The decision is made by the vehicle through an assessment of the surrounding traffic. A free agent will use a deceleration to come to stop in time or to minimize the impact speed with the obstacle. The leader of a platoon will coordinate with its followers to use an appropriate braking strategy to mitigate the consequences for the whole platoon.

7.5.3 Exit and Check-Out

A vehicle exits the AHS lane by moving into the transition lane first. If the vehicle is in a platoon, it needs to request a split maneuver so that it can depart from the platoon. Once in the transition lane, the vehicle will pass through check-out stations. Once the check-out process is completed, the vehicle switches from automated to manual modes and the driver resumes control. The driver will move the vehicle manually from the transition lane into the manual traffic lane.

7.5.4 Flow Control

There is no system or infrastructure control of traffic flow. The traffic flow is determined by the local coordination of vehicles. Each free agent or platoon decides its speed by observing the speed limit or maintaining a proper distance from the preceding vehicle. The decision of a vehicle to make a lane change maneuver in a multiple-lane AHS is either prompted by the need to reach destination or by detecting an empty space in the adjacent lane.

7.5.5 Malfunction and Emergency Handling

Drivers are not involved in the obstacle avoidance process described in the preceding section. In malfunction or emergency situations, the automated modes of vehicles may be deactivated and the vehicles are brought to a stop. The drivers may be alerted and requested to resume control and to bring these vehicles to a safe location. The vehicles may also remain disabled until they are removed by highway maintenance crews. The occurrence of malfunction or emergency may be communicated to notify the highway management center.

7.6 IMPLEMENTATIONS

7.6.1 Vehicle

There are multiple specific vehicular technologies for sensing and communication.

7.6.2 Infrastructure

The implementation-related dimensions to consider include barrier configurations, entry/exit placement, lateral expansion of the roadway, vehicle classes allowed on the automated roadway, number of manual lanes, number of automated lanes, lane widths, extent of transition lane, and existence of an emergency/breakdown lane for automated vehicle usage.

In the cooperative concept, there is minimal infrastructure-vehicle communication through basic ITS services, such as traffic advisories that are transmitted globally, if not regionally. The vehicles sense the roadway through the use of magnetic markers/nails through which the automated steering system would be implemented. There would be physical barriers with openings to separate the automated lane(s) and the transition lane, and the transition lane and the manual lane(s).

7.6.2.1. <u>Barrier Configurations & Entry/Exit Placement</u>

Alternative configurations exist to implement this concept. These configurations may be classified by two parameters: (I) design, extent, and placement of barriers separating automated, transition, and manual traffic and (II) proximity of entry and exit activities. For the first parameter, the following three alternatives were considered:

1. Physical barrier between automated lane(s) and transition lane with openings and only a virtual barrier (lane stripings) between the transition lane and the manual lane(s). Only standard lane boundary markings would exist separating multiple automated lanes.

2. Physical barrier between both automated lane(s) and transition lane and between transition lane and manual lane(s). Both barriers would have openings for access to and egress from the automated lane(s). Openings in the barriers between the transition and manual lane(s) would be slightly upstream, i.e. offset, from their respective counterparts in the barrier between the automated and transition lane, though there is still substantial overlap in the two barrier opening areas.

3. Same as (2) except that the offset in the barrier openings would be substantially more pronounced. That is, the area for barrier openings between the manual lane(s) and the transition lane has NO overlap with the area for barrier openings between the transition lane and automated lane(s). In fact, corresponding to the barrier opening area between the transition and automated lane(s) is a continuous barrier between the transition and manual lane(s).

For proximity of entry and exit areas, the following two alternatives were considered:

1. A single area allowing for all entry and exit maneuvers or movements to occur

2. Two areas that are sequentially placed, first entry and then exit completely segregated from each other.

Alternative (1) would require substantially more complex communication and sensing coordination among the vehicles to insure the same level of safety than for alternative (2) since vehicles would be entering and exiting within the same general physical area.

It is suggested that entry points, i.e. automated facility check-in points, be located approximately 3.5 km apart. Exit points (check-out) would need to be located approximately 2 km following each entry point in order to allow for adequate space in which to perform entry and exit maneuvers to and from the automated lane. Vehicles wishing to exit the freeway must use an exit point far enough upstream of the desired off-ramp to allow sufficient distance in which to weave through traffic to the right lane prior to reaching the off-ramp, which will vary with traffic conditions. Entry/exit zones (check-in to check-out), areas of approximately 2 km in length in which automated lane entry and exit maneuvers take place between the automated and transition lanes, would be spaced approximately 1.5 km apart to allow for the movement of vehicles between manual and transition lanes. Within these 1.5 km weaving zones, there would be no barrier between the transition lane and the adjacent manual lane and no openings in the barrier between the transition lane and the automated lane.

Barrier openings should be offset so that at all points along the automated facility at least one barrier separates the automated and non-automated lanes. Under this option, vehicles utilizing the automated facility enter and exit the highway through existing on- and off-ramps, thereby minimizing construction costs and environmental impacts.

7.6.2.2. <u>Lateral expansion of the roadway</u>

Due to the spatial requirements of lane barriers, on many urban freeways lateral expansion of roadways would be necessary. In each direction of travel, lane barriers and barrier shoulders would require the traveled way to be widened. The need for lateral expansion of the roadway beyond the outside shoulder is dependent upon the availability of median space and lane widths. The standard minimum median width for freeways is typically considered to be 1.2 meters, comprised of a concrete median barrier (0.6 meters wide at the base) and 0.3 meters inside shoulders on each side of the barrier. It is proposed that inside shoulders would not be necessary along median barriers in an automated system since vehicles in the median lanes would be under automated control at all times. Many freeway medians are wider than 1.2 meters and in many cases are significantly wider. Upon conversion of a freeway to this configuration, it is recommended that, to the extent possible after allowing for needed center supports for overpasses, available median space be converted to roadway in order to minimize the extent of lateral expansion beyond the outside shoulder.

7.6.2.3. Vehicle classes allowed on the automated roadway

The classes of vehicles allowed on the automated facility is another implementation-based feature, which has consequences for lane width and need for multiple automated lane usage. The mixing-of-vehicle-classes-in-a-lane feature may also be implemented in more than one way. The mixing may be allowed on all lanes carrying automated vehicles, i.e. the mainline automated lane and the transition lane, or the transition lane only. If mixing is permitted on the automated mainline, then we only need a single automated lane, though more than one lane may be desired. If mixing of vehicle classes is allowed only on the transition lane, and we assume that all vehicle classes are allowed on the automated facility, multiple automated mainline lanes would be required to carry the different vehicle class traffic.

7.6.2.4. Number of manual lanes

A minimum of four lanes in each direction of travel would likely be required, assuming one automated lane, one transition lane, and two manual lanes. It is implicitly assumed that the market penetration of automated vehicles is consistent with having taken away two lanes from manual use. A minimum of two manual lanes is necessary, to adequately accommodate AHS entry/exit maneuvers, weaving movements between the manual lanes and transition lane, on- and off-ramp movements, and to allow for passing in the manual lanes to accommodate slower moving manual traffic. For highway segments with less than four lanes in each direction, the implementation would require the lateral expansion of the roadway. Depending upon the availability of usable space within the existing ROW and the severity of restrictions to lateral expansion beyond the ROW, implementation may be costly and may displace existing land uses and other physical obstacles.

