1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, gives over full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and also possibly for lateral control. The main mode of operation of the infrastructure is a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles to respond to that request. Infrastructure takes a more pro-active role in monitoring traffic flow, broadcasting traffic flow messages, advising lane changes to individual vehicles and the other usual ITS functions. The infrastructure is also capable of highly intelligent functions like taking over complete control of any individual vehicle, i.e., infrastructure can completely substitute for a vehicle's intelligence and assume longitudinal, lateral and navigational control. However, it might not have enough resources to control more than just a fraction of vehicles on the road at a time. The local officials may opt for an infrastructure that takes over the vehicle only in case the vehicle (or the driver) authorizes such a transfer of control. Such a practice might be limited to off-peak hours.

2. Longitudinal separation policy is based upon the assumption that the traffic is composed of vehicles driven as free agents. The longitudinal separation between two free agent vehicles, though not quite as little as within a platoon, is still appreciably less than that in the conventional highways because of the intelligent longitudinal control system. Therefore maximum throughput of the system is expected to be somewhere between that of AHS system with extensive platooning and the conventional highways.

3. Only those vehicles that have fully functioning AHS capabilities are allowed to enter the AHS. Moreover, non-AHS vehicles are separated by physical barriers from AHS vehicles. The only way a non-AHS vehicle can make its way to an AHS lane is either by trespassing at the entry point, or if its AHS capabilities fail during travel. The local tailorability is minimal in this regard as the system is jeopardized in case a lot of non-AHS vehicles find their way to AHS lanes. It implies a dual highway system in which the AHS system is completely independent of the non-AHS system.

4. Each AHS lane is meant for use by only certain classes of vehicles. No mixing is allowed. The heavy vehicles are naturally barred from the lane of lighter vehicles. The light vehicles also can not use the lane reserved for heavy vehicles, not even for transition purposes. The local tailorability is minimal since any modification would classify as a different concept, e.g., Concept #11, or #19. It implies a tiered AHS system, each tier catering to a different set of vehicle classes. There is little interaction between the tiers; therefore highway-to-highway interchanges would be tiered making its design highly complicated. A separate entry/exit would be required for each tier. Such a design is perhaps suitable for city commute traffic which is often composed of similar vehicle classes.

5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and no mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes. Since there is no mixing of vehicle classes in a lane under this concept, a separate entry/exit lane is provided for each class of vehicles. The incoming vehicles access the correct AHS lane directly without first passing through a transition area. Similarly, vehicles do not transition through lanes of other vehicle classes before exiting.

6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both

on-board the vehicle and the ones in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle is made, if possible. Possible maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking. The response takes into account the size and type of the obstacle. The safety of the vehicle in question, and the others around it, are the supreme concern. At no stage, is human involvement expected, except possibly in the sensing of the obstacle. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporarily or permanent non-AHS vehicles on the highway are considered obstacles.

15.3 OPERATIONAL CONCEPT

Two different point of views are considered to illustrate the operational design of the system, that of the driver of each vehicle and that of the vehicle. The emphasis is limited to the normal operating conditions.

Before these point of views are presented, it is illustrative to look at four modes of operation a vehicle can be under from the point of view of who is in charge. The intelligent agent in charge makes the high level decisions, which are executed by the agents further down in the control hierarchy.

The vehicle is in charge through the use of an array of intelligent control systems.

1. Vehicle (and in exceptional circumstances the driver) authorizes infrastructure to take charge, for example during the lane changes, entry/exit and emergencies.
2. Infrastructure wrests control away from the vehicle. The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle loses the charge, it is unable to get it back on its own. The infrastructure has to reinstate the charge. Whenever a transfer of control takes place from infrastructure to the vehicle, the vehicle has to actively take over the control and convince the infrastructure that it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains the control. Similarly, once the driver loses the charge to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate the charge; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains the control.

15.3.1 Driver Point of View

A driver decides to enter the AHS and picks the right entry point for its vehicle classes, in case there are multiple entry points. He logs in the vehicle classes and the trip description, possibly without ever stopping. Permission to enter might be denied at this point, if the vehicle fails the AHS-capability tests. The driver is given a suggested route to the destination. The driver is expected to be a passive observer until exit under normal circumstances. Under emergency conditions, full control may be passed to the driver, who then assumes manual control of the vehicle.

The only operation a driver can possibly perform is the following:

1. Change of Exit: The driver registers a change of exit with the vehicle, which then informs the infrastructure.

15.3.2 Vehicle Point of View

The vehicle is guided to one of the AHS lanes (decided upon by the infrastructure to optimize the traffic flow). It may involve automatic lane merging, lane changing, acceleration, and deceleration. When the lane-positioning is complete, the vehicle control is given to the vehicle.

Once a vehicle is in a lane in charge of itself, it can be involved in various operations. All of the following operations are initiated by the vehicle. Some of these can be redundant if a navigational subsystem is in place.

1. Lane Following: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are

located on-board, control the vehicle longitudinally.

2. Request Lane Change: The vehicle decides to change lane and registers a request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agent aboard the vehicle. The request cannot normally be denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and taken out of the control loop until the lane has been automatically changed. Control passes to the vehicle by the infrastructure when the vehicle is stably located in the new lane.
3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit, in any case a request is registered with the infrastructure. The request is granted under normal circumstances, unless the exit requested is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of infrastructure. Automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.

Certain operations are not initiated by the vehicle. The infrastructure, after informing the vehicle, takes over the control and performs these operations. These are the operations that can appear unexpected to the driver.

1. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the infrastructure may decide to take charge of the vehicle, and automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.
2. Automatic Acceleration/Deceleration: The above operations are performed to create room for vehicles that are attempting a lane change.
3. Automatic Rerouting: Automatic rerouting is done by the infrastructure to optimize the overall traffic flow from the point of view of throughput and congestion.

15.4 SYSTEM DIAGRAM

Information and control commands and parameters flow between "free agent" vehicles, and between "free agent" vehicles and the infrastructure.

The vehicle to vehicle data communication is related to maneuver coordination, position, velocity, acceleration data and vehicle dynamics. The vehicle-to-infrastructure data communication consists mostly of requests, e.g., lane change request, entry/exit request, etc. as well as vehicle status information. In addition, vehicles transmit information regarding obstacles detected by the sensors on the vehicle.

The infrastructure-to-vehicle data communication consists mainly of responses to vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc.

While the exact content of the communicated messages has not been defined yet, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are the following.

The bulk of the communication probably takes place between vehicles. Based on prior experiments, it is estimated that messages of up to 100 bytes with a repetition rate of 1/10th of a second will be

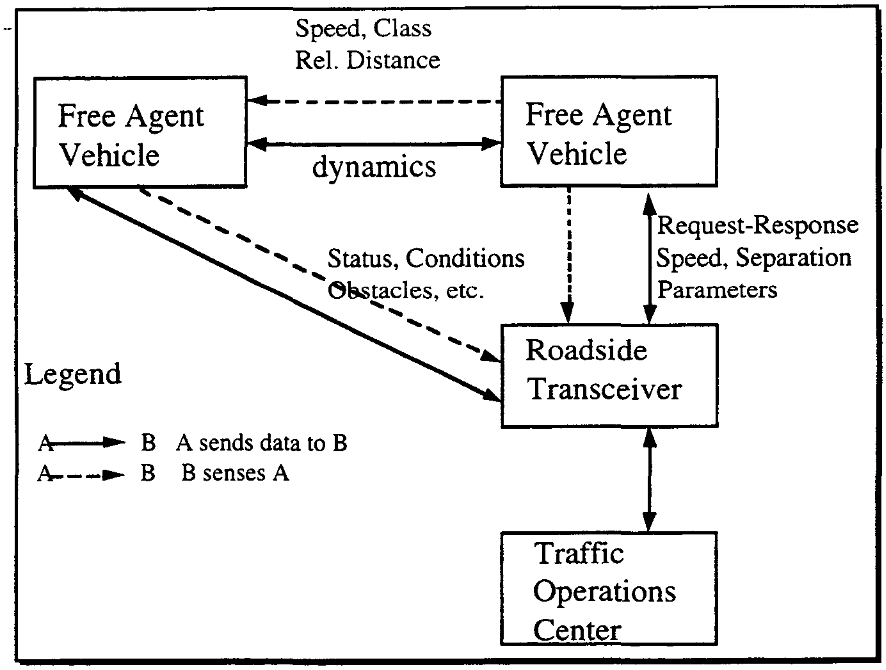

Figure H.15.4-1. System Diagram

used. This requires a channel with 9600 bps capacity and a variable duty cycle, i.e. the communication channel may not always need to transmit the maximum possible message size. Vehicles that are at some distance apart are not likely to have a need to communicate as their dynamics and trajectories do not affect each other. At the same time it is desirable to minimize the transmitting power and range of vehicle to vehicle communication to minimize interference to other vehicles and to allow for efficient spectrum reuse. At this time, a 1/4 mile maximum range seems sufficient and reasonable.

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control should be localized. Each roadside transceiver should only have to communicate with a finite and limited number of vehicles. The optimal numbers must be computed after a careful analysis. It is a good idea to make it possible for two adjacent roadside transceivers to be receiving the vehicle to infrastructure communications, for purposes of redundancy and reliability. Therefore double the range of communication from the vehicle to the roadside is allowed, compared to the other way around. The roadside to vehicle communications can be made reliable by on-vehicle redundancies, but it would be desirable for one and only one roadside transceiver to be attempting to communicate with each vehicle. The handover of the vehicle from one roadside transceiver to the next can be handled by the Traffic Operations Center.

So, to summarize:
Vehicle in front to the Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.

Vehicle in front to the Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back, permits the vehicle on back to detect relative position and relative speed.

Vehicle in back to the Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1/4 mile maximum range

Infrastructure to Vehicle: Message Content: Command and control requests, speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1 mile maximum range

Vehicle to Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 5% duty cycle, 2 mile maximum range

Infrastructure to ANY vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range

Furthermore, the infrastructure must sense the presence, position and velocity of vehicles within the range of authority of its Traffic Operations Center. While most of that information is provided by the vehicles themselves through the vehicle to infrastructure communications channel, the infrastructure should have independent means of obtaining the same information for the purpose of reliability through redundancy and to allow the identification of non-equipped or malfunctioning vehicles. The interval of installation of roadside sensors equals the roadside transceiver distance from each other, and the bandwidth of the communication channel between roadside sensors and TOC is roughly equal to that of the vehicle to infrastructure data channel times the maximum number of vehicles that have to be supervised at once.

15.5 FUNCTIONAL ALLOCATION

15.5.1 Baseline functions

Check-in: Allocated to vehicle in combination with the infrastructure. Function performed in coordination with the infrastructure after vehicle passes operational test. Equipped vehicles are coordinated and assisted in merging. Non-equipped or non-fit vehicles are not allowed to enter. Sequence of events description: The driver decides to enter the AHS and selects an entry point that is appropriate for his vehicle class. Once the vehicle reaches the entry point an operational test is performed. Some operational status data may have been collected during normal driving before reaching the entry point while other data may be collected on the spot. The results are communicated to the infrastructure. The infrastructure makes the go/no-go decision regarding the operability of the vehicle. A traffic light with arrows directs the driver towards the AHS lanes if the result is "go" or towards the manual lanes if the result is "no-go" As soon as the "go" condition is given and the vehicle approaches the AHS lane it's velocity control is assumed by the infrastructure in order to coordinate its motion in preparation for merging.

Transition from manual to automatic control: Allocated to the vehicle. The transition is contingent upon successful check in. Sequence of events description: Velocity control is assumed by the automatic controller first. If the vehicle velocity responds to the infrastructure commands as intended, lateral control is subsequently assumed by the automatic controller. If a failure is detected at this time, the driver is immediately notified to continue driving the vehicle as a manual vehicle and to direct it towards the manual lanes or an emergency lane.

Automated Sensing of roadway, vehicles and obstacles: Allocated to the vehicle. Sequence of events description: Electronic sensors mounted on the vehicle perform the sensing and detection functions continuously or with a repetition frequency adequate for the required bandwidth of the on-vehicle automatic controllers.

Longitudinal sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle. Lateral sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle. Obstacle sensing: Vehicle sensors are able to sense at least some kinds of obstructions other than vehicles.

Vehicle longitudinal position sensing: Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy). Vehicle lateral position sensing: Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

Automated Sensing of vehicles and obstacles: Allocated to the infrastructure. Roadway sensors belonging to the infrastructure collect information about obstacles, and the information is passed from the infrastructure to the vehicle. Sequence of events description: The infrastructure employs video cameras, radar, inductive loops and other sensors to sense as accurately as possible the location position and velocity of vehicles in the AHS lanes. Disables vehicles automatically get classified as obstacles. Detection of other obstacles (foreign objects, stray animals etc.) may be possible but of limited success.

Collision avoidance: Information from the vehicle sensors and the infrastructure is passed to the Longitudinal Velocity Controller, which acts as a longitudinal collision avoidance system. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If the information is deemed consistent it is used as input to the Longitudinal Velocity Controller. If minor inconsistencies are found the worst case scenario is assumed by the controller and the infrastructure is notified via the status report. If major inconsistencies are found an emergency is declared and the driver is notified that he may have to resume manual control. At the same time the infrastructure and other vehicles in the vicinity are notified and requested to increase their distance from the malfunctioning vehicle. If the information from all sensors is consistent and indicates that the vehicle is in a collision path with another vehicle or a newly identified obstacle, the Longitudinal Velocity Controller attempts to reduce the velocity by applying emergency braking. A change lane request may also be generated by the vehicle and transmitted to the infrastructure.

