diagnostics equipment.
- Brake Pad Condition: Brake pad thickness measurement may be included to increase the reliability of the system.
- Engine Temperature: Currently available diagnostics will be sufficient.
- Pressure And Level Of Critical Fluids: Currently available diagnostics will be sufficient.
- Headlights and Wipers: Currently available diagnostics will be sufficient.
- Turn Signals: Currently available diagnostics will be sufficient.
- Emergency Flashers: Currently available diagnostics will be sufficient.

System-Level Testing of the Vehicle:
The system-level interactions of vehicle functions must also be monitored to verify the correct response and fitness of the overall system using a validated vehicle simulation model residing as software in the vehicle computer. This would involve comparing the actual vehicle output (e.g. speed) for a given input (e.g. brake, throttle, or steering actuation) with the output of the vehicle model implemented in the software for the same inputs (Figure 15). Such validated vehicle models are generated as part of the vehicle design process, and hence are easily available.
Vehicle-Roadway Communication:
The vehicle-roadway communication can be attempted to be established before the vehicle reaches the entry point. Once communication is established, a built-in error checking protocol will be used to test the link. The communication link will then operate under continuous error checking to ensure non-faulty communication.
Driver Interface:
The driver interface is expected to be developed mostly independent of AHS, and it is expected to have built-in diagnostics and tests accomplished via testing signals at various locations of the diagnostic system. Depending on the display technology used, resistance measurements may be used to detect faulty displays. Alternatively, the operator can check the displays at power-on. Audio signals may be redundant to displays for critical information. The controls can be designed to have redundant paths and contacts, and audio and/or visual feedback signals, so that the driver can monitor the operational status of controls.
Lane Detection Sensor(s):
The lane keeping controller is a higher bandwidth (i.e. faster responding) controller than the longitudinal controller. Therefore, it would not be very long before the vehicle leaves the lane after a malfunction in the lane keeping control system. Hence, we cannot rely on the operator to be the backup controller for lane keeping. This makes it essential to introduce redundancies. Once we have redundant sensors, it is fairly straightforward to test the sensor system as part of on-board built-in diagnostics. Each redundant path would produce some outputs and the results would simply be compared for consistency. A voting system similar to the one used in aircraft systems could be used to accomplish this. This procedure can be performed continuously wherever the road is modified to allow sensing of its lanes. It is recommended that access ramps and roads be so fitted to allow pre-entry checks of lane keeping sensors. Both accuracy and dynamic range will have to be better than a predetermined standard as required by the control system designers. Additionally, a loop-back test similar to the one discussed for the longitudinal sensor can be performed to test the lane detection sensor.
Steering Actuator:
In order to perform the on-board built-in diagnostic steering actuator tests, some modifications in the steering system design may be indicated, since the steering actuators may not be activated in manual driving mode. As soon as the steering actuator becomes part of the manual steering loop, the steering loop test can be accomplished as an on-board built-in diagnostic test. This would mean that the driver commands will activate the steering actuator directly; the technology for this type of a system is currently available. The test can be accomplished anytime the driver steers the vehicle. A steering wheel motion will send a signal to the steering actuator, which in turn will increase the pressure in the hydraulic system, and the vehicle will turn. Using a rate gyro, the angular velocity of the vehicle can be measured, which is then compared with the expected angular velocity. This expected value is computed using the steering wheel input and a mathematical model of the vehicle. Due to the condition of the steering links, weather, highway levelness, tire condition etc., there will be some variation from the expected results. Therefore, some region will have to be established, outside of which the driver would be given a warning that the steering system performance might be deteriorating. If the problem is not taken care of, the steering performance will eventually fall

below the minimum acceptable limit, and the vehicle will fail the check-in test. Both accuracy and dynamic range of the steering system will have to be better than a predetermined standard as required by the control system designers.