7.6.2.5. Number of automated lanes

The number of automated lanes is an additional implementation-based characteristics. Again, if the implementation includes multiple vehicle classes and mixing of these classes is transitory, i.e. only allowed on the transition lane, then multiple automated lanes are necessary. With multiple automated lanes, barriers may or may not be used. Since traffic is automated in both lanes, barriers between automated lanes would not be necessary. In the case of two automated lanes, one for light-duty vehicles and the other for heavy-duty vehicles, another implementation issue to address would be the placement of these automated lanes, i.e. should the light-duty vehicle automated lane be the inner-most lane or not? If the light-duty vehicle automated lane were to be traveling at faster speeds than the other automated lane and of narrower width, than it is recommended that the light-duty vehicle automated lane be the inner-most lane, i.e. closest to the median barrier.

7.6.2.6. Lane widths

The lane widths for both the automated mainline lane and the transition lane is another implementation-related characteristic. If heavy-duty vehicles such as buses and trucks are allowed on the automated facility, then lane widths would probably have to remain the standard width they currently are. If there were two automated lanes, one for light-duty vehicles and one for heavy-duty vehicles, then an implementation option would be to have the light-duty vehicle lane be of shorter lane width than the other automated lane and possibly having these vehicles traveling at faster speeds.

7.6.2.7. Extent of transition lane

The transition lane may be a continuous lane or an intermittent lane. To save on the use of real estate, it would be prudent to begin and end the transition lane to accommodate the entry and exit functions. The transition lane may, however, be a de facto continuous lane if adjacent entry/exit zones are very closely spaced together.

7.6.2.8. Existence of breakdown/emergency lane for automated usage

If the need for a breakdown lane to the left of the automated lane for emergency purposes to help avoid blocking the automated lane under such circumstances, then additional right-of-way would be needed. This lane would not necessarily have to be a continuous lane for the entire length of the automated lane. A combination of both an intermittent transition and breakdown lane could be configured so as to require only an additional single lane-width of space.

7.6.2.9. Additional right-of-way needed

As mentioned above, additional right-of-way may be needed to accommodate lateral roadway expansion for a breakdown lane, physical barriers, any needed additional buffer space to help alleviate any feeling of confinement while driving through areas where there are barriers, possibly short roadway sections with barriers on both sides of the roadway, and shoulder space.

7.6.3 Differences Between Urban and Rural Implementation

There are numerous differences in the physical aspects between urban and rural/suburban environments. Such aspects including roadway characteristics and surrounding land use are listed as follows:

- availability of median and median widths
- availability of right-of-way for lateral expansion
- terrain: mountainous with possible steep cuts and slopes in rural areas
- extent of separation of roadbeds in opposite directions
- possibility of lots of congestion at entry/exit points in urban areas
- possible overpass bridge reconstruction necessary to accommodate lateral expansion of roadway

7.6.4 Deployment

- Minimal deployable system
- Incentive to buy an AHS vehicle
- Incentive to extend AHS facility

7.7 GENERAL ISSUES AND CONSIDERATIONS

7.7.1 Local Coordination

Coordination is local. Difficulties may arise in achieving an optimal flow control for numerous functions, such as entry and exit, merging, and emergency maneuvers.

7.7.2 Heavy Reliance on Individual Vehicle Intelligence

Since no support is received from the infrastructure other than static information such as posted speed limits, or location and distance to an off-ramp, vehicles must carry out all sensing and communication functions. The requirements on these components, therefore, must be made more stringent than if there were more substantive infrastructure support.

7.7.3 Cooperative or Selfish?

Protocols for cooperative maneuvers must be developed to avoid selfishness. A communication of priority or urgency may be necessary. For example, upon entry to the automated lane(s) from the transition lane, an entering vehicle must first determine whether there is sufficient lane space with which to merge into the automated lane and get permission to enter from the closest approaching platoon to execute this merge maneuver. What happens if permission is repeatedly not granted causing backups on the transition lane? This potential problem needs to be avoided.

7.7.4 Communication Range and Channels

To effectively coordinate maneuvers, the means for vehicles to "tune in" to appropriate communication channels must be established. Difficulties in assigning proper channels or frequencies may arise when no infrastructure support is provided.

7.7.5 Transition Lane

- The transition lane at entry and exit points should be designed to minimize the mixing of manual and automated traffic.
- Accessibility of automated lanes may be hindered due to the difficulty in weaving through manual lanes to access the automated lanes.
- Capacity of manual lanes may be reduced due to the increased weaving activity to access the automated lanes.

7.7.6 Platooning and Mixed Classes of Vehicles

Prohibition of mixed classes in the same platoon will increase numbers of free agents while mixing classes of vehicles in the same platoon could substantially complicate user comfort and safety of automated facility users. If upon entry to the automated facility a heavy duty vehicle, such as a truck or a bus, either enters the automated lane as a free agent or waits until a platoon of the same vehicle class approaches. Waiting for such a platoon could lead to backups on the transition lane for vehicles waiting to enter the automated lane. Safety issues need to be addressed in the event of a multi-vehicle class platoon during an incident, due to the potentially large differences in size and mass of the vehicles within the same platoon.

7.7.7 Potential for Additional Right-of-Way Required

Implementation of this concept in a dense urban environment may not always be feasible if there is insufficient right-of-way that could be needed to accommodate roadway lateral expansion for barriers or shoulder space.

8. CONCEPT 6: FREE AGENT WITH MODERATE NON-AHS EXPOSURE

8.1 OVERVIEW

This configuration features free agent separation using infrastructure supported intelligence. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for this configuration is a single vehicle. This concept is very similar to #8a, with the exception of the attribute defining the mixing of AHS and non-AHS vehicles. Concept #6 operates the automated lanes in dedicated facilities with gaps in the physical barrier, introducing the possibility for intrusion by unauthorized vehicles. A transition lane is defined as the entry/exit facility for this concept, introducing another level of interface with non-AHS vehicles. Other attributes concept #6 has in common with #8a are integration of vehicle classes within a single lane and automated sensing and avoidance of obstacles.

Concept #6 features the ability to accommodate entry/exit in a dedicated facility with physical barriers through transition lanes rather than a dedicated ramp. Gaps in the barriers will be evaluated as an access and egress method. Another influence on the definition of this concept will be effect of non-AHS vehicles on infrastructure supported free-agent operation in mixed-vehicle class lanes.

8.2 DIMENSION ATTRIBUTES

8.2.1 Distribution of Intelligence: Infrastructure Supported

This dimension assumes that acceleration, deceleration and possibly maneuver data concerning adjacent vehicles in a local area is available to the single vehicle coordination unit. The infrastructure supported dimension provides infrastructure monitoring of global events such as traffic flow and incidents. The infrastructure communicates pertinent information to vehicles within its local zone. Data is expected to include general parameters such as assigned travel speed, headway, or roadway geometry.

Vehicle control loop commands are generated by the vehicle. The vehicle control loop can use local zone information generated by the infrastructure to improve maneuver planning. Individual vehicles are not responsible for roadway condition or environment sensing, allowing vehicle sensors to focus on obstacle detection and headway measurement. The reduced responsibility in terms of vehicle sensors is balanced by an increase in infrastructure instrumentation to support sensing and communications between the vehicle and the infrastructure.