Automated headway keeping: Allocated to the vehicle. Vehicle sensors measure relative position and relative speed to the vehicle in front. The controller can control the velocity and headway of the vehicle down to zero velocity, including stop and go situations. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If deemed consistent, this information becomes the input to the Longitudinal Controller, which applies throttle or brake as necessary to maintain the headway that is recommended by the infrastructure. The headway recommendation of the infrastructure can be adjusted by the vehicle controller depending on information from the vehicles in front and in the back and also according to the road surface conditions and the infrastructure notified of any changes.

Automated Lateral Controller. (Lane Keeping): Vehicle based, but it most likely will require the presence of "markers" or other aids from the infrastructure. Sequence of events description: The on-vehicle sensors detect the position of the vehicle in absolute terms and also relative to the lane boundaries and relative to any other vehicles on adjacent lanes. The information is used to control the steering angle such that the vehicle follows a smooth trajectory near the center of its assigned traffic lane.

Detection of hazards: Vehicle-based or in combination with the infrastructure. The vehicle may use the longitudinal and lateral sensors. The infrastructure may assist by transmitting to all vehicles the exact location of known hazards. Sequence of events description: The longitudinal and lateral sensors on the vehicle pass the information collected to the controller. The information is correlated to the information received via communications from other vehicles and the infrastructure. Any objects detected by the vehicle sensors that do not coincide with any objects known to the infrastructure are automatically classified as potential hazards and the infrastructure is immediately notified of their presence. Furthermore, if the position of the hazards appears to be in the path of the vehicle, the collision avoidance procedures is initiated automatically as well.

Normal Maneuver planning: Allocated to the vehicle in combination with the infrastructure. Executed by the vehicle based on information from the sensors and the infrastructure Sequence of events description: Based on the desired destination declared by the driver, the vehicle navigation controller employs information provided by the infrastructure to implement the vehicle travel plan. The plan is submitted to the infrastructure for approval. Depending on local conditions the infrastructure may opt to alter the travel plan and may request additional maneuvers at any time.

Emergency Maneuver planning: Allocated to the vehicle, possibly in combination with the infrastructure. In some cases it might be managed by the infrastructure. Sequence of events description: This is a very sensitive problem. It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own.

Normal Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

Emergency Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller but in some cases the driver may be called in to take over control. The exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller may apply the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver may have the option to intervene but his intervention power may be limited or his intervention power may depend on the situation, i.e. certain scenarios may allow more driver input than others. This is likely to be one of the thorniest issues regarding the eventual deployment of AHS.

Transition from automatic to manual control: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: It may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response fallback mode and normally happens immediately after check out. A likely scenario is as follows: The vehicle relinquishes partial control to the driver who is notified and expected to apply certain corrections to the vehicle velocity and path by applying a moderate amount of braking and steering. By doing so, he effectively verifies his alertness and readiness to resume full manual control. If he fails to perform the required actions within the allocated time, the vehicle controller declares the driver unfit and resumes fully automatic vehicle control. In this case the vehicle is driven automatically to a designated exit that has been designed for the accommodation of "sleeping" drivers and brought to a complete stop. A human operator will approach the vehicle and investigate the condition of the driver. If he has suffered death, loss of senses and such he is taken to a hospital. If he is found to be under the influence of drugs or alcohol he is taken to jail. If he is found to be sleeping he is rudely awakened. If he is found to be playing games i.e. testing the system, he is cited for a traffic violation.

Check out: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: Check-out may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response option. In most cases the vehicle self guides towards the exit ramp and a transition from automatic to manual control is initiated.

Flow control: Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. Sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS and a central controller at the Traffic Operations Center makes the decisions on optimal velocity, spacing and traffic routing in order to control and optimize the flow.

Malfunction management: Allocated to the vehicle, infrastructure and possibly the driver, in combination. In most cases it is cooperative between vehicle and infrastructure. Several different scenarios exist. Sequence of events description: If the malfunction is identified to be on the vehicle, it is assumed that it can be fully or partially compensated by redundancy and the vehicle is requested to check-out at the earliest opportunity. If the malfunction is identified to be on the vehicle but it is not covered by redundancy, the driver is notified and requested to resume full manual control. If the malfunction is identified to be on the infrastructure, the vehicle and the driver are notified of the exact nature and the extent of the loss of functionality and the AHS either continues operating at a degraded mode of operation or shuts down or temporarily converts to manual operation.

Handling of emergencies: Normally allocated to the vehicle or to the vehicle and the driver in combination. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. In at least some cases, it may become necessary to pass control responsibility to the driver, who would be expected to assume manual control of the vehicle.

15.6 IMPLEMENTATION

In this section we describe one possible implementation of the concept. This is by no means the only possible implementation or even the most recommended one. It is only a representative example of an implementation that allows visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between the components of the system.

15.6.1 Vehicle

The vehicle requires the following functions and subsystems:

Fail-proof longitudinal control system. The longitudinal control system serves the function of velocity and headway maintenance. The requirement for fail-proof operation of the longitudinal controller under all conditions imposes extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Accurate longitudinal position sensing. The longitudinal position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for navigation and trip destination control purposes and the relative position is for velocity and headway maintenance and control as well as for collision avoidance.

Accurate lateral position sensing and lane position identification. The lateral position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for lane keeping, lane changing and navigation purposes and the relative position is mostly for collision avoidance especially during lane changing.

Collision avoidance based on obstacle sensing in combination with vehicle to vehicle and vehicle to infrastructure communications. Vehicle sensors are not adequate and do not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.

Maneuver coordination between vehicles. Every aspect of the motion of the vehicle and especially lane changes is orchestrated and coordinated by a control authority at a higher level than the each vehicle itself. This control authority is distributed collectively among vehicles or is assigned to the infrastructure. It is most likely that a local decision affects the assignment of this control authority. In urban regions the authority may be exclusive to the infrastructure. In rural regions the authority is distributed among vehicles and in every case it is dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.

Automatic route guidance based on navigation computers and interaction with the infrastructure.

Supervisory controller that monitors everything and alerts the driver of any single point failure. Malfunction management is one of the more complicated issues facing the designers of the AHS system. It is very desirable if not essential that every part of the automation is covered by multiple redundancies so that no single point failure affects the operation of the system. At the same time, any failure must be immediately detectable and the driver must become aware of it as soon as possible. If necessary the driver is required to assume partial or full control of the vehicle.

15.6.1.1 Required vehicle components

Two longitudinal range and range rate sensors based on Forward looking Doppler radar, FMCW radar, infrared laser ranging system, optical recognition method or combination of the above are required.

Side looking vehicle and obstacle sensors based on very low power radar, sonar, or infrared light are required.

Redundant lateral lane position sensors are required. These same sensors provide absolute longitudinal position information. The sensing method includes Differential GPS and the use of lane markers, which requires a potentially large investment in the infrastructure. Candidate lane marking methods include magnetic nails, magnetic lane marking paint, corner reflectors for radar, optical patterns, and others. A single method with optimal performance cannot be identified at this time. Each system has potential merits and a number of shortcomings and limitations.

A transceiver for vehicle-to-vehicle communications is required. Communication includes, but is not limited to, velocity, acceleration and braking force. Also required is a communication ability with cars in adjacent lanes for cooperation in merging.

A lateral collision warning coupled with the steering actuator for assistance in checking in and out is required.

Environmental conditions sensors are required. The primary purpose of these sensors is to sense and/or estimate road surface conditions and friction coefficients for cornering and braking.

Driver status monitors and diagnostics are required. Although the driver is not involved in the control of the vehicle when traveling in an AHS environment, his readiness status and alertness are essential in case of detected failures in some part of the redundant controllers and needed before and during the check-out stage.

Supervisory controller monitors the performance and functionality of every part of the system, including every redundant part of the controllers, sensors and actuators, the communications systems, and driver status. The supervisory controller has the responsibility to reassign responsibilities among system parts, based on a well-defined priority system. The supervisory controller attempts to detect and recover any detectable failure. In doing so it reassigns actuator responsibilities to different parts of the system when actuator malfunctions are detected. Control responsibilities are reassigned to different controllers when control malfunctions are detected, i.e. to the infrastructure and eventually to the driver. Sensing responsibilities are reassigned to different sensors when sensing malfunctions are detected, i.e. to alternative sensors first, then to the infrastructure and eventually to the driver.

15.6.1.2. Vehicle implementation issues and considerations

In considering acceptable versus unacceptable failures of vehicle components, two independent ways of controlling the throttle, brake and steering are needed to accommodate any single point failure in the sensor, controller or actuator.

Furthermore, no single point failure of any subsystem should escape diagnosis or lead to loss of control. Care must be taken to avoid common mode failures such as loss of power to both parts of a redundant controller simultaneously.

15.6.2 Infrastructure

Required infrastructure components:

1. Low-level infrastructure components:

   Markers must be provided to assist the vehicles in performing the lane keeping function. These markers must be unambiguous and extremely reliable under all traffic, lighting, weather and temperature conditions. It is not expected that different type sensors are needed in rural versus urban sections of the highways.

   Physical barriers have to be provided to separate the AHS system from the non-AHS part of the highways. For cost considerations it might be considered as an option not to have those barriers in rural sections of the highways, though a safe alternative is unknown.

   Mixing of vehicle classes is allowed. Therefore, no separate entry/exit ramps and highway interchanges are needed.

2. Intermediate-level infrastructure components

   Low bandwidth communication (broadcasting) must be provided to all vehicles within the authority of the infrastructure and may contain "traveler information" type data. The roadside transmitters of broadcast type information are allocated as a dual redundant station with a range of 4 miles located every 6 to 8 miles in rural highway sections. In urban sections of the highways it might be preferable to employ lower power transmitters more closely spaced, e.g., 1 mile range transmitters located every 2 miles.

3. High-level infrastructure components

   Medium bandwidth bi-directional communication with individual vehicles is required. Vehicles must be individually identifiable and individually addressable both by the infrastructure controllers and by the communication transceivers. This requirement is the same in both rural and urban sections of the highways.

   Sensing of traffic flow speed and flow density, under all traffic, lighting, weather and temperature conditions is required. The accuracy requirements may be slightly relaxed in sparsely traveled rural highways, but the sensing requirements are basically the same as in urban highways.

   Sensing of individual vehicle position and velocity under all traffic, lighting, weather and temperature conditions is required. This is required in urban highway sections but may not have to be implemented in sparsely traveled rural highway sections.

   The Traffic Operations Centers must be present along the roadside at intervals that are determined based on the typical and expected traffic density. The location and the distance between those

TOCs will be different for rural and urban sections of the highways.

15.6.2.1. Rural Highway

In a rural highway environment, the necessary infrastructure may be different to some extent. It may be more cost efficient to cover larger areas with fewer traffic control stations. Those sparsely spaced traffic control stations must cover a larger number of vehicles over extended distances. If the distance between the infrastructure equipment and the vehicle is extended, long range communications, medium to high capacity communication channels, and reliable backup equipment are required. In rural environments, infrastructure sensing may be limited to flow rate and average velocity every few miles.

15.6.2.2. Urban Highway

In an urban highway environment it is likely more efficient to employ short range communications, high capacity communication channels, and closely spaced traffic control stations. Knowledge of individual vehicle position coordinates may be required at each infrastructure Traffic Operations Center site.

15.6.3 Deployment

The minimal deployable system has a longitudinal controller (maintain velocity or headway) and a lateral controller (maintain lane position) on the vehicle as well as an infrastructure system to manage the flow of traffic by providing commands and information to the vehicle.

The longitudinal controller needs a longitudinal sensor, an actuator system. and the controller hardware and software.

The lateral controller needs a lateral sensor, an actuator, and the lateral controller hardware and software.

The required communication needs a medium to high bandwidth communication transceiver on the vehicle and a communication system built into the infrastructure.

Some way for the infrastructure to monitor the traffic flow is also essential.

The incentive to buy a vehicle so equipped is that an automated vehicle driven on an automated highway offers the potential for shorter travel times and a major improvement in the comfort of the driver and passengers.

The incentive for the roadway operator to deploy an AHS roadway is the potential for reduced highway travel times, reduced pollution and most important the postponement of the need to build more highway lanes if the existing ones can be used more efficiently.

15.7 GENERAL ISSUES AND CONSIDERATIONS

What degree of automation is there in the navigation function?
The system has the capability for fully automatic navigation for any individual vehicle though it is not included as a specific requirement in the architecture. What is a characteristic of the baseline model is monitoring of each vehicle that enters the AHS, which is the most important element of a navigational system. Such information is used by infrastructure-based agents or on-board agents to navigate the vehicle automatically. The communication load on the infrastructure grows dramatically if all the vehicles are navigated by its agents. In a more reasonable scenario, the infrastructure performs the specific navigation function of initial route selection and leaves the rest of the navigation to the agents aboard an individual vehicle.

What are the obvious failure modes for the concept?
The system consists of so many subsystems that a variety of failure modes are possible. The primary failure modes can be classified into the following categories. Each category is illustrated by examples.

Sensory Failures
Vehicle cannot sense its own position:

Vehicle cannot sense the presence of other vehicles ahead,

Vehicle cannot sense the presence of obstacles ahead,

Vehicle cannot sense the presence of other vehicles aside,

Vehicle cannot sense the presence of obstacles aside, and

Vehicle cannot sense the weather conditions around.

Longitudinal Control
Vehicle cannot maintain velocity,

Vehicle cannot maintain the desired headway Lateral Control Failures, and

Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles,

Vehicle cannot receive communication from other infrastructure,

Vehicle cannot transmit to other vehicles, and

Vehicle cannot transmit to the infrastructure.

Entry/Exit Function Failures
Vehicle fails the check-in procedure.

Vehicle (or driver) fails the check-out procedure.