As discussed earlier, safety considerations mandate redundancy in the lateral control system. Therefore, we need to test all redundant paths of steering actuation. This could be achieved by a design modification where both actuators are activated when steering is activated either by the driver or by the lateral control system. A failure detection mechanism could then detect and compensate for a malfunctioning actuator preventing steering performance degradation while the driver is alerted. If failure occurs while the vehicle is in automated mode, fall-back to ERSC2 level of lateral control is activated.

Vehicle-to-vehicle Communication:

Once vehicle-to-vehicle communication is established, a built-in error checking protocol will be used to test the link.

Driver Alertness:

Once all sensors and actuators are tested, the driver's response to the traffic conditions can be evaluated to determine the driving capabilities of the driver. This will not only enable the detection of non-alert (e.g. drunk) drivers, but also will be useful in the driver readiness testing during the check-out phase.

4. ***On-site Testing at Check-in Point:***

Because the system is continuously tested by on-board diagnostics, on-site check-in tests are not expected to be needed at ERSC4, with the exception of testing the communications and the lane keeping sensors. Nevertheless, on-site testing is an alternative to on-board diagnostics, albeit a time consuming and hence disruptive one. We briefly discuss alternative on-site test procedures below for the sake of completeness.

Longitudinal Sensor(s):

The longitudinal sensor could also be tested via calibration checks at the designated check-in points. When the vehicle is at a predetermined position, the on-board computer will instruct the sensor(s) to measure the distance from the vehicle to the stationary test target. If the sensor is designed such that it can pick up signals emitted from a source imbedded into the highway surface, this source can be used as a test target. The relative velocity measurement could be verified via the vehicle speedometer or possibly by lane detection sensors. This procedure, however, will require roadway modifications. Therefore, it is not recommended.

Brakes:

The brake paths can be tested on-site. This test would require the driver to perform a standard braking maneuver before the entry point. The resulting velocity profile would then be required to lie in a certain region. If maximum braking capability needs to be determined, a more desirable, but still somewhat disturbing to the passengers, procedure would be to apply the brakes to the wheels until they lock up. When ABS kicks in, maximum braking capability for that wheel has been reached, and the brakes can be released. This procedure, however, will still be disturbing and time consuming, and is not recommended.

Throttle:

The throttle path can be tested on-site. This test would require the driver to perform a standard acceleration maneuver. The resulting velocity profile would then be required to lie in a certain region. This procedure, however, will be time consuming and may disturb traffic flow.

Lateral Collision Detection Sensor(s):

The lateral collision detection sensor(s) could be tested on-site using stationary test targets at predetermined locations. This procedure, however, will be complex, offers no clear advantages over built-in on-board diagnostic tests, and is not recommended.

Vehicle-Roadway Communication:

If communication is not established by the time on-site tests begin, these tests will be part of the on-site testing procedure.

Lane Detection Sensor:

The lane detection sensors could be tested by checking that the vehicle is in the middle of the lane while the driver is steering the vehicle manually. This procedure, however, will not be as conclusive as the on-board built-in diagnostic test described above.

Steering Actuator:

Once the lane detection sensor and the controller are tested, the automated lane keeping controller can be turned on to test the actuator. If the controller performance is satisfactory, the steering actuator performance can be deduced to be satisfactory.

System-Level Tests:

As discussed earlier, system-level tests can be performed continuously as built-in diagnostic tests. System-level tests can also be performed as on-site tests by briefly activating automatic control, while the driver is alerted to be ready to manually override. This procedure, however, is complicated and, therefore, not recommended.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment, and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

Table 8 summarizes the criticality and practicality of performing each type of test for each function. The criticality measure indicates how crucial that particular test is. In this table "essential" means the test is crucial to safe and reliable operation of the system, and failure to test may lead to serious accidents; "required" means the test is required in order to guarantee smooth operation providing the expected performance benefits; and "desired" means it would be nice if the test could be performed to provide additional system reliability, but the lack of such a test would not by itself indicate serious reliability problems. In order to decide whether the test designated as "desired" should be performed, another measure is devised which designates the practicality of the test. If a particular test is practical (i.e. cost and time efficient, transparent and undisturbing to the users and traffic flow, etc.), and the test is designated as being desired, then we may recommend the test to be performed.