8.2.2 Separation Policy: Free Agent

The separation policy specifies that individual vehicles operate as the coordination unit for AHS maneuvers such as merge and separation to and from the automated lane. The vehicle separation is determined by an infrastructure controller at the zone or regional level and communicated to the vehicles at check-in or enroute. The vehicles maintain their own headway through sensing of adjacent vehicles and internal generation of acceleration, deceleration, and turning control loop commands. Vehicles may cooperate by sharing speed and acceleration/deceleration data with adjacent vehicles, allowing coordination of maneuvers within a local zone.

8.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Some Gaps in the Physical Barriers

The geometry of the barrier gaps will be dictated by the vehicle classes which must access the automated lane. Longer gaps will be required to support commercial and transit vehicles. The roadway design can be tailored to accommodate local needs. Areas with a high percentage of truck and bus traffic might allow access at all barrier gaps. Areas with greater passenger vehicle congestion might shift the balance and allow passenger cars only at certain barriers to minimize the impact to traffic flow as slower and less maneuverable vehicles enter the automated lane.

The impact to roadway infrastructure of transition lanes to access the dedicated facility will be evaluated with respect to dedicated entry and exit ramps. The impact to facility size and geometry are considerations. The spacing of gaps will impact system efficiency and the physical design of the barrier opening will have safety implications.

Continuous physical barriers are expected to prevent intrusion of unauthorized vehicles into the automated lane. Gaps in the physical barrier provide the opportunity for AHS vehicles to merge into and out of the AHS lanes, but allows the possibility for unqualified vehicles to access the automated lane. Unauthorized vehicles which breach the barrier gap must be detected by AHS vehicles and speed and spacing will be adjusted independently by the free agent since the coordination unit is a single vehicle. Information concerning emergency maneuvers will be shared with adjacent vehicles, and each free agent will plan and execute related emergency maneuvers as necessary in response to obstacles or rogue vehicles.

8.2.4 Mixing of Vehicle Classes: Mixed

This attribute assignment specifies allowing integration of vehicle classes within a lane. Mixing of commercial, transit, and passenger vehicles will impact the maximum lane density and operating capacity. This feature is best suited for areas with little congestion problem and a need to improve the safety and reliability of long trips. A minimum trip length may be necessary to optimize the frequency and location of barrier gaps.

An option for highly congested areas might require separate lanes for commercial or transit vehicles. This will allow tailoring of speed and headway to optimize passenger vehicle capacity in areas where trucks and buses provide a large enough population to support a commercial/transit vehicle lane.

8.2.5 Entry/Exit: Transition

Vehicles will access the automated lanes via a transition lane. The vehicle will transfer to automated control while in the transition lane. The vehicle will be informed of the location of gaps in the barrier by the infrastructure. The vehicle must move into the automated lane while sensing for potential obstacles in the transition lane and the automated lane. The ability to cooperate among vehicles will enhance the ability to enter the automated lane safely. An entering vehicle can monitor adjacent vehicle position and speed information prior to initiating a lane change maneuver through the gap.

Vehicles will exit the automated lanes via a transition lane. The vehicle will transfer to manual control while in the transition lane. The vehicle will be informed of the location of gaps in the barrier by the infrastructure. The vehicle must move into the transition lane while sensing for potential obstacles in the transition lane and the automated lane. The ability to cooperate among vehicles will enhance the ability to exit the automated lane safely. The exiting vehicle can communicate position and speed information to adjacent vehicles prior to initiating a lane change maneuver through the gap. Following vehicles may adjust their spacing in a cooperative manner if necessary.

8.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

Obstacle detection is performed by the vehicle. Vehicle detection of obstacles can be shared cooperatively with adjacent vehicles. Acceleration, deceleration, and maneuver commands are generated by single vehicle units based on internal information and data obtained cooperatively.

8.3 OPERATIONAL CONCEPT

Vehicles will initiate entry to the automated lanes from a transition lane. Preliminary speed and headway parameters are provided by the infrastructure. The vehicle plans its maneuver into the automated lane based on lane availability gathered cooperatively from adjacent vehicles and the vehicle obstacle detection sensors.

Vehicles monitor infrastructure instrumentation to gather roadway operational data such as surface conditions, environmental factors, speed advisories, and route information. Vehicles monitor adjacent vehicles to gather position and speed data and obstacle information to enhance maneuver planning.

The vehicle exits the automated lane under automated control into a transition lane. Barrier gap information is gathered from the infrastructure and exit maneuver data is shared cooperatively with adjacent vehicles. Control is transferred from automated to manual in the transition lane. The vehicle may continue traveling in the transition lane or may be maneuvered under manual control to other non-AHS lanes.

8.4 SYSTEM DIAGRAM

8.4.1 TOC to Zone Controller Interface

The TOC provides flow control information to the zone level regarding lane closures, entry and exit availability. The zone controller passes environment and incident reports to the TOC.

8.4.2 Zone Controller to Roadway Condition Sensors

The roadway condition sensors pass congestion and environment information to the zone controllers.

8.4.3 Roadway Condition Sensors to Roadway

The roadway condition sensors detect congestion levels, surface parameters, and weather conditions.

8.4.4 Range Detection Sensors to Vehicle

The range sensors detect the distance between vehicles and speed of vehicles. Range detection may include comparison to known slot assignments to identify all moving objects not in an assigned slot as an obstacle.

8.4.5 Vehicle to Vehicle Communications Interface

Vehicles transmit position and maneuver planning data. Vehicles within receive range respond with position and maneuver plan information.

8.4.6 Zone Controller to Vehicles

The zone controllers transmit traffic flow parameters to vehicles within receive range.

8.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

8.5 FUNCTIONAL ALLOCATION

8.5.1 Position Control:

The position control function is performed in the vehicle. Free agent spacing can be maintained by vehicle-based sensing of adjacent vehicles to maintain headway and lane parameters to maintain lateral position. Vehicle position can also be determined using absolute position location and map matching, with position location data gathered cooperatively used to maintain relative spacing between adjacent vehicles. The individual vehicle is also responsible for obstacle detection and avoidance. The position control function receives absolute position and speed data from onboard vehicle sensors. This function receives commands to change position and speed from the maneuver coordination function. The position control function generates throttle, brake, and steering signals and implements longitudinal and lateral changes to maintain headway and lane keeping, and in response to maneuver commands as required.

8.5.2 Maneuver Coordination

The maneuver coordination function is performed in the vehicle. The maneuver coordination function receives zone and regional roadway information from the flow control function, hazard warnings concerning local obstacles from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function.

The maneuver coordination function receives acceleration, deceleration, and turning information from adjacent vehicles allowing maneuvers to be planned in terms of local vehicle motion. This function generates commands to change speed or lane position based on information received from the infrastructure regarding current travel conditions and from adjacent vehicles regarding their position and speed.

The maneuver coordination function receives a message from the check-in function when a vehicle is prepared to access the automated lane and control has been transferred from manual to automated. The maneuver coordination function responds by generating speed and lane change commands which allow the vehicle to move into the automated lane.