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy is required for most automation subsystems to guarantee fail-safe operation. Triple redundancy is required on the most critical subsystems. If designed properly, degradation of the system, in case of failure, occurs in a fashion so that if the infrastructure is unable to control a particular vehicle, it should pass control to the vehicle. In case the vehicle is unable to control itself, it is able to pass control to the driver. Each has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

The feasibility of such a design, however, is far from a settled issue.

Under what circumstances (if any) is control passed to the driver?
The driver has no control, except the high-level navigational one, e.g., choice of the destination, during normal operations on the AHS, which include lane keeping, lane following, lane-changes, automatic obstacle avoidance maneuvers.

The only circumstances in which the driver might get the control are exceptional ones. In a malfunctioning system, the infrastructure may perceive the manual option to be the safest one. In such a case it alerts the drivers and passes over the control to the drivers. Malfunctions could be of various types. If the control and execution mechanisms on the vehicle breakdown, and it renders the vehicle uncontrollable, then there is no choice but to give control to the driver. If the vehicle is functioning well, but the infrastructure manager breaks down, then the vehicle takes over the infrastructure responsibilities and still manages to keep the driver out of the loop. The performance is naturally degraded.

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?
The infrastructure constantly senses the highway environs for weather conditions, like visibility, temperature and precipitation. Some of these conditions might be localized, e.g., ice on a bridge, water collected on the inside lane, and some other might be characteristic to a larger area. The system senses the two kind of conditions in different fashion.

The weather parameters, like temperature and wind speed, are measured on a regional basis using standard technology.

Precipitation is monitored for both type and quantity, also on a regional basis.

Some weather-related conditions are measured more locally. All the bridges are monitored for icy conditions under near-zero weather conditions. The snow level on a road during or after a snowstorm, water level if it tends to log in certain locations, are measured at regular distances in each lane and at known trouble spots.

The infrastructure uses sensors that are on each vehicle to sense localized trouble spots. The vehicle passes the relevant information to the infrastructure, which can alert the on-coming traffic of the trouble spots. Vision-based systems coupled with image processing hardware may be able to discriminate some of these conditions. Local visibility, pools of water, icy patches, and friction coefficients are examples of weather elements that might be sensed by the vehicles.

Some of the weather-related information gathered by the infrastructure is directly passed on to the vehicles, who add that information to the knowledge they already possess from their own sensors or some other prior information. The weather parameters play a very important role in the functioning of the control mechanisms in adverse conditions. Certain other information is first processed by the infrastructure to generate warnings, advisories, and commands for vehicles in specific areas and lanes. It is possible for the same piece of information to result in different courses of action for different vehicles depending upon their location, class, and lane.

What speed(s) would typical users travel at? How tailorable is this?
These are conflicting requirements. A low typical velocity hurts efficiency and performance. A high typical velocity hurts fuel economy and generates potentially dangerous conditions in case of malfunctions. The risks increase exponentially with speed. The exact figures must be analyzed. An estimate is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed needs to be tailorable to local conditions, but the maximum speed probably does not.

What enhanced functions would a vehicle from this concept be able to perform on a conventional highway?
Except for basic speed and headway control, a vehicle is not currently able to perform other enhanced functions on conventional highways. However, a low-level infrastructure modification like magnetic nails and exit sensors, opens various possibilities. A vehicle, with capabilities of this concept, can possibly perform a variety of enhanced functions on these slightly modified highways. Longitudinal control functions, e.g., sophisticated lane keeping and lane following functions can be performed by such a vehicle. The technology needed to accurately sense the surroundings of a vehicle are improving. A dynamic map of the surroundings can form the basis of lateral control functions, like lane changing and even elementary obstacle avoidance. Further analysis is needed to estimate the quality of such localized lateral control. Enhanced functions that seem to be definitely out of the reach of even intelligent vehicles, in the absence of intermediate or high-level infrastructure, are advanced obstacle avoidance, global traffic flow control, route selection, and other traffic management functions.

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?
No special assistance to public transportation is expected, unless explicitly provided for in the design, e.g., direct excess to subway, rails from the AHS system. In fact, faster speeds and more throughput means that roads will be more widely used than ever. As history has told us in the past, more capacity means more drivers.

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. Their attention to actual driving operations will be of a very high-level, infrequent type.

On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept, though mixing of vehicle classes in a lane makes it a uphill task. The infrastructure has to constantly monitor the vehicle (the on-board agents still perform the micro-control), so the additional cost can be justifiably passed on to the freight carrier.

What features of this concept will most contribute to increasing throughput over the present system?
The variety of intelligent agents present aboard the vehicle or on the infrastructure most contribute to increasing throughput.

The most important are the agents aboard the vehicles which, with sophisticated longitudinal control, enable small separation between vehicles at higher speeds thereby leading to increase in throughput. Spontaneous platooning is not part of the baseline model under this concept. Even if it included as part of the concept, but not supported by the infrastructure, it is not expected to lead to significant throughput increase.

The second most important feature is the traffic flow management of the infrastructure. Since the infrastructure monitors each and every vehicle, it sets global flow parameters to maximize throughput. The specific infrastructure tasks that influence the throughput in a significant fashion are the initial placement of the vehicle in a lane, routing the vehicle to the destination, the control over the lane changing, control over exit inflow, the capability to shut down an exit temporarily, and setting localized speed limits. Each one of these is a tool in the infrastructure hands to increase throughput of the system.

The feature of mixing vehicle classes in a lane adversely affects the throughput in a significant fashion. Vehicles of similar performance level and size can safely travel closer to each other than vehicles of different classes. Moreover, the lighter vehicles can travel at a speed significantly higher than that of the heavier vehicles, since they have a lane of their own. The two factors directly result in lesser throughput.

What features of this concept will most contribute to increasing safety over the present system?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features function as designed all the time. No serious attempt is include into consideration the reliability point of view, which is often the most important one to evaluate safety.

The features which lead to fewer accident situations in the first place are listed below.

Automatic Headway Maintenance
"Rear-ends" are frequent cause of accidents in the present system. These are avoidable if a headway is maintained automatically. The control mechanism needed is the least sophisticated and most reliable among the set needed to implement this concept.

Automatic Lane-Keeping
Automatic lane-keeping enables vehicles to stay in their own lanes at all times and leads to fewer side collisions.

Automatic Lane-Changing
Many accidents in the current system occur during the process of lane changing, the reason being that the driver has to be aware of the traffic in front, side and, to some extent, back of the vehicle at the same time. All these duties are shared by different sensors under the concept implementation, therefore enabling a better decision to be taken by the intelligent agent. Moreover, the infrastructure has a control over the involved vehicles during the lane-changing process which means that there are no surprises during the process.

Automatic Obstacle Detection
Likely obstacles are detected early to give more time to the agents on-board and on the infrastructure to plan a avoidance maneuver.

Traffic Flow Management
The features like localized speed control and knowledge of traffic conditions ahead of time are important factors in improving system safety.

The features that lead to lesser injuries to limb and property in an accident situation are listed below.

Automatic Obstacle Avoidance
The maneuvers of the vehicles are coordinated to avoid the impending obstacles so that the obstacle is completely avoided or only minimal impact and injuries to limb and property occur.

Physical Barriers: The high-speed AHS traffic is separated from the non-AHS traffic using physical barriers. No manually driven vehicle is allowed to stray into the AHS lanes. An accident in low-speed lanes does not have a spill-over effect on the high-speed AHS lanes.

On the other hand, the features that lead to more accident situations are listed below.

High Speeds
The vehicles travel at much higher speeds with reduced reaction times. The chances of an accident increase in direct proportion.

Separation Policy
Vehicles are separated by smaller distances so there is a greater chance of an accident. Mixing of vehicle classes, although a feature of the present system, is not a critical factor today because of the low speeds. At high speed, mixing together with close separation can lead to more accidents.

Multitude of Electronic Control Mechanisms
Each control mechanism alone is designed to operate at levels that are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of system reliability. Heavy redundancy and multiple backup systems can improve the reliability of the system. The extent and at what cost remains to be studied.

What features of this concept will most contribute to making it cost-effective?
The costs involved in the implementation, operation and maintenance of this concept are tremendous. Instead of trying to list these, consider the relative benefits which accrue out of this concept.

As far as the user is concerned, the principal benefit is the reduced average travel-time. Even the cost of spending time in the vehicle goes down because the driver is relatively free to perform non-driving and perhaps work-related tasks. Increased comfort level and safety level are the other two major benefits. Automatic navigation is a relatively intangible benefit to the user.

The principal cost to the user is the increased cost of the vehicle, and the user fees of the system.

The features that most increase throughput are also the features that most make it cost-effective.

What will be the required vehicle maintenance?
Most electronic subsystems added to the vehicle to enable automation can be designed to be sufficiently reliable. The wear out mechanisms for electronic components have an occurrence rate in the order of a few tens of years. Random failures do occur, but maintenance cannot alter random failure rate.

It is predicted that required vehicle maintenance will only be necessary for mechanical subsystems that are subject to wear, just like with the current generation of vehicles. However, the control systems need tighter performance from the engine and the transmission. This leads to the need of more regular required check-ups and maintenance.

What will be the required infrastructure maintenance?
Infrastructure maintenance is expected to be most severe for the hardware embedded in the roads, like lane markers. Communication equipment, being key to numerous functions of the AHS, requires careful maintenance. Since the AHS cannot be stopped or taken off-line, the maintenance has to be done in a continuous fashion.

Tight enforcement has to form the backbone of this concept. A non-AHS vehicle in a AHS lane is a safety hazard. Even a momentary lapse in the AHS capabilities of a vehicle jeopardizes the well-being of it and its neighboring vehicles. To avoid this situation, a number of enforcements must be in place. Some of them are yearly safety checks while others are enforced every time the vehicle enters an AHS system. Control systems/sensors/communication devices and other electronic components must be designed to have multiple levels of redundancy and be easily testable for malfunctions. Physical parts like brakes and throttles, keys for vehicle safety, must also be checked on a regular basis.

Technically, the driver is not in the control loop as soon as the vehicle enters the system. Therefore, any problems that arise and result in an accident are not the fault of the driver. The vehicle is the responsible agent. In order for this to work as a legal argument, responsibility for the well-functioning of the vehicle must be assumed by someone. The only way the driver could be held responsible in this regard is through a system of certified checks a vehicle has to go through on regular basis. Only those cars that have the required checks are expected to enter the system. The certificates could be checked electronically every time the vehicle enters the AHS, or it could be an implicit requirement.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user)?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view?

Could you describe how the AHS operates, and the personal driving experience, from the point of view of a naive user who knows how to operate the system, but doesn't know how it works?
For a user of the AHS system under this concept, the driving experience could be compared to taking a train-ride except that you have a personalized bogey when you reach the station; you can actually drive the bogey home.

A well functioning AHS system under this concept has relatively few lane changes and lane-keeping and lane-following are so uniform that the user feels that his vehicle is just a part of a big and long procession.

In a malfunctioning AHS system, where control is passed to the driver, the driving would return to the usual non-AHS experience.

The users feel out of control in the event of automatic obstacle avoidance. Jerky, non-uniform maneuvers made by the vehicle to avoid the obstacle would appear somewhat akin to being in the seat next to the driver in the event of an accident in the current system.

The user will not feel comfortable closely following bigger vehicles. Even if mixing is allowed, the modern protocol of bigger vehicles on the right should be observed on AHS. Mixing should be used only for the transition purposes.

The users will feel strangest when driving manually in AHS lanes, if and when they have to do that (e.g., in case of breakdown of AHS capabilities of the vehicle). It is difficult to imagine how that experience would seem. The high speeds involved would make the user feel unsafe under manual control. The transition from automatic to manual control would be a nervous experience for some drivers.

16. CONCEPT 13: INFRASTRUCTURE MANAGED UNMIXED PLATOONING

16.1 OVERVIEW

This document describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Unmixed Platooning".

Concept #13 is one of four infrastructure managed AHS concepts that call for complete separation of AHS and non-AHS traffic, thereby leading to a dual highway system in the country. Among these four concepts (#12a, #12b, #13, #19), one (#19) calls for manual avoidance of obstacles, thereby depending upon the driver for an extremely important maneuver. The other three concepts, including #13, do not expect the driver to do any maneuvering from the point of entry to the point of exit and call for completely hands-off driving. These three concepts all share the feature of automatic sensing and avoidance of obstacles.

Two of these three concepts (#12b, #13) divide the highway system even further, on the basis of vehicle class. No mixing of vehicle classes is envisioned, even at the point of entry/exit and for transition purposes. This leads to a tiered AHS system, each tier catering only to certain classes.

Concept #13 is one of the two tiered concepts. It differs from the other one in that it calls for platoons instead of free agents as the primary units of longitudinal and lateral control.

This concept represents the possibility that the safest, and possibly most cost-effective, way of achieving maximum throughput is by making platoons the basic unit of traveling on roads. This boosts road capacity and takes a middle path in infrastructure-based control. The infrastructure is expected to be an intelligent agent that monitors every vehicle, but, under normal circumstances, does not control any vehicle unless requested. This keeps the cost low. The vehicle is expected to be intelligent enough to keep its lane, sense its immediate surroundings, and perform platooning functions, but is not expected to accomplish lane changes, or manage the initial placement after entry without the infrastructure's help.

The distinguishing feature of this concept is the maximum achievable throughput. Platooning, complete vehicle automation, global traffic flow management and no mixing of vehicle classes are important factors in achieving that goal. However, infrastructure investment is an important cost. Because of the tiered nature of AHS, complex and expensive interchanges and exits are required to implement this concept.