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within a couple of seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as "essential" or "required", the test is also determined to be practical (see table 8).

Human Factors Issues:

There are various studies and guidelines for the operator interface (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous, or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue, and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

User acceptance is an important human factors issue [15,16] . Since many functions at ERSC4 are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Table 8: Criticality and Practicality of Check-in Test Categories for Each Function for ERSC4 (essential - required - desired; practical - not practical)

FUNCTION TO BE TESTED	Initial Testing and Certification	Periodic Off-site Testing	On-board Built-in Diagnostic Tests	On-site Testing
Speed and Headway Maintenance	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Rear-end Collision Warning	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Lateral Collision Avoidance	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Receive Speed, Headway, and Traffic Information from Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Driver Interface	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Transmit Vehicle Status and Speed to Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Maneuver Coordination	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Essential/ Practical
Lane Keeping	Required/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Lane Changing	Required/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Route Planning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Other Vehicle Functions	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
System-Level Vehicle Testing	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. The system is responsible for most of the functions at ERSC4. Hence, there is a potential for a major shift in liability from the driver to the system.

In the scenarios where the driver is responsible for not entering the automated lane when the roadway does not give authorization, law enforcement efforts may be needed to ensure compliance. Automation could help the law enforcement by identifying unauthorized vehicles in the dedicated lane. Traffic signals and law enforcement may also be used to ensure that drivers of failed vehicles do not cause additional delays, and clear the AHS entrance area promptly.

Another major issue for implementation of AHS is dedicating lanes to AHS operations. Construction of a new lane will be costly, and taking away an existing lane from manual traffic may provoke major political turbulence [18,19] . It may, therefore, be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions at ERSC4 are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software will be an activity of major importance. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:

There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles at ERSC4 beyond the ones discussed above.

Key Findings

- For ERSC4, continuous on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical since crucial sensor tests can be performed via consistency checks on the redundant paths. Furthermore, the design modifications for the brake and steering systems discussed earlier allow on-board built-in diagnostic testing of brake and steering actuators while operating in manual as well as automatic modes. Therefore, no on-site tests are expected to be needed.
- Whenever a malfunction is determined in any redundant path, fall-back procedures to the next lower level of automation not requiring that particular redundancy will have to be initiated.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

Evolutionary Representative System Configuration Five (ERSC5)

At ERSC5, the roadway coordinates vehicle maneuvers, sends lateral/longitudinal control commands to each vehicle, and receives speed, acceleration, headway, and destination information from each vehicle. Route planning is also performed by the roadway.

Vehicle and Driver Functions to Be Tested for Check-in

The functions needed to be tested for ERSC5, and the required components for each function are shown in table 9. Note that the vehicle components in this table are identical to the ones presented for ERSC4, since all the new features at ERSC5 are roadway related. If any of these roadway related features fail, the system will fall back to ERSC4, where the vehicle performs all the functions performed by the roadway at ERSC5. Hence, ERSC4 vehicle functions are redundant to the ERSC5 roadway functions.

We first describe alternative scenarios for each entry/exit configuration.

Designated Check-in with a Dedicated Ramp

In this scenario, communication between the vehicle and the roadway is used to verify the fitness of the vehicle, as a result of which the entry gate opens to allow the vehicle into the automated lane, and the roadway guides the vehicle automatically into the automated lane. Note that the gate mechanism is required at ERSC5 to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes. Figure 5 illustrates this scenario conceptually. The functions of the driver, roadway, and vehicle in this scenario are described as follows:

Driver Functions: The driver guides the vehicle onto the ramp. The driver is also responsible for setting the longitudinal control parameters (headway, maximum speed) within the limits that he/she is allowed to set.

Vehicle Functions: The on-board vehicle diagnostics results are presented to the roadway for verification via a standard protocol. If vehicle fitness is verified, the vehicle receives a signal from the roadway and displays this information to the driver. Additionally, the vehicle communicates with the roadway to receive lateral and longitudinal control commands and to transmit vehicle information.