The maneuver coordination function receives a message from the check-out function when a vehicle is prepared to exit the automated lane. In the case of exit, control is transferred from automated to manual after the vehicle has moved into the transition lane. The maneuver coordination function generates speed and lane change commands which allow the vehicle to move out of the automated lane. Control is transferred to the operator while the vehicle is traveling in the transition lane.

The maneuver coordination function responds to hazard and malfunction warnings by generating commands to change speed or lane position which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits the control signals addressed to the vehicle in the affected slot. The maneuver coordination function provides notification to the operator interface of merge, demerge, or emergency maneuvers. Notification to the operator interface will be coordinated with the maneuver to prepare the driver for unexpected changes in vehicle speed or position.

8.5.3 Hazard Management

The hazard management function is performed in the vehicle. The hazard management function detects obstacles and adjacent vehicles using onboard vehicle sensors. The hazard management function generates a hazard warning message when an obstacle or vehicle enters a specified control zone, and it is passed to the maneuver coordination function for appropriate action.

This concept does not include a vehicle-infrastructure communications link. The infrastructure cannot be informed of hazards by the vehicle directly. Hazards which affect traffic flow significantly will be detected by the incident detection sensors, and the zone processor will be able to generate traffic flow commands to adjust traffic flow downstream as necessary.

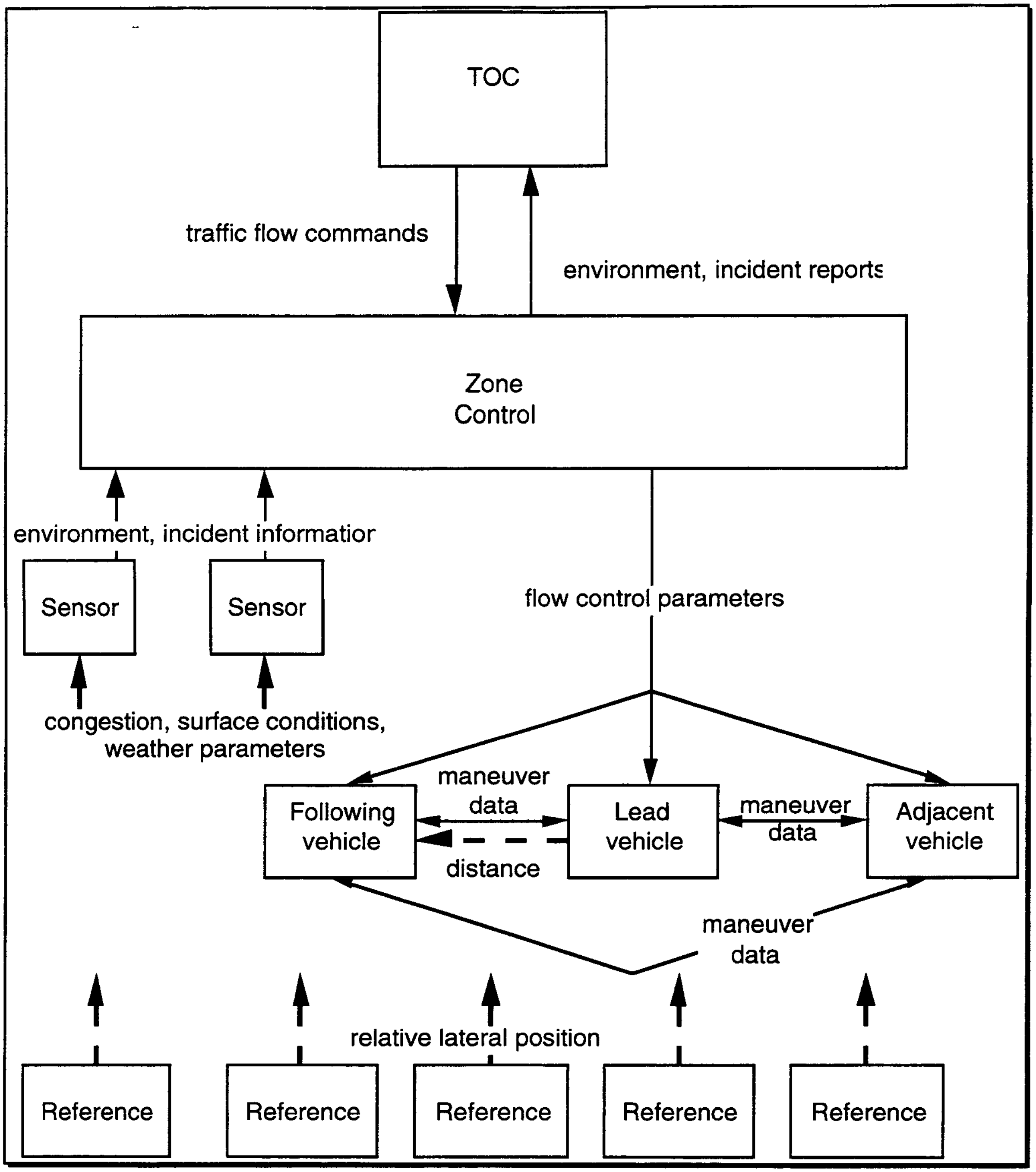

Figure H.8.5-1. System Interface Diagram

8.5.4 Malfunction Management

The malfunction management function is performed in the vehicle. This function receives vehicle system status information from onboard vehicle diagnostics, and operator input regarding system conditions or hazards. The malfunction management function generates a malfunction warning message which is passed to the maneuver coordination function for appropriate action based on processing of vehicle and operator data. This function provides vehicle or system failure information to the traffic operations center and provides status messages to the operator.

8.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function monitors infrastructure sensors at the zone level and provides information regarding roadway conditions and local incidents to the maneuver coordination function. This function monitors traffic flow at the regional level and provides operating information to the maneuver coordination function such as congestion at entry/exit points, travel speed, and lane or route closures.

8.5.6 Operator Interface

The operator interface function is performed in the vehicle. The operator interface receives inputs from the operator concerning entry and exit requests and generates requests to enter and exit the automated lanes for the check-in and check-out functions. This function processes inputs from the operator concerning system operating conditions, including hazards or malfunctions and generates messages to the malfunction management function indicating a detected hazard or malfunction.

The operator interface provides sensory notification to the driver to indicate impending maneuvers based on messages received from the maneuver coordination function. This function also provides status to the operator concerning ongoing vehicle and system operating conditions. The operator interface will generate messages which provide status and instructions regarding entry or exit procedures.

8.5.7 Check-In

The check-in function is performed in the vehicle. This function receives operator requests to enter the automated system and initiates the check-in process. The check-in function processes vehicle condition information received from the malfunction management function concerning the integrity of the automated control subsystems. This function verifies the ability to perform the transition from manual to automated control safely and generates a message to the maneuver coordination function to initiate entry to the automated lane. The transfer of control from manual to automated takes place in the transition lane prior to entry to the automated lane.

Vehicles which fail the check-in process will be denied access to the automated lane. A message will be generated to the operator interface function which indicates the status of the check-in results and notifies the driver that the vehicle will remain in manual control and will not maneuver to the automated lane.