Selected Alternative from Each Dimension

16.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Concept Characteristic	Dimension Alternative
1 Distribution of Intelligence	Infrastructure managed
2 Separation Policy	Platooning
3 Mixing of AHS and non-AHS Vehicles in the Same Lane	Dedicated lanes with physical barriers
4 Mixing of Vehicle Classes in a Lane	Not Mixed
5 Entry/Exit	Dedicated
6 Obstacle Avoidance	Automatic sensing and automatic maneuver if possible

1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, passes full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and platooning functions, but may possibly use them for lateral control. The main mode of operation of the infrastructure is a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles/platoons, which respond to that request. Infrastructure takes a more pro-active role in monitoring traffic flow; it broadcasts traffic flow messages, advises lane changes to individual vehicles and performs other typical ITS functions. The infrastructure is also capable of highly intelligent functions; it takes complete control of any individual vehicle, i.e., infrastructure can completely substitute for a vehicle's intelligence and assumes longitudinal, lateral and navigational control. However, it might not have enough resources to control more than a fraction of the vehicles on the road at any time. Local officials may opt for an infrastructure that controls the vehicle only in case the vehicle (or the driver) authorizes such a transfer of control. Such a practice might be limited to off-peak hours.

2. The longitudinal separation policy is based upon platooning requirements. Extensive use of platooning is supported by the system. When used properly, it should lead to a dramatic increase in the throughput of the highway. In the baseline system, every vehicle that enters the AHS immediately becomes a candidate for platooning. Local authorities may elect to offer every individual the choice of joining a platoon or driving as a free agent. In a more likely scenario, local authorities may offer this only during light traffic conditions, e.g., during the off-peak hours of the day in a city environment, or on a sparsely used highway.

3. Only those vehicles that have fully functioning AHS capabilities are allowed to enter the AHS. Moreover, non-AHS vehicles are separated by physical barriers from AHS vehicles. The only way a non-AHS vehicle can make its way to an AHS lane is either by trespassing at the entry point, or if its AHS capabilities fail during travel. The local tailorability is minimal in this regard, as the system is jeopardized if many non-AHS vehicles find their way to AHS lanes. It implies a dual highway system in which the AHS system is completely independent of the non-AHS system.

4. Each AHS lane is meant for use by only certain classes of vehicles. No mixing is allowed. The heavy vehicles are naturally barred from the lane of lighter vehicles. The light vehicles also can not use the lane reserved for heavy vehicles, not even for transition purposes. The local tailorability is minimal since any modification would classify as a different concept, e.g., Concept #11, or #19. It implies a tiered AHS system, with each tier catering to a different set of vehicle classes. There is little interaction between the tiers; therefore, highway-to-highway interchanges would be tiered making its design highly complicated. A separate entry/exit would be required for each tier. Such a design is perhaps suitable for city commute traffic, which is often composed of similar vehicle classes.

5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and no mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes. Since there is no mixing of vehicle classes in a lane with this concept, a separate entry/exit lane is provided for each class of vehicles. The incoming vehicles can access the correct AHS lane directly without first passing through a transition area. Similarly, vehicles do not transition through lanes of other vehicle classes before exiting.

6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both on-board the vehicle and in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle would be made, if considered possible. Possible maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, emergency braking. The response takes into account the size and the type of the obstacle. The safety of the vehicle in question, and the others around it, are of supreme concern. At no stage, is human involvement expected, except possibly in the obstacle sensing. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporarily or permanent non-AHS vehicles on the highway are considered obstacles.

16.3 OPERATIONAL CONCEPT

Three different point of views are considered to illustrate the operational design of the system, that of the driver of each vehicle, that of the vehicle and that of a platoon. The emphasis is limited to the normal operating conditions.

Before these point of views are presented, it is illustrative to look at four modes of operation a vehicle can be under from the point of view of who is in charge. The intelligent agent in charge makes the high level decisions, which are executed by the agents further down in the control hierarchy.

The vehicle is in charge through the use of an array of intelligent control systems. The vehicle (and in exceptional circumstances the driver) authorizes the infrastructure to take charge, for example during the lane changes, platooning, deplatooning, entry/exit and emergencies. A platoon is in charge of the vehicle. The platoon leadership can be collective or individual, depending upon the implementation. Infrastructure wrests the charge away from the vehicle or the platoon. The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle loses the charge, it is unable to get it back on its own. The infrastructure has to reinstate the charge. Whenever a transfer of control takes place from infrastructure to the vehicle, the vehicle has to actively take control and convince the infrastructure that it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains the control. Similarly, once the driver loses the charge to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate the charge; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains the control.

16.3.1 Driver Point of View

A driver decides to enter the AHS and picks the right entry point for its vehicle classes, in case there are multiple entry points. He logs in the vehicle classes and the trip description, possibly without ever stopping. Permission to enter might be denied at this point, if the vehicle fails the AHS-capability tests. The driver is given a suggested route to the destination. The driver is expected to be a passive observer from now on under normal circumstances. Under emergency conditions, the full control may be passed over to the driver, who then assumes manual control of the vehicle.

The only operation a driver can possibly perform is the following:

1. Change of Exit: The driver registers a change of exit with the vehicle, which informs the infrastructure. Request Deplatooning: The driver may be free to make this request under the implementation where platooning is not uniformly enforced but only encouraged. If the permission is granted, the platoon breaks at one or two places to make the vehicle a free agent. Full control is passed to the vehicle.

16.3.2 Vehicle Point of View

The vehicle is guided to a position in one of the AHS lanes (decided upon by the infrastructure to optimize the traffic flow). It may involve automatic lane merging, lane changing, acceleration, deceleration, platoon formation and platoon modification. When the lane-positioning is complete, vehicle control is transferred to the vehicle. Under the baseline model, the vehicle at this point is part of a platoon, and so has very limited authority. The platoon operates as a unit. If the vehicle is a free agent, it might be expected to initiate the process of joining a platoon at this point.

Once a vehicle is in a lane in charge of itself but not a member of a platoon, it can be involved in various operations. All of the following operations are initiated by the vehicle. Some of these are redundant if a navigational subsystem is in place.

1. Lane Following and Lane Keeping: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are located on-board, control the vehicle longitudinally.
2. Request Lane Change: The vehicle decides to change lane and registers a request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agent aboard the vehicle. The request is not normally denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and the infrastructure takes charge of the vehicle. The high level decisions regarding lane changes are passed on to the from the infrastructure until the lane has been automatically changed. Control passes to the vehicle from the infrastructure when the vehicle is stably located in the new lane.
3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit, in any case a request is registered with the infrastructure. The request is granted under normal circumstances, unless the exit requested is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Platooning Request: The vehicle (or the driver) may have to make this request in the implementation where platooning is not uniformly enforced, but encouraged using other incentives. Otherwise, the infrastructure commands the vehicle to join a platoon. The infrastructure selects a platoon that is suitably located for the vehicle to join, takes control of the vehicle, and sends control commands to navigate the vehicle to the platoon. Once in position to join the platoon, the control is passed to the platoon. The platoon performs the necessary control actions to incorporate the new vehicle. The platoon retains the high level control of the vehicle as long as the vehicle is a member.
5. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of infrastructure. Automatic maneuvers are performed to avoid a collision and include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.
6. Certain operations are not initiated by the vehicle. The infrastructure, after informing the vehicle, takes control and performs these operations. These are the operations that may appear unexpected to the driver.
7. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the infrastructure may decide to take charge of the vehicle. Automatic maneuvers are then performed to avoid a collision and include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking. Automatic Deplatooning: Automatic Acceleration/Deceleration:

The above operations are performed to create room for vehicles that are attempting a lane change. Automatic Rerouting: Automatic rerouting is done by the infrastructure to optimize the overall traffic flow from the point of view of throughput and congestion.

The limited high level operations a vehicle is able to do as a member of the platoon are the following.

1. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit. In any case, a request is registered both with the infrastructure and the platoon. The request is granted under normal circumstances, unless the exit requested is overflowing or is not available for some other reasons. If the request is granted, the platoon breaks at one or two places to make the exiting vehicle a one vehicle platoon that is still under the control of the infrastructure. A series of automatic lane changes occur and the vehicle is guided to the exit lane, where the control is returned to the vehicle. Request Deplatooning: The driver may be free to make this request under the implementation where platooning is not uniformly enforced, but only encouraged. If permission is granted, the platoon breaks at one or two places to make the vehicle a free agent. Full control is passed to the vehicle.

16.3.3 Platoon Point of View

A platoon as an entity is created by the infrastructure but is not controlled by it. The intelligent agents behind it reside on the member vehicles. One particular member of a platoon is usually denoted as the leader of the platoon. Once formed, it has a life and a death. During its life it can perform many operations, some akin to a free agent vehicle and others quite different from those of a free agent vehicle.

1. Lane Following and Lane Keeping: The platoon does lane following, with assistance from an assortment of intelligent control mechanisms, to maintain speed or headway or for lane-keeping. Request Lane Change: The platoon can request a lane change for the entire platoon. It is not expected to be a frequent request as it is a very expensive maneuver from the communication point of view. The infrastructure has control of the platoon during the lane change. Removal of a Vehicle: Once a platoon gets a request from a member vehicle to deplatoon, the platoon first isolates the vehicle and then requests the infrastructure to change its lane. The broken platoon may be merged as one again afterwards. Addition of a Vehicle or a Platoon: The platoon receives a request from the infrastructure to add a suitably positioned vehicle. The platoon takes control of the vehicle and maneuvers it to join the platoon.

16.4 SYSTEM DIAGRAM

Information and control commands and parameters flow between individual vehicles, vehicles and the platoon entity, between vehicles and the infrastructure and between the platoon entity and the infrastructure. The vehicle-to-vehicle data communication is related to maneuver coordination, platooning parameters and vehicle dynamics. The vehicle-to-infrastructure data communication consists mostly of requests, e.g., lane change request, platooning requests, entry/exit request, etc. There is some additional non-request type data flow regarding obstacles detected by the sensors on the vehicle. The infrastructure to vehicle data communication consists mainly of responses to the vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc.

While the exact content of the communicated messages has not been defined yet, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are the following.

The bulk of the communication will probably take place between vehicles.

Based on prior experiments, it is estimated that messages of up to 100 bytes with a repetition rate of 1/10th of a second will be used. This requires a channel with 9600 bps capacity. A variable duty cycle is estimated, i.e. the communication channel may not always need to transmit the maximum possible message size. Vehicles that are some distance apart are not likely to need to communicate since their dynamics and trajectories do not affect each other. At the same time, it is desirable to minimize the transmitting power and range of vehicle-to-vehicle communication to minimize interference with other vehicles and to permit an efficient spectrum reuse. At this time, a 1/4 mile maximum range seems sufficient and reasonable.

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control should be localized. Each roadside transceiver only needs to communicate with a finite and limited number of vehicles. The optimal numbers must be computed after a careful analysis. At this time, only a rough estimate is possible. For reliability through redundancy, it is a good idea to make it possible for two adjacent roadside transceivers to receive the vehicle-to-infrastructure communications. Therefore, twice the range of communication from the vehicle to the roadside, as opposed to the other way around, should be allowed. The roadside-to-vehicle communications is made reliable by on-vehicle redundancies, but it would be desirable for one and only one roadside transceiver to attempt to communicate with each vehicle. The handover of the vehicle from one roadside transceiver to the next is handled by the Traffic Operations Center.

So, to summarize:
Vehicle in front-to-Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.

Vehicle in front to the Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back permits the vehicle on back to detect relative position and relative speed.

Vehicle in back to the Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1/4 mile maximum range

Infrastructure-to-Vehicle: Message Content: Command and control requests, speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1 mile maximum range

Vehicle-to-Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 5% duty cycle, 2 mile maximum range

Infrastructure-to-ANY-Vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range

Furthermore, there is a need for the infrastructure to be able to sense the presence, position and velocity of vehicles, within the range of authority of its Traffic Operations Center. Most of that information is provided by the vehicles themselves, through the vehicle to infrastructure communications channel. However, for reliability through redundancy, the infrastructure should have an independent way to obtain the same information. This also allows the identification of non-equipped or malfunctioning vehicles. The installation interval for roadside sensors is approximately equal to the roadside transceiver distance from each other. The bandwidth of the communication channel between roadside sensors and the TOC is roughly equal to that of the vehicle-to-infrastructure data channel times the maximum number of vehicles that may need supervision at once.

16.5 FUNCTIONAL ALLOCATION

16.5.1 Baseline Functions

Check-in: Allocated to vehicle in combination with the infrastructure. Function performed in coordination with the infrastructure after vehicle passes operational test. Equipped vehicles are coordinated and assisted in merging. Non-equipped or non-fit vehicles are not allowed to enter. Sequence of events description: The driver decides to enter the AHS and selects an entry point that is appropriate for his vehicle class. Once the vehicle reaches the entry point, an operational test is performed. Some operational status data has been collected during normal driving before reaching the entry point, while other data must be collected on the spot. The results are communicated to the infrastructure. The infrastructure makes the go/no-go decision regarding the operability of the vehicle. A traffic light with arrows directs the driver towards the AHS lanes, if the result is "go", or towards the manual lanes, if the result is "no-go" As soon as the "go" condition is given and the vehicle approaches the AHS lane, its velocity control is assumed by the infrastructure to coordinate its motion in preparation for merging into traffic.

Transition from manual to automatic control: Allocated to the vehicle. The transition is contingent upon a successful check in. Sequence of events description: Velocity control is assumed by the automatic controller first. If the vehicle velocity responds to the infrastructure commands as intended, lateral control is subsequently assumed by the automatic controller. If a failure is detected at this time, the driver is immediately notified to continue driving the vehicle as a manual vehicle and to direct it towards the manual lanes or an emergency lane.

Automated Sensing of roadway, vehicles and obstacles: Allocated to the vehicle. Sequence of events description: Electronic sensors mounted on the vehicle perform the sensing and detection functions continuously or with a repetition frequency adequate for the required bandwidth of the on-vehicle automatic controllers.