Roadway Functions: Results of all tests are verified by the roadway via communication with the vehicle. If check-in tests are passed, the gate is opened, and the roadway guides the vehicle into the automated lane. Apart from providing the dedicated lane with lane keeping reference aids for lane keeping, the roadway provides control commands, and receives vehicle information from the vehicles. The roadway coordinates all maneuvers. A possible roadway passive role is to perform ramp metering as currently done in many manual ramps. Also, toll paying, registration status and outstanding ticket checking may be accomplished on the ramp.

Table 9: Functions to Be Tested at Check-in for ERSC5

FUNCTION TO BE TESTED	REQUIRED COMPONENTS
Speed and Headway Maintenance	Sensors: Speed sensor; headway and relative speed sensor Actuators: Brake; throttle Computer control system
Rear-end Collision Avoidance	Sensors: Speed sensor; headway and relative speed sensor Vehicle-vehicle communication devices Actuators: Brake; throttle Computer control system
Lateral Collision Avoidance	Sensors: Lateral detection sensor Vehicle-vehicle communication devices Actuators: Steering Computer control system
Receive Control Commands from Roadway	Roadway-vehicle communication devices
Driver Interface	Driver interface controls and displays
Transmit Vehicle Information to Roadway	Vehicle-roadway communication devices
Maneuver Coordination	Vehicle-vehicle communication devices
Lane Keeping	Sensors: Lane detection and preview sensor Actuators: Steering Computer control system
Lane Changing	Sensors: Lateral detection sensor Vehicle-vehicle communication devices Actuators: Steering Computer control system
Route Planning	Roadway-vehicle communication devices Sensors: Lateral detection sensor Vehicle-vehicle communication devices
Other Vehicle Functions	Critical fluids level and pressure, engine temperature, brake pad condition, tire pressure and condition, wipers, headlights, etc.

Designated Check-in without a Dedicated Ramp

This entry configuration is not possible for ERSC5 since a gate mechanism is required to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes.

Continuous Check-in

This entry configuration is not possible for ERSC5 since a gate mechanism is required to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes.

Check-in Testing Procedures:

Since the vehicle components to be tested for ERSC5 are the same as the vehicle components for ERSC4, the testing procedures for ERSC5 are identical to those discussed for ERSC4.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

Table 10 summarizes the criticality and practicality of performing each type of test for each function. The criticality measure indicates how crucial that particular test is. In this table, “essential” means the test is crucial to safe and reliable operation of the system, and failure to test may lead to serious accidents; “required” means the test is required in order to guarantee smooth operation providing the expected performance benefits; and “desired” means it would be nice if the test could be performed to provide additional system reliability, but the lack of such a test would not by itself indicate serious reliability problems. In order to decide whether the test designated as “desired” should be performed, another measure is devised which designates the practicality of the test. If a particular test is practical (i.e. cost and time efficient, transparent and undisturbing to the users and traffic flow, etc.), and the test is designated as being desired, then we may recommend the test to be performed.

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within couple of seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as “essential” or “required”, the test is also determined to be practical (see table 10).

The gate mechanism is required at ERSC5 to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes. Because of this, designated entry with a ramp is the only recommended entry configuration for ERSC5.

Whenever a malfunction occurs at ERSC5, the system falls back to ERSC4, where the vehicle performs all functions performed by the roadway at ERSC5. In ERSC5 operations, these vehicle functions are redundant.

Human Factors Issues:

There are various studies and guidelines for the operator interface (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous, or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue, and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

Table 10: Criticality and Practicality of Check-in Test Categories for Each Function for ERSC4 (essential - required - desired; practical - not practical)