8.5.8 Check-Out

The check-out function is performed in the vehicle. This function receives operator requests to exit the automated system and initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely and generates a message to the maneuver coordination function to initiate exit from the automated lane.

The check-out function will generate a message to the operator interface function which will allow the transition of control to occur. The operator interface will pass a message back to the check-out function when the operator has performed the required tasks successfully. The vehicle will be maneuvered through the barrier gap and the operator will be prompted to resume manual control prior to transfer from automated to manual control.

Vehicles which fail the check-out process will remain in automated control and will be moved to a safe location. A message will be generated to the operator interface function which indicates the status of the check-out results and initiates the process for exiting under automated control.

8.6 IMPLEMENTATION OPTION(S)

The separation policy specifies that individual vehicles operate as the coordination unit for AHS maneuvers such as merge and separation to and from the automated lane. The vehicle separation is determined by an infrastructure controller at the zone or regional level and communicated to the vehicles at check-in or enroute. The vehicles maintain their own headway through sensing of adjacent vehicles and internal generation of acceleration, deceleration, and turning control loop commands. Vehicles may cooperate by sharing speed and acceleration/deceleration data with adjacent vehicles, allowing coordination of non-emergency maneuvers within a local zone.

8.6.1 Vehicle Electronics

Headway maintenance: Longitudinal position relative to leading vehicle is measured using vehicle-based radar ranging. Speed adjustments are calculated based on range and closing rate to the vehicle immediately in front, and control signals are generated within the vehicle to maintain headway. Obstacle detection will be integrated with the headway maintenance function. A ranging radar similar to adaptive cruise control (ACC) technology may be implemented. Range and resolution are key considerations in evaluating the effectiveness of radar technology in performing the obstacle detection function. A system which provides adequate performance for obstacle detection may increase the cost of the radar subsystem dramatically. Processing required to support target discrimination is also an issue.

Lane keeping: Cooperative sharing of lane position data between free agents will allow coordination of lane changes between adjacent vehicles.

(option A): A vision based lateral control approach to determining lateral position relative to lane markings can be implemented.

(option B): A lateral control approach using passive lane markers can be used to determine lateral position relative to the lane boundaries.

(option C): Absolute position can be determined using geographic positioning techniques, combined with map matching to maintain lateral position.

Transfer maneuver coordination messages: Two-way vehicle-vehicle communications will provide transfer of relative longitudinal and lateral position data between adjacent vehicles. Vehicles planning to make maneuvers will broadcast their position data and intended maneuver. Vehicles in communication range respond with appropriate position information. Access to the receive bandwidth of the vehicle requesting adjacent position data is an issue. The vehicles may require addressing to avoid collisions of return messages. The vehicle must have roadway knowledge to map the positions of cooperating vehicles in the general vicinity to assist in maneuver coordination. The vehicle operates as a free agent, generating maneuvers independently of other vehicle's travel plans using knowledge shared with other vehicles to facilitate lane change, merge and demerge maneuvers.

Receive and process traffic flow commands: Vehicle receiver monitors infrastructure transmissions of flow control information. Vehicle operating speed and minimum headway are adjusted according to environmental and incident advisories. Lane closure and congestion information are incorporated into route planning.

Operator interface: generate entry and exit request messages, support maneuver notification and obstacle avoidance alerts.

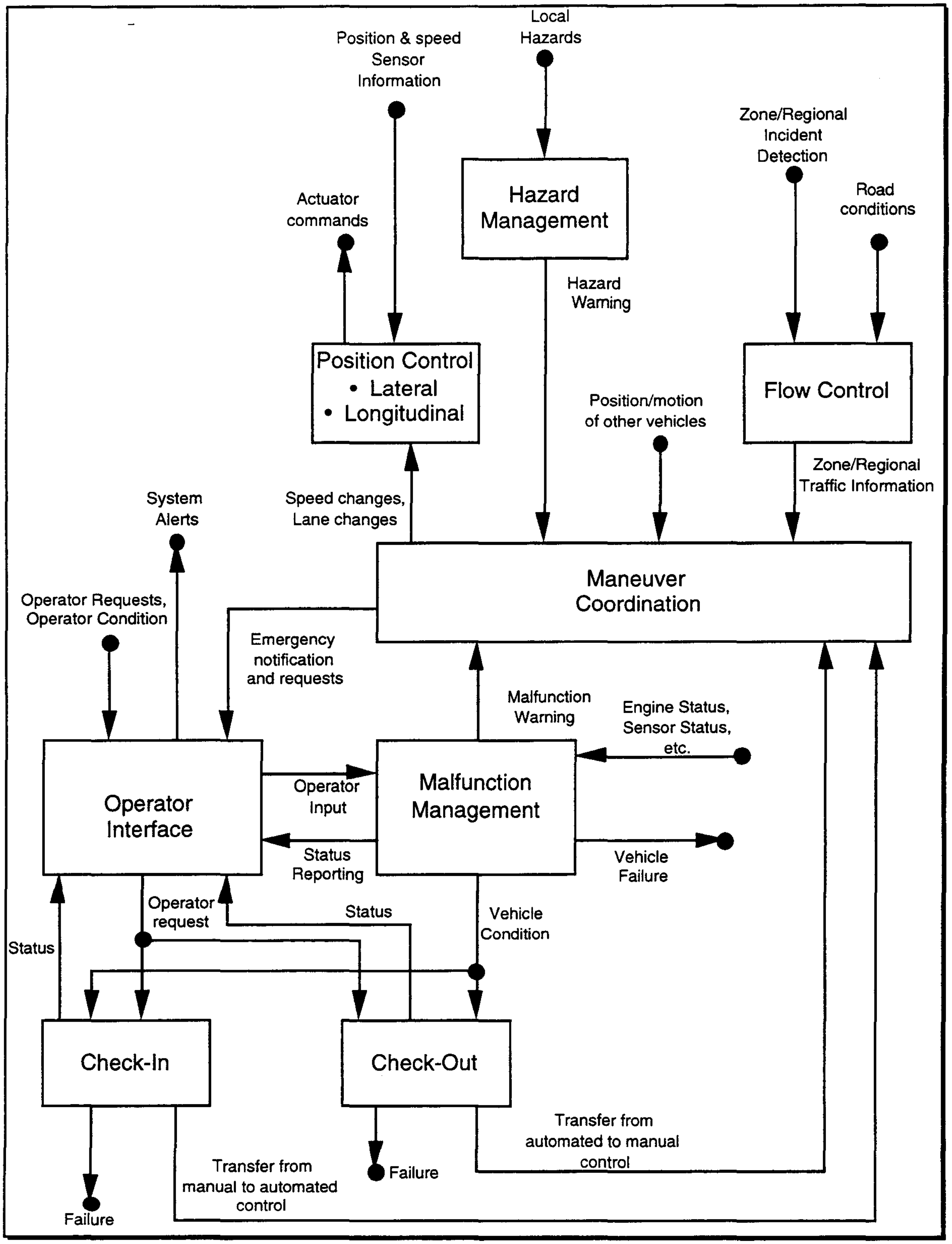

Figure H.8.6-1. Functional Block Diagram

8.6.2 Infrastructure Instrumentation

TOC: monitor global traffic flow. Collect incident information from zone controllers and modify travel advisories as necessary.