Longitudinal sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle. Lateral sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle. Obstacle sensing: Vehicle sensors are able to sense at least some kinds of obstructions, other than vehicles.

Vehicle longitudinal position sensing: Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy). Vehicle lateral position sensing: Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

Automated Sensing of vehicles and obstacles: Allocated to the infrastructure. Roadway sensors belonging to the infrastructure collect information about obstacles, and the information is passed from the infrastructure to the vehicle. Sequence of events description: The infrastructure employs video cameras, radar, inductive loops and other sensors to sense as accurately as possible the location position and velocity of vehicles in the AHS lanes. Disabled vehicles are automatically classified as obstacles. Detection of other obstacles (foreign objects, stray animals etc.) may be possible but of limited success.

Collision avoidance: Information from the vehicle sensors and the infrastructure is passed to the Longitudinal Velocity Controller which acts as a longitudinal collision avoidance system. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If the information is deemed consistent it is used as input to the Longitudinal Velocity Controller. If minor inconsistencies are found the worst case scenario is assumed by the controller and the infrastructure is notified via the status report. If major inconsistencies are found, an emergency is declared and the driver is notified that he may have to resume manual control. At the same time the infrastructure and other vehicles in the vicinity are notified and requested to increase their distance from the malfunctioning vehicle. If the information from all sensors is consistent and indicates that the vehicle is in a collision path with another vehicle or a newly identified obstacle, the Longitudinal Velocity Controller attempts to reduce the velocity by applying emergency braking. A change lane request may also be generated by the vehicle and transmitted to the infrastructure.

Automated headway keeping: Allocated to the vehicle. Vehicle sensors measure relative position and relative speed to the vehicle in front. The controller can control the velocity and headway of the vehicle down to zero velocity, including stop and go situations. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If deemed consistent, this information becomes the input to the Longitudinal Controller, which applies throttle or brake as necessary to maintain the headway that is recommended by the infrastructure. The headway recommended of the infrastructure can be adjusted by the vehicle controller depending on information from the vehicles in front and back and also according to the road surface conditions. The infrastructure is notified of any changes.

Automated Lateral Controller. (Lane Keeping): Vehicle based, but it most likely will require the presence of "markers" or other aids from the infrastructure. Sequence of events description: The on-vehicle sensors detect the position of the vehicle in absolute terms and also relative to the lane boundaries and relative to any other vehicles on adjacent lanes. The information is used to control the steering angle so that the vehicle follows a smooth trajectory near the center of its assigned traffic lane.

Detection of hazards: Vehicle-based or in combination with the infrastructure. The vehicle may use the longitudinal and lateral sensors. The infrastructure assists by transmitting to all vehicles the exact location of known hazards. Sequence of events description: The longitudinal and lateral sensors on the vehicle pass the information collected to the controller. The information is correlated to the information received via communications from other vehicles and the infrastructure. Any objects detected by the vehicle sensors that do not coincide with any objects known to the infrastructure are automatically classified as potential hazards and the infrastructure is immediately notified of their presence. Furthermore, if the position of the hazards appears to be in the path of the vehicle, the collision avoidance procedures are automatically initiated as well.

Normal Maneuver planning: Allocated to the vehicle in combination with the infrastructure. Executed by the vehicle based on information from the sensors and the infrastructure Sequence of events description: Based on the desired destination declared by the driver, the vehicle navigation controller employs information provided by the infrastructure to implement the vehicle travel plan. The plan is submitted to the infrastructure for approval. Depending on local conditions the infrastructure may opt to alter the travel plan and may request additional maneuvers at any time.

Emergency Maneuver planning: Allocated to the vehicle, possibly in combination with the infrastructure. In some cases it may be managed by the infrastructure. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own.

Normal Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

Emergency Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller but in some cases the driver may be called in to take over control. The exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver has the option to intervene but his intervention power is limited or depends on the situation, i.e., certain scenarios allow more driver input than others. This is likely to be one of the thorniest issues regarding the eventual deployment of AHS.

Leading a platoon: Allocated to the vehicle in combination with the infrastructure. Sequence of events description: The leader and/or the infrastructure decides the speed, inter-vehicle spacing and other parameters of the platoon. The parameters are communicated to the member vehicles who generate their local control commands (micro-commands) using those parameters.

Transition from free agent vehicle to platoon control: Allocated to the vehicle and the platoon and possibly to the infrastructure as well. Sequence of events description: The platoon receives a request from a new vehicle that wants to join-in. The infrastructure is notified, and when the infrastructure approves, the vehicle is given the appropriate commands to maneuver and join the platoon.

Transition from platoon to free agent vehicle control: Allocated to the vehicle and the platoon. Sequence of events description: The platoon receives a request from a vehicle for deplatooning, isolates the vehicle, slowly transfers control to the vehicle and breaks into two separate platoons. If the vehicle changes the lane immediately, the two platoons may rejoin.

Transition from automatic to manual control: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: It may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response fallback mode. This normally happens immediately after check out. A likely scenario is as follows: The vehicle relinquishes partial control to the driver who is notified and expected to apply certain corrections to the vehicle velocity and path through the application of a moderate amount of braking and steering. By doing so he effectively verifies his alertness and readiness to resume full manual control. If he fails to perform the required actions within the allocated time, the vehicle controller declares that the driver is unfit and resumes fully automatic vehicle control. In this case, the vehicle is driven automatically to a designated exit that has been designed for the accommodation of "sleeping" drivers and brought to a complete stop. A human operator will approach the vehicle and investigate the condition of the driver. If he has suffered death, loss of senses, and such he is taken to a hospital. If he is found to be under the influence of drugs or alcohol he is taken to jail. If he is found to be sleeping he is awakened. If he is found to be playing games i.e., testing the system, he is cited for a traffic violation.

Check out: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: Check-out may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response option. In most cases, the vehicle is self guided towards the exit ramp and a transition from automatic to manual control is initiated.

Flow control: Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. Sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS and a central controller at the Traffic Operations Center makes the decisions on optimal velocity, spacing and traffic routing in order to control and optimize the flow.

Malfunction management: Allocated to the vehicle, infrastructure and possibly the driver, in combination. In most cases it is cooperative between vehicle and infrastructure. Several different scenarios exist. Sequence of events description: If the malfunction is identified to be on the vehicle, it is assumed that it can be fully or partially compensated by redundancy and the vehicle will be requested to check-out at the earliest opportunity. If the malfunction is identified to be on the vehicle but it is not covered by redundancy, the driver is notified and requested to resume full manual control. If the malfunction is identified to be on the infrastructure, the vehicle and the driver are notified of the exact nature and the extent of the loss of functionality and the AHS either continues operating in a degraded mode, shuts down or it is temporarily converted to manual operation.

Handling of emergencies: Normally allocated to the vehicle or to the vehicle and the driver in combination. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. In at least some cases, it may become necessary to pass control responsibility to the driver, who would be expected to assume manual control of the vehicle.

16.6 IMPLEMENTATION

In this section one *possible* implementation of the concept is described. This is by no means the only possible implementation or even the most recommended one. It is only a representative example of an implementation that allows visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between the components of the system.

16.6.1 Vehicle

The vehicle requires the following functions and subsystems:

Fail-proof longitudinal control system. The longitudinal control system serves the function of velocity and headway maintenance. The requirement for fail-proof operation of the longitudinal controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Accurate longitudinal position sensing. The longitudinal position of the vehicle must be known both in absolute terms and in terms of relative position to other vehicles. The absolute position must be known for navigation and trip destination control purposes and the relative position must be known for velocity and headway maintenance and control as well as for collision avoidance.

Accurate lateral position sensing and lane position identification. The lateral position of the vehicle must be known both in absolute terms and in terms of relative position to other vehicles. The absolute position must be known for lane keeping, lane changing and navigation purposes and the relative position must be known mostly for collision avoidance especially during lane changing.

Collision avoidance based on obstacle sensing in combination with vehicle to vehicle and vehicle to infrastructure communications. It is anticipated that vehicle sensors will not be adequate and will not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.

Maneuver coordination between vehicles. Every aspect of the motion of the vehicle and especially lane changes has to be orchestrated and coordinated by a control authority at a higher level than the each vehicle itself. This control authority is distributed collectively among vehicles or is assigned to the infrastructure. It is most likely that a local decision will affect the assignment of this control authority. In urban regions the authority may be exclusive to the infrastructure. In rural regions the authority may be distributed among vehicles and in every case it may be dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.

Automatic route guidance based on navigation computers and interaction with the infrastructure.

Supervisory controller, which monitors everything and alerts the driver of any single point failure. Malfunction management will be one of the most complicated issues facing the designers of the AHS system. It is very desirable if not absolutely essential that every part of the automation be covered by multiple redundancies such that no single point failure can affect the operation of the system. At the same time, any failure must be immediately detectable and the driver should become aware of it as soon as possible. If necessary the driver is required to assume partial or full control of the vehicle.

16.6.1.1. Required vehicle components

Two longitudinal range and range rate sensors. They are based on Forward looking Doppler radar, FMCW radar, infrared laser ranging system, optical recognition method or combination of the above.

Side looking vehicle and obstacle sensors. They are based on very low power radar, sonar, or infrared light.

Redundant lateral lane position sensors. The same sensors provide absolute longitudinal position information. The sensing method will include Differential GPS and the use of lane markers, which requires a potentially large investment in infrastructure. Candidate lane marking methods include magnetic nails, magnetic lane marking paint, corner reflectors for radar, optical patterns and others. A single method with optimal performance cannot be identified at this time. Each system has potential merits and a number of shortcomings and limitations at the same time.

Transceiver for vehicle to vehicle communications. Communication includes but is not limited to velocity, acceleration and braking force. Also required is communication ability with cars in adjacent lanes for cooperation in merging.

Platooning protocol controller. Requires extended bandwidth longitudinal and lateral controllers, as well as high precision sensors and actuators.

Lateral collision warning coupled with the steering actuator for assistance in checking in and out.

Environmental conditions sensors. The primary purpose of these sensors is to sense and/or estimate road surface conditions and especially friction coefficients for cornering and braking.

Driver status monitors and diagnostics. Although the driver is not involved in the control of the vehicle when traveling in an AHS environment, his readiness status and alertness are essential pieces of information in case of detected failures of some part of the redundant controllers, as well as before and during the check out stage.

Supervisory controller. The supervisory controller monitors the performance and functionality of every part of the system, including every redundant part of the controllers, sensors and actuators, the communications systems and also driver status. The supervisory controller has the responsibility of reassigning responsibilities among parts of the system based on a well defined system of priorities. The supervisory controller attempts to detect and recover any detectable failure. In doing so it reassigns actuator responsibilities to different parts of the system when actuator malfunctions are detected. Control responsibilities are reassigned to different controllers when control malfunctions are detected, i.e. to the infrastructure and eventually to the driver. Sensing responsibilities are reassigned to different sensors when sensing malfunctions are detected, i.e. to alternative sensors first, then to the infrastructure and eventually to the driver.

16.6.1.2. Vehicle implementation issues and considerations

In considering acceptable versus unacceptable failures of vehicle components, two independent ways of controlling the throttle, brake and steering must be provided to accommodate any single point failure in the sensor, controller or actuator.

Furthermore, no single point failure of any subsystem must escape diagnosis or lead to loss of control. Care must be taken to avoid common mode failures such as loss of power to both parts of a redundant controller simultaneously.

16.6.2 Infrastructure

Required low-level infrastructure components
Markers must be provided to assist the vehicles in performing the lane keeping function. The markers must be unambiguous and extremely reliable under all traffic, lighting, weather and temperature conditions. It is not expected that different type sensors will be needed in rural versus urban sections of the highways.

Physical barriers must be provided to separate the AHS system from the non-AHS part of the highways. For cost considerations it might be considered as an option not to have those barriers in rural sections of the highways, although a safe alternative at this time is not known.

No mixing of vehicle classes is allowed. This implies that separate entry/exit ramps and highway interchanges are needed to accommodate more than one vehicle class. Again this may be the subject of a cost versus benefit analysis on sparsely traveled rural highways.

Required intermediate-level infrastructure components
Low bandwidth communication (broadcasting) to all vehicles within the authority of the infrastructure. May contain "traveler information" type data. The roadside transmitters of broadcast type information are allocated as a dual redundant station with a range of 4 miles located every 6 to 8 miles in rural highway sections. In urban sections of the highways, it might be preferable to employ lower power transmitters more closely spaced. For example, 1 mile range transmitters located every 2 miles.

Required high-level infrastructure components
Medium bandwidth bi-directional communication with individual vehicles is required. Vehicles must be individually identifiable and individually addressable, both by the infrastructure controllers and by the communication transceivers. This requirement is the same in both rural and urban sections of the highways.

Sensing of traffic flow speed and flow density, under all traffic, lighting, weather and temperature conditions must be possible. The accuracy requirements may be slightly relaxed in sparsely traveled rural highways, but the sensing requirements are basically the same as in urban highways.

Sensing of individual vehicle position and velocity under all traffic, lighting, weather and temperature conditions. This is required in urban highway sections but may not have to be implemented in sparsely traveled rural highway sections.

Traffic Operations Centers are required to be present along the roadside at intervals to be determined based on the typical and the expected traffic density. The location and the distance between those TOCs will be different for rural and urban sections of the highways.

16.6.2.1. Rural Highway

In a rural highway environment the necessary infrastructure will probably be different to some extent. It may be more cost efficient to cover larger areas with fewer traffic control stations. Those sparsely spaced traffic control stations must cover a larger number of vehicles over extended distances. If the distance between the infrastructure equipment and the vehicle is extended, long range communications, medium to high capacity communication channels, and reliable backup equipment are needed. In rural environments, infrastructure sensing may be limited to flow rate and average velocity every few miles.