FUNCTION TO BE TESTED	Initial Testing and Certification	Periodic Off-site Testing	On-board Built-in Diagnostic Tests	On-site Testing
Speed and Headway Maintenance	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Rear-end Collision Warning	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Lateral Collision Avoidance	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Receive Control Commands from Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Driver Interface	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
Transmit Vehicle Information to Roadway	Required/ Practical	Desirable/ Practical	Required/ Practical	Required/ Practical
Maneuver Coordination	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Essential/ Practical
Lane Keeping	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Lane Changing	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical
Route Planning	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Practical
Other Vehicle Functions	Required/ Practical	Desirable/ Practical	Required/ Practical	Desirable/ Not Practical
System-Level Vehicle Testing	Essential/ Practical	Desirable/ Practical	Essential/ Practical	Desirable/ Not Practical

User acceptance is an important human factors issue [15,16] . Since many functions at ERSC4 are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. The system is responsible for most of the functions at ERSC5. Hence, there is a potential for a major shift in liability from the driver to the system.

Another major issue for implementation of AHS is dedicating lanes to AHS operations. Construction of a new lane will be costly, and taking away an existing lane from manual traffic may provoke major political turbulence [18,19] . It may therefore be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions at ERSC5 are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software will be an activity of major importance. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:

There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles at ERSC4 beyond the ones discussed above.

Key Findings

- For ERSC5, continuous on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical since crucial sensor tests can be performed via consistency checks on the redundant paths. Furthermore, the design modifications for the brake and steering systems discussed earlier allow on-board built-in diagnostic testing of brake and steering actuators while operating in manual as well as automatic modes. Therefore, no on-site tests are expected to be needed.
- The gate mechanism is required at ERSC5 to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes. Because of this, designated entry with a ramp is the only recommended entry configuration for ERSC5.
- Whenever a malfunction occurs at ERSC5, the system falls back to ERSC4, where the vehicle performs many functions performed by the roadway at ERSC5. In ERSC5 operations, these vehicle functions are redundant.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.

Conclusions

Key Findings

We have analyzed situations in AHS where transition from manual to automated control takes place. In particular, the vehicle fitness testing to ensure safe and smooth automated operation has been emphasized. The check-in procedures presented here and an effective malfunction management system, together with a reliable control system, would ensure a safe, smoothly operating AHS system.

For each Evolutionary Representative System Configuration (ERSC), alternative scenarios have been developed, and relevant functions to be tested are determined. Each function is then evaluated for its criticality with respect to safety. Criticality and feasibility considerations lead to a subset of functions to be tested for each of the ERSCs. Test procedures for each function in these subsets are also discussed. The main goal is to accomplish all tests while the vehicle is driven under manual control as on-board built-in diagnostic tests. This minimizes the check-in procedures at the check-in site, is transparent to the driver and the traffic flow, and allows smooth transition between manual and automated lane.

Below is a summary of key findings:

- Since the driver is ultimately responsible for the overall control of the vehicle at lower ERSCs, check-in testing of automated equipment is not essential, and on-board built-in diagnostic testing procedures are required primarily for efficient and reliable operation.
- The operator interface issues may be left to vehicle manufacturers and consumers to resolve within the context of competitive market forces. This process would also involve human factors experiments and experience.
- For higher ERSCs, on-board built-in diagnostic tests are expected to be the predominant type of tests. This is practical for sensor testing, since crucial sensor tests can be performed via consistency checks on the redundant paths; on-board built-in tests of control actuators and electronics is also practical, *provided the systems are designed for testability*. This requires certain non-standard design modifications for the brake, throttle, and steering systems that allow on-board built-in diagnostic testing of automatic control electronics and actuators during manual operation. Provided that such testable control system designs are adopted, no on-site tests are expected to be needed.
- Whenever a malfunction is determined in any redundant path, procedures for fall-back to the next lower level of automation not requiring that particular redundancy will have to be initiated.
- On-board built-in diagnostic testing of the lane keeping sensor can be accomplished in the manual lanes only if portions of the manual lanes are modified to include lane keeping reference aids. This is easily accomplished on the entry ramps and at designated entry points. In continuous entry AHS configurations, the lane keeping aids might be fitted every few miles along portions of manual lanes.
- The gate mechanism is required at ERSC5 to prevent unauthorized vehicles from entering the dedicated lanes. Otherwise, the roadway will have incomplete information about the traffic situation in the dedicated lanes. Because of this, designated entry with a ramp is the only recommended entry configuration for ERSC5.
- Whenever a malfunction occurs at ERSC5, the system falls back to ERSC4, where the vehicle performs many functions performed by the roadway at ERSC5. In ERSC5 operations, these vehicle functions are redundant. In view of the relatively limited efficiency and safety gains expected in going from ERSC4 to ERSC5 this final evolutionary step may not be economically justifiable.