Zone controller: collect incident information, transfer to TOC as necessary. Transmit local travel advisories on one-way channel to vehicles. Broadcast RF can be used since headway and speed commands will be set at the local zone level and is not addressed to individual vehicles. Expected range of transmission is on the order of 100 ft. Spacing of local transmitters linked to the zone controller necessary to provide effective zone control is an issue. One transmitter for every entry/exit location may be sufficient.

There may be long sections of roadway between entry/exit points not within the range of zone transmissions in rural areas. This may be acceptable since traffic flow dynamics are not expected to affect lane throughput significantly in the time elapsed until the next transmission in less congested areas. Urban areas typically have frequently spaced entry/exit points. Vehicles can be expected to pass an entry/exit point on the order of once per minute in urban areas.

Incident detection: sense local traffic congestion.

Monitor environment: sense roadway conditions such as surface wetness or visibility.

Lateral reference:

(option A): existing lane striping may be used.

(option B): passive markers in the roadway must be installed.

(option C): assumes existing geographic positioning infrastructure, local beacons possibly required in urban canyons.

8.6.3 Roadway Infrastructure

This concept requires a dedicated lane with a barrier separating the conventional and AHS lanes. A physical barrier provides separation between the AHS lane and the conventional lanes, with a transition lane used to access the automated lane through gap in the barrier. It is assumed that the transition lane is used only by vehicles entering or exiting the automated lane(s).

8.6.3.1. Rural Highway

Areas in which right-of-way is available may be compatible with construction of additional facilities. A dedicated automated lane might be built parallel to existing highways. Adding a transition lane may also be necessary, depending on the number of conventional lanes available for AHS use. Construction of both lanes may be required in areas where only two lanes are available on the conventional highway.

Rural areas with traffic flow which does not justify two AHS lanes in addition to two conventional highway lanes in each direction of travel may not be compatible with an approach which requires two full length AHS lanes to support AHS travel and the transition lane. The transition lane may be little more than an entry/exit ramp connecting the conventional lanes with the gap in the barrier in areas with low congestion. This implementation would appear similar to divided roadways with occasional strips of pavement connecting them to form the transition lane at access and egress points. Using unpaved physical space between the automated lane and the conventional lanes can be considered a barrier, and construction of a vertical barrier may be avoided. This approach is illustrated in Figure H.8.6-3, which illustrates two lanes of a four-lane divided highway where the AHS lane is placed in the median and transition lanes are built at periodic intervals to accommodate entry and exit.

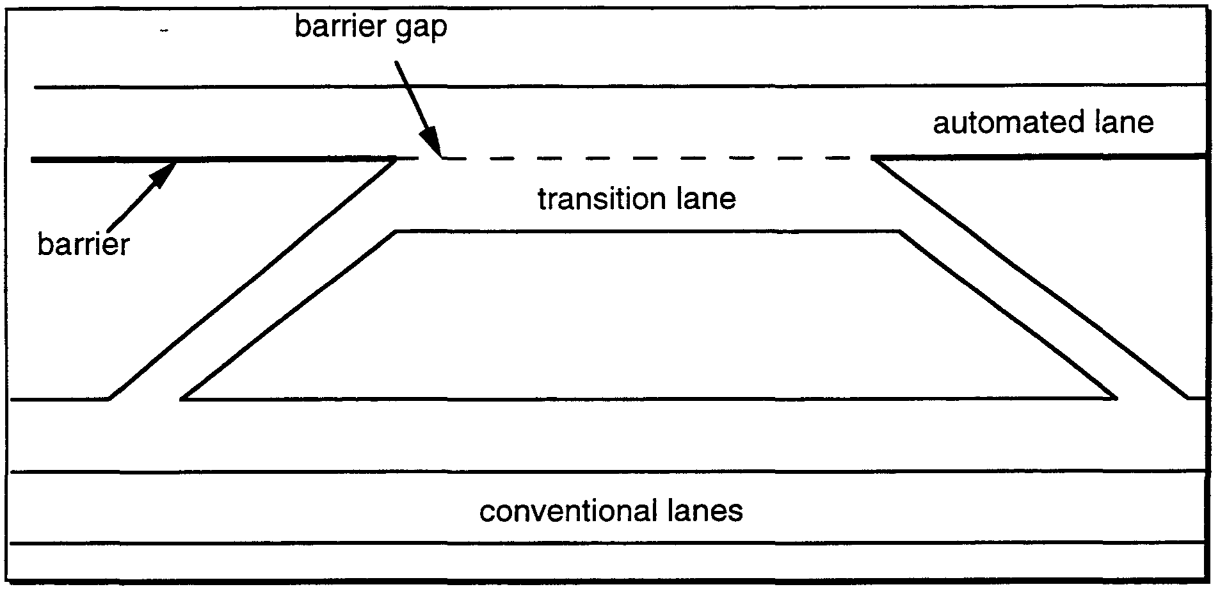

Figure H.8.6-2. Possible Rural Transition from Conventional Lanes to Automated Lane

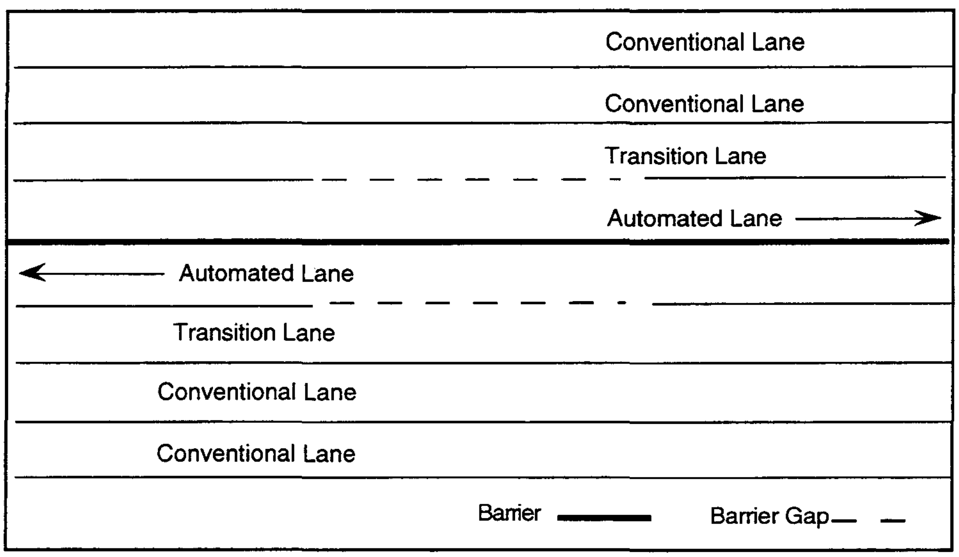

Figure H.8.6-3. Possible Urban Transition from Conventional Lanes to Automated Lane

8.6.3.2. Urban Region

It is expected that the transition lane would extend parallel to the entire length of the automated lane in urban areas. The transition lane is expected to be continuous in urban regions due to higher volumes of traffic entering and exiting the AHS facility at more closely spaced intervals. Spacing and usage of access and egress points will determine the configuration of the transition lane. The barrier gap spacing should be designed to optimize capacity in congested areas. The number and frequency of entry and exit points may be limited to encourage longer trips and improve efficiency. Another urban alternative is to restrict heavy vehicles to off-peak hours due to the longer transition time required to reach AHS speeds and perform merge and lane change maneuvers.