16.6.2.2. Urban Highway

In an urban highway environment, it is likely more efficient to employ short range communications, high capacity communication channels, and closely spaced traffic control stations. Knowledge of individual vehicle position coordinates may be required at each infrastructure Traffic Operations Center site.

16.6.3 Deployment

The minimal deployable system requires a longitudinal controller (maintain velocity or headway) and a lateral controller (maintain lane position) on the vehicle as well as an infrastructure system to manage the flow of traffic by providing commands and information to the vehicle.

For the longitudinal controller a longitudinal sensor, an actuator system, and the controller hardware and software are needed.

For the lateral controller a lateral sensor, an actuator and the lateral controller hardware and software are needed.

For the communication required a medium to high bandwidth communication transceiver on the vehicle and a communication system built into the infrastructure are needed.

Some way for the infrastructure to monitor the traffic flow is essential.

The incentive for the buyer to obtain a vehicle so equipped is that an automated vehicle driven on an automated highway offers the potential for shorter travel times and a major improvement in the comfort of the driver and passengers.

The incentive for the roadway operator to deploy an AHS roadway is the potential for reduced highway travel times, reduced pollution and most important the postponement of the need to build more highway lanes if the existing ones can be used more efficiently.

16.7 GENERAL ISSUES AND CONSIDERATIONS

What degree of automation is there in the navigation function?
The system has the capability for fully automatic navigation for any individual vehicle though it is not included as a specific requirement in the architecture. What is a characteristic of the baseline model is monitoring of each vehicle which enters the AHS. That is, however, the most important element of a navigational system. Such information can be used by infrastructure-based agents or on-board agents to navigate the vehicle automatically. The communication load on the infrastructure would grow dramatically if all the vehicles are being navigated by its agents. In a more reasonable scenario, the infrastructure performs the specific navigation function of initial route selection and leaves the rest of the navigation to the agents aboard an individual vehicle.

What are the obvious failure modes for the concept?
The system consists of so many subsystems that it will have a variety of failure modes. The primary failure modes can be classified into the following categories. Each category is illustrated by examples.

Sensory Failures
Vehicle cannot sense it's own position.

Vehicle cannot sense the presence of other vehicles ahead.

Vehicle cannot sense the presence of obstacles ahead.

Vehicle cannot sense the presence of other vehicles aside.

Vehicle cannot sense the presence of obstacles aside.

Vehicle cannot sense the weather conditions around.

Longitudinal Control Failures
Vehicle cannot maintain velocity.

Vehicle cannot maintain the desired headway.

Lateral Control Failures
Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles.

Vehicle cannot receive communication from other infrastructure.

Vehicle cannot transmit to other vehicles.

Vehicle cannot transmit to the infrastructure.

Platooning Function Failures
Vehicle cannot coordinate its maneuvers with the platoon.

Entry/Exit Function Failures
Vehicle fails the check-in procedure.

Vehicle (or driver) fails the check-out procedure.

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy will be required for most automation subsystems to guarantee fail-safe operation. Triple redundancy will be required on the most critical subsystems. If designed properly, degradation of the system, in case of failure, occurs in a fashion so that if the infrastructure (or a platoon) is unable to control a particular vehicle then it should pass down the control to the vehicle; in case the vehicle is unable to control itself, it is able to pass down the control to the driver. Each of these infrastructure, platoon, vehicle has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

The feasibility of such a design, however, is far from a settled issue. If a platoon looses control of a member vehicle, it is unlikely that vehicle has enough time to take over the control without colliding with the neighboring vehicles. It implies that platoon functions should be designed such that each vehicle is always under control of itself as much as it is feasible within the concept of a platoon. The control subsystems have to be intelligent enough to recognize and differentiate the impending failures of other subsystems.

Under what circumstances (if any) is control passed to the driver?
The driver has no control, except the high-level navigational one, e.g., choice of the destination, during normal operations on the AHS which include lane keeping, lane following, lane-changes, automatic obstacle avoidance maneuvers.

The only circumstances in which the driver might get the control are exceptional ones. In a malfunctioning system, the infrastructure may perceive the manual option to be the safest one. In such a case it will alert the drivers and pass over the control to the drivers. Malfunctions could be of various types. If the control and execution mechanisms on the vehicle breakdown, and it renders the vehicle uncontrollable, then there is no choice but to give over the control to the driver. If the vehicle is functioning well but the infrastructure manager breaks down, then the vehicle could take over the infrastructure responsibilities and still manage to keep the driver out of the loop. The performance will be naturally degraded.

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?
The infrastructure constantly senses the highway environs for weather conditions, like visibility, temperature and precipitation. Some of these conditions might be localized, e.g., ice on a bridge, water collected on the inside lane, and some other might be

characteristic to a larger area. The system senses the two kind of conditions in different fashion.

The weather parameters like temperature and wind speed are measured on regional basis using the standard technology. The precipitation is monitored for both type and quantity also on a regional basis.

Some weather-related conditions are measured more locally. All the bridges are constantly monitored for icy conditions under near-zero weather conditions. The snow level on road during or after a snowstorm, water level if it tends to log in certain locations are measured at regular distances in each lane and at the known trouble spots.

The infrastructure may use the sensors which are on each vehicle for sensing localized trouble spots. The vehicle passes on the relevant information to the infrastructure which can alert the on-coming traffic of the trouble spots. Vision based systems coupled with image processing hardware may be able to discriminate some of these conditions. Local visibility, pools of water, icy patches, and friction coefficients are examples of weather elements which might be sensed by the vehicles.

Some of the weather related information gathered by the infrastructure is directly passed on to the vehicles, who add that information to the knowledge they already possess from their own sensors or some other prior information. The weather parameters play a very important role in functioning of the control mechanisms in the adverse conditions. Certain other information is first processed by the infrastructure to generate warnings, advisories and commands for vehicles in specific areas and lanes. Same piece of information can result into different course of action for different vehicles depending upon their location, class, and lane.

What speed(s) would typical users travel at? How tailorable is this?

There are conflicting requirements. A low typical velocity will hurt efficiency and performance. A high typical velocity will hurt fuel economy and may generate potentially dangerous conditions in case of malfunctions. The risks increase exponentially with speed. The exact figures will have to be analyzed. A ball-park figure is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed will have to be tailorable to local conditions, but the maximum speed probably not.

What enhanced functions would a vehicle from this concept be able to perform on a conventional highway?

Except for basic speed and headway control, no other enhanced functions would a vehicle be able to perform on conventional highways of today. However, a low-level infrastructure modification like magnetic nails and exit sensors, could open up various possibilities. A vehicle, with capabilities of this concept, can possibly perform a variety of enhanced functions on these slightly modified highways. Longitudinal control functions, e.g., sophisticated lane keeping and lane following functions can be performed by such a vehicle. Platooning is also within reach of these vehicles. The technology needed to accurately sense the surroundings of a vehicle are improving day-by-day. A dynamic map of the surroundings can form the basis of lateral control functions, like lane changing and even elementary obstacle avoidance. Further analysis is needed to estimate the quality of such localized lateral control. The enhanced functions which seem to be definitely out of the reach of even intelligent vehicles, in the absence of intermediate or high-level infrastructure, are advanced obstacle avoidance, global traffic flow control, route selection, and other traffic management functions.

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?

No special assistance to public transportation is expected, unless explicitly provided for in the design, e.g., direct excess to subway, rails from the AHS system. In fact, faster speeds and more throughput means that more will use the roads than ever, as history has told us in the past, more capacity means more drivers.

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. The attention they need to give to actual driving operations will be of very high-level infrequent type. On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept. The infrastructure will have to constantly monitor the vehicle (the on-board agents still perform the micro-control), therefore the additional cost can be justifiably passed on to the freight carrier. No mixing of vehicle classes in a lane further enable the possibility of a platoon of human-less freight carriers, just like cargo trains. With no fear of incursion of small vehicles in their lanes, the automation of freight carriers is much easier to carry out.

What features of this concept will most contribute to increasing throughput over the present system ?
The variety of intelligent agents present aboard the vehicle or on the infrastructure will most contribute to increasing throughput.

The most important feature is platooning. It is estimated that extensive platooning can quadruple the capacity of the present system, even if the speed stays the same. The platooning is enabled by the agents aboard the vehicles. They, with sophisticated longitudinal control, enable small separation between vehicles at higher speeds thereby leading to increase in throughput.

The feature of not mixing vehicle classes in a lane is second most important factor. Vehicles of similar performance level and size can safely travel closer to each other than vehicles of different classes. Moreover, the lighter vehicles can travel at a speed significantly higher than that of the heavier vehicles, since they have a lane of their own. The two factors directly result in more throughput.

The third most important feature is the traffic flow management of the infrastructure. Since the infrastructure monitors each and every vehicle, it can set global flow parameters to maximize throughput. The specific infrastructure tasks that influence the throughput in a significant fashion are the initial placement of the vehicle in a lane, routing the vehicle to the destination, the control over the lane changing, control over exit inflow, the capability to shut down an exit temporarily, and setting localized speed limits. Each one of these is a tool in the infrastructure hands to increase throughput of the system.

What features of this concept will most contribute to increasing safety over the present system ?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features provided function as designed all the time. No serious attempt is include into consideration the reliability point of view, which is often the most important one to evaluate safety.

The features which lead to fewer accident situations in the first place are listed below.

Automatic Headway Maintenance: "Rear-ends" are frequent cause of accidents in the present system. It can be avoided if a headway is maintained automatically. The control mechanism needed is least sophisticated and most reliable among the set needed to implement this concept. Automatic Lane-Keeping: Automatic lane-keeping enables vehicles to stay in their own lanes at all times leading to fewer side collisions. Automatic Lane-Changing: A lot of accidents in the current system occur during the process of lane changing, the reason being that the driver has to be aware of the traffic in front, side and, to some extent, back of the vehicle at the same time. All these duties will be shared by different sensors under the concept implementation, therefore enabling a better decision to be taken by the intelligent agent. Moreover, the infrastructure has a control over the involved vehicles during the lane-changing process which means that there are no surprises during the process. Automatic Obstacle Detection: Likely obstacles are detected early thereby giving more time to the agents on-board and on the infrastructure to plan a avoidance maneuver. Traffic Flow Management: The features like localized speed control and knowledge of traffic conditions ahead of time are important factors in improving safety of the system. No Mixing of Vehicle Classes: Each lane contains vehicles of only the same class. A tighter longitudinal control is possible resulting into safer operations.

The feature which lead to lesser injuries to limb and property in an accident situation are listed below.

Automatic Obstacle Avoidance: The maneuvers of the vehicles are coordinated to avoid the impending obstacles thereby leading to completely avoiding the obstacle or minimal impact and injuries to limb and property. Physical Barriers: The high-speed AHS traffic is separated from the non-AHS traffic using physical barriers. No manually driven vehicle is allowed to stray into the AHS lanes. An accident in low-speed lanes does not have a spill-over effect on the high-speed AHS lanes.

On the other hand, the features which lead to more accident situations are listed below.

High Speeds: The vehicles travel at much higher speeds with reduced reaction times. The chances of an accident increase in direct proportion. Separation Policy: The platooning policy is fraught with dangers of serious accidents because of the small separation between the vehicles. Multitude of Electronic Control Mechanisms: Each control mechanism alone is designed to be operate at levels which are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of reliability of such a system. Heavy redundancy and multiple backup systems can improve the reliability of the system but to what extent and at what cost remains to be studied.

What features of this concept will most contribute to making it cost-effective?
The costs involved in the implementation, operation and maintenance of this concept are obviously tremendous. Instead of trying to list these, we look at the relative benefits which accrue out of this concept. The features which most increase the throughput are also the features which most make it cost-effective.

As far as the user is concerned the principal benefit is the reduced average travel-time. Even the cost of spending time in the vehicle goes down because the driver is relatively free to perform non-driving and perhaps work-related tasks. Increased comfort level and safety level are the other two major benefits. Automatic navigation has an associated relatively intangible benefit to the user.

The principal cost to the user is the increased cost of the vehicle, and the user fees of the system.

What will be the required vehicle maintenance?
Most electronic subsystems that will be added on the vehicle to enable automation can be designed to be sufficiently reliable. The wear out mechanisms for electronic components have an occurrence rate in the order of a few tens of years. Random failures do occur but maintenance cannot alter the random failure rate.

It is predicted that required vehicle maintenance will only be necessary for mechanical subsystems that are subject to wear, just like with the current generation of vehicles. However, the control systems needs tighter performance from the engine and the transmission. This leads to the need of more regular required check-ups and maintenance.

What will be the required infrastructure maintenance?
Infrastructure maintenance is expected to most severe for the hardware embedded in the roads, like lane markers. Communication equipment, being key to numerous functions of the AHS, will require careful maintenance. Since the AHS cannot be stopped or taken off-line, the maintenance has to be done in a continuous fashion. What does this concept assume in the way of support from the external world (e.g., enforcement, safety checks,...) ?

Tight enforcement will have to form the backbone of this concept. A non-AHS vehicle in a AHS lane is a safety hazard. Even a momentary lapse in the AHS capabilities of a vehicle can jeopardize the well-being of it and its neighboring vehicles. To avoid this situation, a number of enforcement have to be put into place. Some of them would be yearly safety checks while others would be enforced every time the vehicle enters a AHS system. Control systems/sensors/communication devices and other electronic components have to be designed so that they have multiple levels of redundancy and they are easily testable for malfunctions. Physical parts like brakes, throttle which are key for vehicle safety have to be also checked on a very regular basis.