Issues, Risks, and Recommendations

Various issues and risks relevant to check-in functions will be discussed in this section. These issues and risks are categorized into subsections: design issues, human factors issues, institutional issues, program issues, and user type issues. The major design issue is determining what type of test to use for each function to be tested. User friendliness of the driver interface, user acceptance, and perceived safety are human factors related issues. Although they are not our main emphasis areas, we will also briefly discuss some institutional issues (legal, liability, privacy, law enforcement, dedicating a lane to AHS, attempts to tamper with equipment and cheating), program issues (consortium role, funding, deployment schedule, developments independent of AHS), and user type issues (emergency vehicles, commercial vehicles), as they relate to check-in procedures.

The analysis in this section yields specific conclusions and recommendations.

Design Issues:

On-site testing may have many disadvantages with respect to smooth and safe operation. If, for example, the vehicles are required to perform a standard braking and acceleration maneuver just before joining the automated lane, this can be time consuming and disturbing to normal traffic flow. It is also inconvenient for the drivers; testing procedures should ideally be completely transparent to the driver, and on-site testing, if required at all, should be performed within couple of seconds. Therefore, our approach is to perform as much on-board built-in diagnostic testing as is practical and feasible. If a function can be tested using both an on-board diagnostic test and an on-site test, we assume in all cases that the on-board diagnostic testing is implemented. Fortunately, whenever a particular test is designated as “essential” or “required”, the test is also determined to be practical.

Whenever a malfunction occurs, the system falls back to a lower level of ERSC.

Human Factors Issues:

There are various studies and guidelines for the operator interface (See references 4-14.) Head-up displays can be particularly useful for visual signals. Other potential technologies include: Liquid Crystal Display (LCD), Light-Emitting Diode (LED), computer generated voice message, sudden vehicle acceleration/deceleration (jerk), and tactile feedback. The interface can be continuous, or only activated when a driver action is needed. The concept of generating progressively stronger warnings may be applied to devise an operationally acceptable interface. How to design the best user interface for AHS operations is still an open issue, and involves selecting a display technology, type and duration of warnings, user controls type and location, etc. Ultimately, experiments on simulators and actual vehicles will need to be carried out to determine the system characteristics that make the system appear natural to the driver, the best way to present the data to the driver, and the most convenient way for the driver to input commands.

User acceptance is an important human factors issue [15,16] . Since many functions are expected to be developed independent of AHS, user friendliness to ensure public acceptance would be integrated into the design process by the manufacturer for each function.

Institutional Issues:

Legal and liability issues are very important for the deployment of AHS [17] . Therefore, designing a fail-safe system is a basic requirement. The system is responsible many functions at higher ERSCs. Hence, there is a potential for a major shift in liability from the driver to the system.

Another major issue for implementation of AHS is dedicating lanes to AHS operations. Construction of a new lane will be costly, and taking away an existing lane from manual traffic may provoke major political turbulence [18,19] . It may therefore be necessary to consider scenarios in which various ERSC level vehicles coexist in the early phases of the deployment.

Program Issues:

Many functions are expected to be developed independent of AHS. Establishing upgradable standards for communications and control software will be an activity of major importance. The deployment schedule will depend on the availability of independently developed components.

User Type Issues:

There may be special check-in procedures for emergency vehicles. In an emergency situation, a certain section of the dedicated lane can be reserved for emergency vehicles by limiting access to other vehicles. Periodic off-site testing may be emphasized for emergency vehicles. If they are allowed in the dedicated lane, there would be no special testing procedures for commercial vehicles beyond the ones discussed.

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