8.6.4 Deployment

This concept contains a moderate degree of infrastructure instrumentation. A large percentage of the infrastructure electronics may be expected to be associated with related ITS services such as automated vehicle location (AVL) and automated vehicle control systems (AVCS). Current trends in incident detection and highway advisory systems also support some of the features included in this concept, providing a smooth evolutionary transition to full automation through instrumentation of the vehicle to allow cooperative maneuver planning through vehicle-vehicle communications.

This concept can be deployed effectively in rural areas with low traffic density using a single lane. Commercial vehicles and passenger vehicles can be permitted to use the lane concurrently, since longer vehicle headways can be specified by the infrastructure supported intelligence as necessary to maintain safety while supporting mixed vehicle class usage. A single lane AHS in rural areas may require supplementation with passing lanes on grades to maintain travel speed for passenger vehicles.

Two full lanes are the minimum required to support efficient deployment in congested urban areas. One lane is dedicated to mainline AHS travel. A second lane is used to provide a transition area for entering and exiting the AHS, and may also be used to divert AHS traffic in emergency situations.

9. CONCEPT 8A: INFRASTRUCTURE SUPPORTED FREE AGENT ON DEDICATED LANES, WITH MIXED CLASSES

9.1 OVERVIEW

We are considering this concept because Infrastructure Supported was widely seen as probably the best answer for distribution of intelligence, and there was a desire to have many concepts exploring this part of the design space. What distinguishes this concept from the other Infrastructure Supported Free Agent on Dedicated Lanes concepts is that this is the only one which supports mixed classes.

It is accomplished in this version using differential GPS between vehicles, along with passive markings on the roadway, and using a significant bandwidth vehicle to vehicle communications wireless LAN. This version puts significant intelligence in the vehicles.

9.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Prior to the generation of this concept, the AHS team developed a set of six dimensions, and selected points within the resulting space of options to be fleshed out as concepts. Where this concept falls on these dimensions is mentioned below.

9.2.1 Infrastructure Supported

Infrastructure support primarily consists of the GPS signal and passive markings on the roadway. Other infrastructure support could include roadside beacons (using the vehicle-to-vehicle communications protocol) and special GPS support such as Pseudolites, or local (regional) GPS Beacons, as local options.

All the infrastructure support is not directed to specific vehicles, except during check in.

This particular concept has been designed with very substantial vehicle-to-vehicle communications bandwidth. The inter-operations of these vehicles will somewhat resemble a Cooperative concept.

9.2.2 Free Agent

Vehicles travel independently as individual units, coordinating with other vehicles through their shared information.

It is plausible that this concept might offer an upgrade path to a more advanced system that would support platooning.

9.2.3 Dedicated Lanes With Continuous Physical Barrier

This concept presumes a continuous physical barrier, such as a Jersey barrier, between the AHS lanes and the non-AHS lanes. This minimizes the need for AHS vehicles to interact with non-AHS vehicles.

The specific concept description in this document might be easily modified to accommodate a less strongly segregated AHS.

9.2.4 Mixed Vehicle Classes in Lanes

This concept can accommodate multiple vehicle classes (e.g., cars and trucks) in the same lane. Non-Mixed class lanes may be specified as a local option.

9.2.5 Dedicated Entry and Exit

Entry and exit to AHS is controlled through physically isolated, dedicated lanes, with physical control of individual entering vehicles. This supports "Dedicated Lanes With Continuous Physical Barriers" in minimizing the need for AHS vehicles to interact with non-AHS vehicles. The entry facilities will function properly to politely prohibit non-AHS vehicles from entering the AHS roadway.

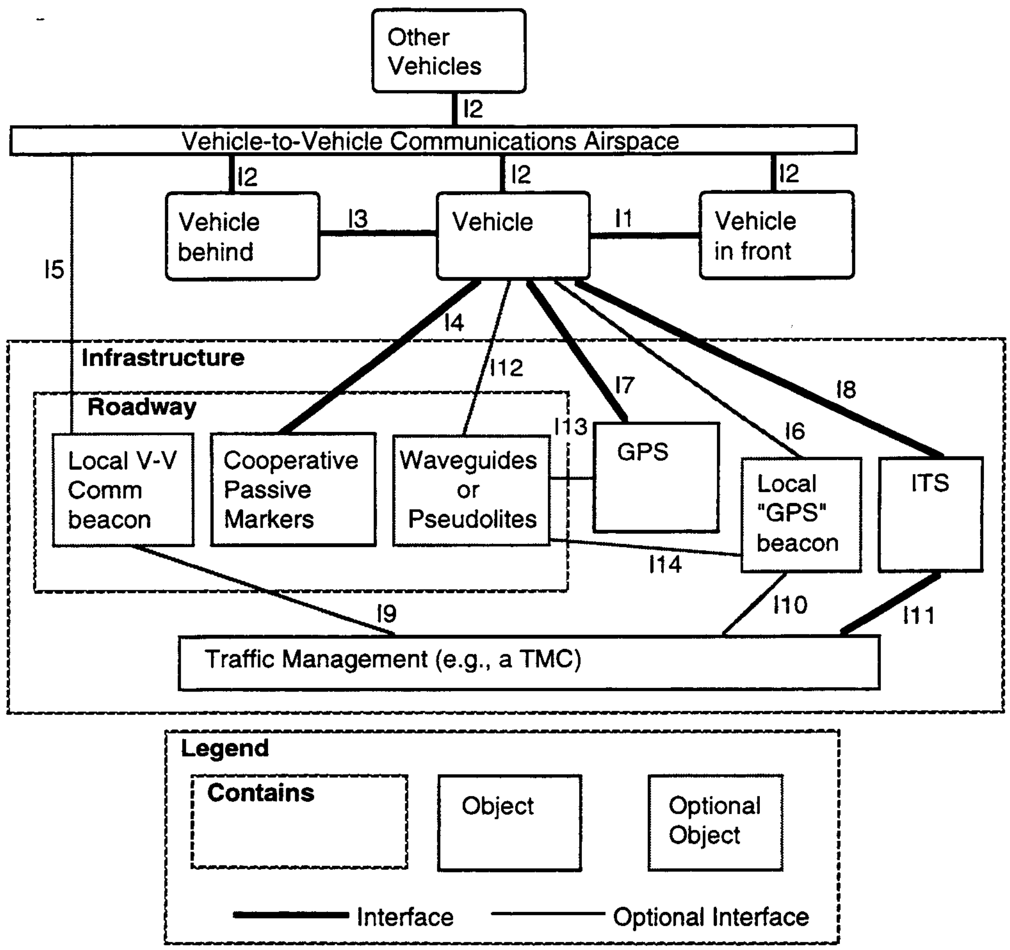

Figure H.9.2-1.

As a local option, there may be AHS entries and exits into specific areas other than into local roadways (e.g., intermodal parking, regional attraction parking, AHS-customer "truck stops," etc.).

The specific concept description in this document might be feasibly modified to accommodate a less strongly segregated AHS.