Technically, the driver is not in the control loop as soon as the vehicle enters the system. Therefore, any problems which might come up and result into an accident are not the fault of the driver. The vehicle is the responsible agent. In order for this to work as a legal argument, somebody has to take responsibility for well-functioning of the vehicle. The only way the driver could be held responsible in this regard is through a system of certified checks a vehicle has to go through on regular basis. Only those cars which have the required checks are expected to enter the system. The certificates could be checked electronically every time the vehicle enters the AHS, or it could be an implicit requirement.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user) ?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view? Could you describe how the AHS operates, and the personal driving experience, from the point of view of a naive user who knows how to operate the system, but doesn't know how it works?

For a user of the AHS system under this concept, the driving experience could be compared to taking a train-ride except that you have a personalized bogey and when you reach the station, you can actually drive the bogey home.

A well functioning AHS system under this concept will have relatively few lane changes and the lane-keeping and lane-following would be so uniform that the user will feel that his vehicle is just a part of a big and long procession and once in a while the vehicle changes lanes and joins another train of vehicles. Platooning will make the experience even more like that of a train.

In a malfunctioning AHS system, where the driver is passed over the control, the driving would be back to the usual non-AHS experience.

The users will feel out of control in the event of automatic obstacle avoidance. Jerky, non-uniform maneuvers made by the vehicle to avoid the obstacle would appear somewhat akin to being in the seat next to the driver in the event of an accident in the current system.

The users will feel the strangest driving manually in AHS lanes, if and when they have to do that, e.g., in case of breakdown of AHS capabilities of the vehicle. It is difficult to imagine how that experience would seem. The high speeds involved would make the user feel unsafe under manual control. The transition from automatic to manual control would be a nervous experience for some drivers.

17. CONCEPT 14: INFRASTRUCTURE SUPPORTED PLATOONS WITH GAPS IN PHYSICAL BARRIERS

17.1 OVERVIEW

Concept #14 considers *infrastructure supported platooning* of vehicles on the AHS while allowing *mixed vehicle classes in a lane*. AHS and non-AHS vehicles have *dedicated lanes with some gaps in the physical barrier*. Entry-exit to the AHS is organized using a *transition lane* structure.

We are considering this concept as it has the potential to achieve significant increase in capacity and safety of the AHS, by adding intelligence to both the vehicles and the roadside.

Traffic on the highway is organized in groups of tightly spaced vehicles, named platoons. It is clear that packing of vehicles in platoons results in increased capacity. What may be more surprising is that this can be done without a negative impact on passenger safety. By having the vehicles within a platoon follow each other with a small intra-platoon separation, we can show that if there is a failure and an impact is unavoidable, the relative speed of the vehicles involved in the collision will be small, hence, the damage will be minimized.

Close separation within platoon also allows use of low-cost inter-vehicle communication for control purposes. The inter-platoon separation, on the other hand, will be large (usual safe separation) to physically isolate the platoons from each other. The infrastructure support allows for the traffic flow to achieve its global optimum.

We now list the distinguishing features of this concept.

17.1.1 Distinguishing Features

- Platooning implies maximum achievable throughput without compromising safety of the vehicles.
- Limited infrastructure involvement implies low cost computing and communications infrastructure.

In the course of developing this concept we show that, to obtain the maximum benefits of infrastructure involvement, it is necessary to add a few special features to the infrastructure other than those allowed by the definition of *infrastructure support*. The increased functionality will be required for two purposes; entry/exit assistance which will be localized at the on-off ramps, and, vehicle specific communication capability used for dynamic routing and emergency notification.

Distributed Intelligence implies:

- Capability to optimize global measures using the roadside controllers, and
- Enhanced fault tolerant operation: The ensuing congestion due to faults/accidents can be eased by infrastructure based flow control.
- Infrastructure support can be used to relay common safety critical information for the entire section {Such as reduced safe speed when it starts raining for example}, resulting in increased safety.
- Entry/exit using transition lane eliminates construction/maintenance cost for dedicated ramps.

17.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

17.2.1 Infrastructure Support

In this concept, infrastructure support is utilized to provide dynamic information to automated vehicles such as suggesting lane changes, safe speeds, informing upcoming exit locations, upcoming lane drops or hazards and facilitating entry/exit. This type of infrastructure support is different from *infrastructure managed* since the information is relayed as a broadcast and is directed at platoon leaders.

Although the definition of *infrastructure supported* architecture rules out the possibility of communication to individual vehicle, it should be allowed for the purposes of emergency notification and dynamic routing so as to fully exploit the capabilities of roadside controllers. Relaying of vehicle specific information is also essential for achieving smooth entry/exit of automated vehicles.

17.2.1.1. Local Tailorability:

- Routing flexibility: Local authorities can influence the routing decisions taken by the infrastructure controller. For example, during construction or during a city marathon, local authorities can choose to close down sections of highway and divert traffic through other highways.
- Speed Control: Maximum speed limit can be set by local authority.
- Ramp Metering: Control over flow of vehicles entering AHS at various points.

17.2.2 Platooning With Mixed Vehicle Classes in a Lane

When automated vehicles of different classes are formed into platoons, the dynamics (such as maximum acceleration, rate of acceleration, speed, etc.) of each platoon is restricted by its slowest vehicle. From safety considerations, the intra-platoon separation should be picked according to the vehicle braking capability. Thus, passenger cars can be platooned with a smaller intra-platoon separation than heavy vehicles such as trucks and buses. A mixed vehicle platoon may be created in following ways:

- Constant intra-platoon separation: The separation between any two successive vehicles is chosen to be the largest needed by a vehicle in the platoon. Introduction of one heavy vehicle in a platoon of passenger cars will increase intra-platoon separation thus, decreasing the throughput.
- Platoons with variable spacing: In this scheme, each vehicle follows its predecessor at the safe intra-platoon spacing for that vehicle. The performance of activities involving two platoons, such as joining and splitting of platoons as well as lane changes, will still be limited by the capabilities of the slower vehicles.

Local options for platooning are summarized as follows:

17.2.2.1. Local Tailorability (Platooning)

- Single vehicle platoons (free agents)
- Mixing of vehicle class in a platoon is allowed: This option can be executed in two ways as explained above. The choice of implementation should be left to the system designer rather than the local authorities.
- All vehicles in a platoon belong to a single class: results in homogeneous platoons. As the vehicles in a lane cannot exchange positions, formation of platoons of a single class depends on the percentage of vehicles of different class. With equal percentages for each class, this scheme can potentially degrade into free agent following. A particular design may force the vehicles to join the appropriate platoon at the time of entry requiring large queuing space for each vehicle class at every on-ramp.

Regardless of the platooning strategy, the AHS throughput strongly depends on the types of vehicles present in each lane at the same time. Local authorities have the following choices in this regard.

17.2.2.2. Local Tailorability (Vehicle classes in a lane)

- Multiple vehicle classes per lane: The automated highway productivity can be significantly reduced due to a relatively small percentage of heavy vehicles such as trucks and buses. For example, a vehicle with reduced acceleration/braking capabilities and lower speed will slow down all the upstream vehicles in the same lane.

- Single vehicle class per lane: Needs at least two AHS lanes to implement this strategy and also provide access to AHS for all types of vehicle all the time. One lane can be reserved for passenger cars yielding high throughput and the other lane supporting heavy vehicles as well as passenger cars. In case of a single lane AHS, the AHS lane can be reserved for passenger cars during commute hour traffic and free to use by buses/trucks during off-peak hours. In fact in can be exclusively used for trucks at night. The infrastructure support allows the local authorities to exercise such a control depending on time of the day.

17.2.3 AHS and Non-AHS Lanes Separated By Physical Barriers With Some Gaps For Entry/Exit

Requires construction of barriers along the length of the AHS. The cost of construction will be offset by enhanced safety due to separation of AHS and non-AHS vehicles.

17.2.4 Transition Lane Entry/Exit

This option has negative impact on throughput of both the AHS and non-AHS traffic. To enter the AHS lanes, vehicle have to weave through the manual lanes creating disturbance and loss of throughput for the manual lanes. Similarly high density of traffic on manual lanes can create a bottleneck at the AHS exit causing backups on the automated lanes. This option also takes away the capacity of the transition lane as the transition lane can not be used for through travel. If the entrances and exits to the AHS are close to each other (typical in an urban area), an entire lane next to the AHS will be converted into transition lane and can not be used by manual traffic. In a rural area, sections of this lane close to entry/exit is reserved for automation equipped vehicles and the other parts of the lane can be used by manual traffic. An advantage of this option is that it does not need construction of dedicated ramps.

17.2.5 Automated Sensing Obstacles and Automatic Avoidance Maneuver If Possible

Humans are good at sensing of obstacles and making decisions but not as fast as an automated system. Automated sensing requires accurate (and probably costly) sensors to detect obstacles as small as a *shoe-box* and to keep down the false alarm rate. These sensors should at least match the human sensing abilities. Design of automated avoidance maneuver should at least match the human intelligence.

Automated obstacle sensing and avoidance will be faster than its human counterpart and will eliminate some of the human driving errors such as inattentiveness.

17.3 OPERATIONAL CONCEPT

Normal operation scenarios for this concept are as follows. The vehicle under manual control first enters the manual highway using the manual on-ramp. To enter the AHS, this vehicle manually enters the transition lane.

At the beginning of the entry (the length of the transition lane needed for the entry maneuver is called entry section. The entry section ends at the gap between the barriers which is used for AHS entry) the vehicle is checked into the AHS.

The check in can be done either manually or on-the-fly.

In case of manual check-in, the driver is required to stop. The vehicle is then checked for AHS compatibility by the infrastructure and the vehicle monitoring systems. If this check is successful then the vehicle is checked into the AHS. If the check-in fails, the vehicle is denied entry into the AHS and it should re-enter the manual lane. At the successful completion of check-in, the vehicle control systems take control of all the vehicle systems and sends a message requesting entry to the infrastructure. The infrastructure should have the capability to ensure that transition lane blockage does not spill over into the manual lanes, both to preserve the capacity of the manual lanes and for the safety of high-speed oncoming traffic in the manual lanes. The infrastructure will have the capability to perform a ramp-metering type function. Thus, based on overall system conditions it decides at some time to allow entry. Once permission is granted the vehicle moves ahead towards the entrance of the highway. The vehicle has the capability to track velocity inputs, distance inputs and execute lane-change maneuvers. The vehicle then waits on the entrance ramp, and sends messages to the infrastructure requesting entry.

A feasible operational scenario for the entry process with minimal infrastructure involvement is as follows. The entry point infrastructure has detectors installed at a specified distance upstream of the point at which the entering vehicle is waiting. These detectors are used to determine the conditions in the entry zone. When the vehicle requests entry the infrastructure checks the occupancy of the entry zone. If nothing is detected then the vehicle is allowed to enter. If a platoon is detected in the entry zone then the infrastructure will have the means to sense the speed of the platoon and its distance from the entry point. If the speed and distance of the oncoming platoon are such as to allow safe entry the infrastructure will request the platoon to allow entry. If the platoon acknowledges it will be required to decelerate to a specified entry speed. After the platoon receives confirmation from the oncoming platoon it will provide the waiting vehicle with its target speed and ask it to enter.

Once the vehicle enters the AHS by performing a successful entry maneuver, it decides, based on advice received from the infrastructure, whether it wishes to change into an inner lane. If it wishes to do so then the vehicle will send lane-change requests until a platoon communicates its willingness to admit the vehicle in front of it. The vehicle will use its sensors to detect if the minimum safe spacing and safe relative velocity with respect to the responding platoon exists in its target lane. If suitable conditions exist then it will change lanes. Otherwise, it will co-ordinate with the adjacent lane platoon that has agreed to accept the vehicle in front of it. The assisting platoon will slow down till the required gap becomes available. Then a lane-change maneuver will be executed. If there is no platoon in the adjacent lane in the *safe lane change distance*, the vehicle will change lane after confirming—through inter-vehicle communication—that no vehicle in the lane beyond the target lane (in case of a three lane AHS) wants to change in the same gap.

The same process can be repeated again. If no further lane changes are required then the vehicle sensors will be used to detect the presence of a platoon that is close enough ahead to join with. If such a platoon is detected then the vehicle, based on advice from the infrastructure may request a join maneuver. If the platoon ahead is not already in excess of the maximum platoon size broadcast by the infrastructure and if the platoon ahead is not already engaged in any other maneuver, then the join maneuver will be executed in which the new vehicle will accelerate to merge with the platoon ahead. If no such vehicle is detected within a specified range then the vehicle simply continues as a one car platoon. In this architecture, we allow each platoon to be engaged in only one maneuver at a time. This restriction is necessary to ensure basic level of safety while executing a maneuver. This will ensure, for example, that during a join maneuver, another vehicle from adjacent lane will not change lane in between the two joining platoons. To maintain routing flexibility to individual vehicles, we also require that only free agents can change lane in a multilane AHS. On the other hand, a follower in a platoon is allowed to exit without creating a separate platoon. The concept does allow lane change of an entire platoon in case of emergencies and faults. A decision to engage in a maneuver is taken by the leader of every platoon. The followers in a platoon can request their leaders to initiate a maneuver for them.

The infrastructure will broadcast approaching exits and advise vehicles to change lanes. For example the infrastructure may suggest that vehicles in the innermost lane wishing to exit three exits downstream should execute one lane change maneuver. Since every vehicle knows its own exit it will process the advice of the infrastructure and act accordingly. The vehicle may also have autonomous capabilities to locate itself and take exit decisions. This is discussed further under degraded mode operation.

Once a vehicle decides to change lanes it must check its platoon status. If it is in a platoon it must request a split. If it is a leader vehicle it sends its split request to the vehicle immediately behind it. The vehicle behind reacts by assuming the role of platoon leader. It then decelerates the entire platoon to create an inter-platoon gap. The original leader vehicle is now a one car platoon. If the vehicle was a follower vehicle then it must send its split request to the platoon leader which then acknowledges the request by asking the vehicle to change mode and become a leader. Once the vehicle changes mode it retards itself and all the vehicle behind it to create a safe inter-platoon gap. Thereafter it splits again like a platoon leader. Once the vehicle is a one-car platoon it is allowed to request and execute lane change maneuvers. Platoons of larger size are not allowed to change lanes. Hereafter the lane changes would go exactly as before.

The automated vehicle exits from AHS into the transition lane. At this time, the transition lane may contain automation equipped vehicles which are driven either manually or automatically. Infrastructure based maneuver coordination is needed for safe execution of this exit maneuver. Once on the transition lane, the control is transferred to the driver. If for some reason, the driver is unable to take over control, the vehicle under automatic control is taken to a parking lot adjacent to the AHS. Upon transfer of control, the exiting vehicle enters the *leftmost* or the *fast* manual lane and continues its journey on the manual highway.

Infrastructure based maneuver coordination, similar to entry maneuver is required for merging two streams of traffic.

Before discussing abnormal or degraded mode operation we review the functional capabilities of vehicle and infrastructure as assumed till this point. A vehicle is capable of tracking a given velocity input and tracking a longitudinal distance input that specifies its distance from the vehicle in front.[5] It is capable of sensing free spaces in adjacent lanes and executing automated lane change maneuvers. It is autonomous with respect to obstacle avoidance and detection. The vehicle possesses sufficient communication capabilities to receive distance, velocity setpoints and destination based lane change advice from the infrastructure. Vehicles also posses vehicle to vehicle communication capabilities as required during join, split, lane-change, entry maneuvers.

The infrastructure on the other hand has the ability to meter entry to the AHS. It is aware of the AHS network topology, flow conditions (average speed, average density) on all parts of the AHS (This information will be obtained using roadside flow sensors such as loop detectors), and destination information collected at the point of entry. Based on this information about exits and network flow conditions the infrastructure formulates lane change policies, velocity policies, platoon separation policies, that help ensure good capacity utilization and timely exiting of vehicles. All this implies that at all sections of the highway the infrastructure has the ability to broadcast lane change advice, velocity and distance setpoints. The role of the infrastructure will still be limited as an advisory controller and the safe execution of maneuvers will be handled by individual vehicle controllers.

Moreover since the infrastructure participates in check-in and collects destination information at the point of entry,

[5]In a design based on this concept, the velocity input provided by the roadside controller will be used as a desired input and will be tracked if it is safe to do so. i.e., maintaining safe distance from the platoon in front will have higher priority. Followers of the platoon will try to maintain safe distance from preceding vehicle while tracking its velocity. Inter-platoon distance will be typically constant-time separation or a small variation thereof whereas intra-platoon separation will typically be constant distance

it has the ability to communicate with a single vehicle at its check-in stations.

We have not yet addressed the issue of vehicle routing. Since routing is dependent on network wide flow conditions, the infrastructure must be responsible at least for the collection and dissemination of network congestion information. ATIS equipped vehicles as per the ITS Architecture will have the ability to receive and process such information. We make the assumption that AHS vehicles also have the same capability. Thus, the infrastructure will support vehicles by providing dynamic travel time estimates for different links of the AHS, and relaying information about the transportation networks connected to the different AHS exits. It will also provide non-AHS traffic management centers with information about traffic flow conditions within the AHS to support the management of AHS demand. Based on this information vehicles will compute their own routes and choose their own exits. Thus, the infrastructure plays a supporting rather than a controlling role in the routing function! In order to accurately estimate the dynamically evolving state of the network it is necessary to have the vehicles periodically broadcast their planned exits to the infrastructure. Since the infrastructure requires only aggregate information, to protect the confidentiality the vehicles need not broadcast any unique identification with its destination.

Abnormal operating conditions can arise either due to the loss of infrastructure or vehicle functions. We start first with the infrastructure functions. We require that the vehicle have default values for all control setpoints, e.g., speed, intra and inter platoon distance setpoints, lane change distances etc., to be used if no inputs are received from the infrastructure for a specified period. These default values should ensure that in the sudden absence of infrastructure capabilities, the AHS continues to operate safely though possible with degraded productivity. For similar reasons, we also require that the vehicle have a default policy by which it moves out one lane per highway section as its exit approaches. Thus, even if infrastructure capabilities are lost a reasonable number of vehicles could be in the outermost lane by the time they reach the highway section containing their exit. However, this requires that the vehicle have the means of determining, without infrastructure support, its current global location to the extent that it knows its current section and how many sections away its exit is located. Such capabilities also ensure that, in the absence of infrastructure routing information, the vehicles are at least able to route themselves based on static information or the preference of the passengers. If the infrastructure capabilities are lost at the check-in station, we require that the station be closed until check-in capabilities are restored. An AHS entry-point can not function without infrastructure control.

If a vehicle loses its vehicle to infrastructure communication capability it must exit the AHS at the first available exit for the safety of surrounding vehicles, although it can safely coordinate maneuvers with other vehicles. The nearest platoon leader will communicate this exit information to the faulty vehicle or the faulty vehicle can figure it out using its own emergency response system as described above.

If a vehicle loses its vehicle-vehicle communication capability, throttle control, brake control, automated lane changing, or automated lane keeping abilities it is required to come to a complete stop in its current lane. If its inter-vehicle communication capability is intact, it can be used to coordinate an emergency maneuver with neighboring platoons to assist the stop maneuver. Assistance from neighbors is particularly needed in case of brake failure as it takes much longer to stop without brakes. The faulty vehicle is required to communicate to the infrastructure the fact that it has stopped. It will then be removed by an emergency vehicle which will be dispatched to the section from which the message was received. It is required to emit some emergency signal detectable by the emergency vehicle (e.g., hazard lights).

One should limit the use of above mentioned stop maneuver to only severe faults as a stopped vehicle in a lane creates significant loss of throughput and large delays to travelers. Thus, in case of all other non-critical faults, the faulty vehicle should use remaining capability along with help from neighboring platoons to get out of the AHS at the nearest exit. More failure specific maneuvers and control laws should be designed for that purpose.

Any vehicle that detects an obstacle on the highway is required to report the obstacle to the infrastructure. The infrastructure will be responsible for clearing the obstacle.

17.4 SYSTEM DIAGRAM

The diagram is in Figure 17.4-1.

We assume that AHS users are also customers of various ITS Services. Thus, information flows both ways from all AHS vehicles to the various ITS Service providers. The AHS operations center also exchanges information with other non-AHS traffic operations centers. This allows both traffic operations centers to know about the state of each others networks and estimate or manage demand. AHS vehicles make decisions about their desired exits and routes based on information received by them from the AHS operations center and the ITS services they purchase (e.g. ATIS). The vehicles are required to convey their routing and exit choices to the AHS operations center. This may be done through the section controllers. This routing and exit information is only required to be in aggregate form since it is required by the AHS operations center to estimate demand.

The highway is divided into sections and each section has a section controller. The section controller receives information about average flow, speed, and density from roadway sensors placed at different points in the section. If the section has an AHS entry then the entry port also has an entry controller. The section controller sends information about average speed, flow, and exiting traffic to the AHS operations center. The AHS operations center sends policies that regulate the average volume of entering traffic, exiting traffic, section flow and speed. The section controller sends the entry rates to all entry controllers in its section. The entry controllers are responsible for controlling free space and platoon speed in the entry zone and for co-ordinating the entry maneuver between the entering vehicle and the first upstream platoon, until the two detect each other and establish communications.

When emergencies occur, i.e. a vehicle experiences degraded control or communication capabilities then it is assumed that the infrastructure is able to send emergency communications to the vehicle in trouble.

Vehicles are organized in platoons. The desired platoon speed, inter platoon spacing, intra-platoon spacing for each section is broadcast by the section to all lead vehicles in the section. Vehicle to vehicle information flow pertains to that required for merge, split, lane change, entry and exit maneuvers. Vehicle to vehicle distance is sensed.

17.5 FUNCTIONAL ALLOCATIONS

17.5.1 Check-In

The human indicates his or her willingness to enter the AHS by driving onto the transition lane. The vehicle senses that it has entered the entry section.

The check-in may be performed either on-the fly or manually. In case of manual check-in, the vehicle is required to stop at the check-in station. In case of on-the-fly check-in, the vehicle performs a diagnosis of its manual and automatic control system. The vehicle checks the ability of the human to perform the hand-off of control tasks. Depending on the results of the vehicle and human checks, the human will be advised by the vehicle to either initiate or abort the transition from manual to automated control. If the vehicle or human fails the checks, and the human or vehicle does not abort the transition process (e.g., due to human error or vehicle system malfunction), then the infrastructure will broadcast to platoons entering the roadway segments in proximity to the entry gap that a rogue vehicle might enter the automated lanes.

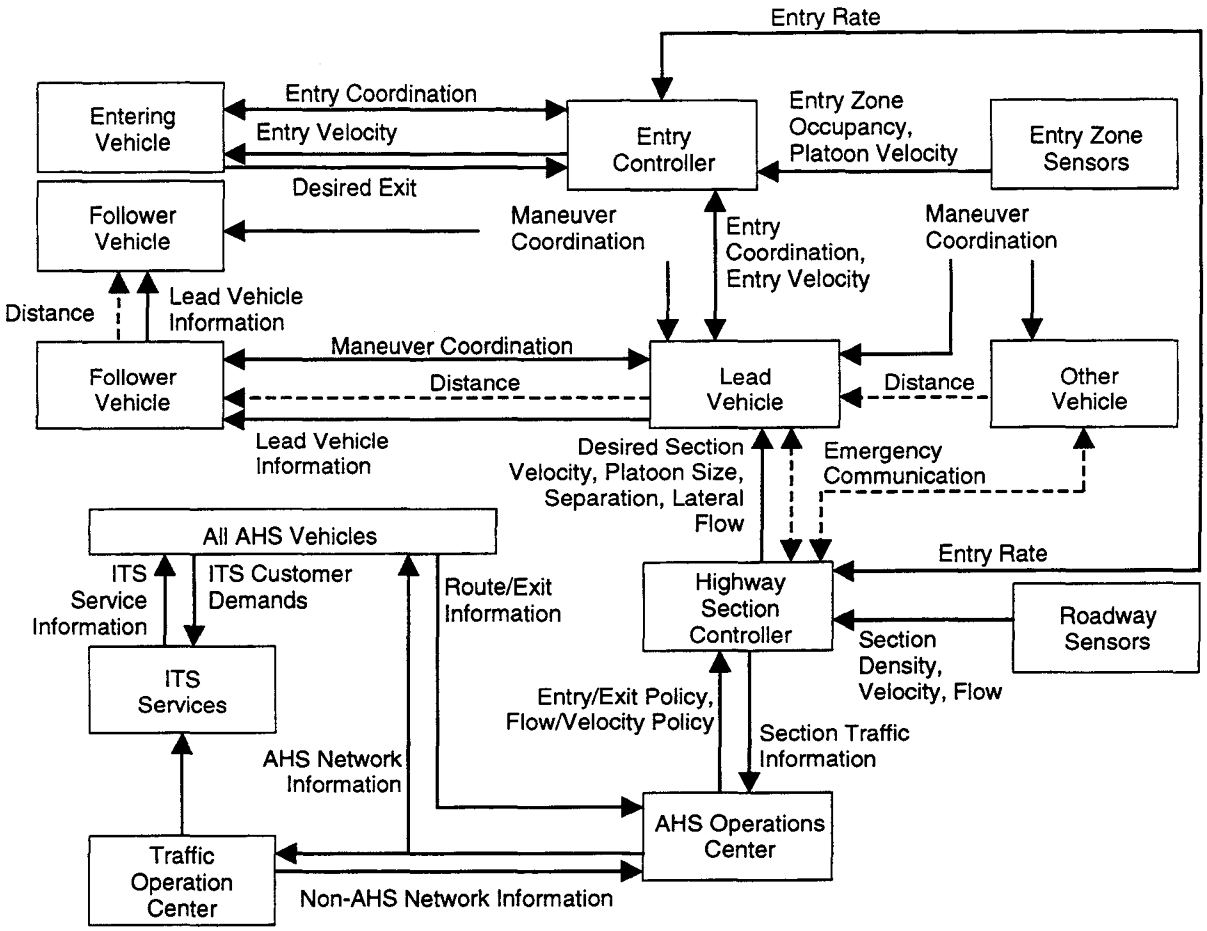

Figure 17.4-1. System Diagram

17.5.2 Transition from Manual to Automatic Control

The human relinquishes driving tasks to the vehicle control system. As each task is transferred, the vehicle acknowledges to the human that the transfer of control is complete and successful. If the transfer is complete and successful, the vehicle continues its journey onto the automated lanes under automatic control. The vehicle signals to the infrastructure that the transfer of control is complete and successful. The infrastructure, in turn, broadcasts to platoons in proximity to the entry gap the fact that a vehicle will enter the automated highway via the ramp.

If the transfer of control is incomplete or unsuccessful, in terms of human error or vehicle malfunction (e.g., failure to acknowledge transfer), then the infrastructure will broadcast to platoons entering the roadway segments in proximity to the entry gap that a rogue vehicle will enter the automated lanes.

17.5.3 Sensing of Roadway, Vehicles, and Obstructions

The vehicle performs all sensing tasks. The sensor data fusion task is shared by the vehicle and infrastructure. Fused data is transmitted to the infrastructure, which performs further fusion, yielding aggregate information regarding platoon position, location of obstruction, etc.

17.5.4 Lane and Headway Keeping

The vehicle performs all lane and headway keeping tasks. Vehicles communicate with each other, providing lane position, velocity, etc.