9.2.6 Automatic Sensing and Avoidance

Vehicles, both individually using on-board sensors, and cooperatively, passing information, are responsible to sensing obstacles and hazards. The vehicles then maneuver (where possible) under automated self control to avoid these obstacles and hazards. As a local option, a section of road could have a sensor suite deployed to monitor for obstacles and hazards, and were detected, inform vehicles using the vehicle-to-vehicle communications protocol.

9.3 OPERATIONAL CONCEPT

AHS vehicles enter and exit the system on dedicated transition lanes, going through check-in via communications with a local beacon, the local traffic, or on its own if entering at an isolated entry with no traffic nearby.

The vehicle receives GPS data, and communicates with vehicles around it. This communication includes passing GPS data for differential GPS between vehicles, allowing the estimation of inter-vehicle distances. The vehicle also senses the distance to the next vehicle. This all allows the maintenance of a comprehensive map of the relative positions and velocities of vehicles around each vehicle. Direct sensing of the passive beacons also allows very accurate absolute positioning.

The vehicle then drives under fully automated control until it approaches the driver's desired exit. At that point, it tests the driver, and if the driver passes, enters the dedicated exit transition lane, where control is handed off to the driver.

9.4 SYSTEM DIAGRAM

Figure H.9.2-1 shows the vehicles and infrastructure and data flows among them, including sensing.

9.4.1 Interface 1 (I1)—Vehicle to Vehicle in Front

Vehicle directly senses the cooperative passive markers on the vehicle in front to measure relative positions. The range should be brick-wall stopping distance (if possible), the update rate should be on the order of at least 10/sec, the information should include very accurate distance measurements, and the ability to infer or measure relative speeds and relative accelerations.

9.4.2 Interface 2 (I2)—Vehicle to Other Vehicle

Pure communications interface. Protocol needs definition, but is should be a very short-range RF system like a wireless LAN. Primary communications load is communication of differential GPS data with other vehicles. Other vehicle-to-vehicle comm includes situational information, and maneuver requests such as slowing to create a gap for merging.

I do not have the actually GPS message description, but ~50 bits is a good guess. Cars need to transmit GPS data from 4 satellites, and will have other data (e.g., speed, direction, obstacles seen), for say

In the worst update rate case, a large number of vehicles would be maneuvering at high speeds at short ranges, with frequent turns and speed changes. (This worst case might be the response of a huge high-speed traffic flow following the catastrophic failure of a vehicle in its midst.) In this case

Broadcast range should be variable. The protocol must support ranges slightly greater than the longest brick-wall-stopping distance of any vehicle that will travel on the AHS. Call that 100 m. It also must support communication with several vehicles to allow triangulation of lengths. A minimum broadcast range of 15 m should keep the worst case communications traffic load below 50 vehicles.

The required bandwidth estimate is then:

> { (4 satellites x 50 bits/satellite + 50 "other" bits)/ transmission x 10 transmissions/ (second • vehicle) x 50 vehicles } x (100% + 100 % margin) = 250, 000 bits/second

In ordinary situations, this bandwidth could be used for other messages.

Other requirements or features. The communications protocol must support multiple overlapping groups (e.g., A & B are in range of each other and talk, B & C are in range of each other and talk, but A & C are not in range of each other and cannot talk. A & C cannot have their signals step on each other, since B won't be able to hear them both. Also, A & C cannot coordinate directly).

The default approach is to have every vehicle transmit its most recent GPS, at the point when it must broadcast. An alternate approach is for the local vehicles to set up a "clock", and send out their GPS information at that last clock time. The first approach is simpler, but the second approach allows the vehicles to directly calculate intervehicle distances between pairs of vehicles other than themselves (which then will support triangulation, and better traffic picture coherence).

9.4.3 Interface 3 (I3)—Vehicle to Vehicle Behind

The exact mirror image of interface I1. The vehicle is responsible for having the appropriate cooperative passive markers for easy sensing by the vehicle behind it.

9.4.4 Interface 4 (I4)—Vehicle to Roadway Markers

Vehicle sensors directly observe passive roadway markers, determining their positions, and thus, roadway boundaries and lanes. These markers would be read at a very high rate (10+/sec) to high positional accuracy (~99%). The range would be on the order of meters, although the lane markings could be center-line, read as they are driven over.

9.4.5 Interface 5 (I5)—Local Vehicle-to-Vehicle Communications Beacon

As a local option, roadside beacons may be deployed to communicate with vehicles. This interface is identical interface protocol to I2; the beacons are perceived by the vehicles as stationary "vehicles" that also can pass information about the immediate surroundings, including messages from the TMC, hazards observed by infrastructure sensors, and local roadway geometry, as well as differential GPS data. The total data rate supported ~5000 bps (broadcast).

9.4.6 Interface 6 (I6)—Local "GPS" Beacon to Vehicle

It is an option for local region to deploy a local "GPS" beacon. This is a transmitter at a fixed point, sending out a signal as if it were a GPS satellite. The likely range would be 10-50 miles. This should allow higher precision in denser traffic areas, and could also be positioned to avoid some GPS signal blockage issues. It might be more accurate than GPS, which is forced to transmit a degraded mode for military reasons.

Also, such Local "GPS" Beacons could be considered in those cases where local geography (e.g., urban "canyons" between skyscrapers) does not permit adequate receipt of GPS satellite signals from GPS satellites, and the use of pseudolites (see 4.12) is more difficult.

9.4.7 Interface 7 (I7)—ITS to Vehicle

The Intelligent Transportation System services, provided as transparently as ITS would serve non-automated vehicles. The content, general message size, update rate, range, bandwidth, and other requirements or features would be as appropriate to match the National ITS Architecture program.

9.4.8 Interface 8 (I8)—GPS to Vehicle

The standard interface between GPS and a GPS receiver. The vehicle receives the GPS signal, with no return signal. That signal primarily consists of a very accurate clock time. I don't know the message size, but I'm guessing ~50 bits/ message, at a high update rate. The range is from the GPS satellites, in high Earth orbit.

9.4.9 Interface 9 (I9)—Traffic Management to Local Vehicle-to-Vehicle Communications Beacon

This link passes information to beacons for their control, and to pass on to vehicles. The beacon can also send information to traffic management on the ongoing status of traffic in it's region, along with special messages provided by vehicles which pass (e.g. "there is a lane-closing obstacle 1/2 mile back in lane #2").

This is a long-range link (1-100 miles), possibly carries by land-lines.

9.4.10 Interface 10 (I10)—Traffic Management to Local "GPS" Beacon

A very low bandwidth connection. May include emergency shutdown of the local "GPS" beacon for emergency reasons. May not exist even when Local "GPS" Beacon is deployed.

9.4.11 Interface 11 (I11)—Traffic Management to ITS

The standard interface between traffic management and the rest of ITS, supplemented with information required to support AHS.

9.4.12 Interface 12 (I12)—Pseudolites to Vehicle

In some locations, line-of-sight to GPS may be blocked. To compensate, the roadway could have devices to carry GPS signals from GPS satellites around the obstruction. These are sometimes called Pseudolites. The interface is identical to I8 (GPS to vehicle). The expected range, however, is very short, as the Pseuduolite is functioning in small areas (e.g., within a tunnel, between a few buildings).

9.4.13 Interface 13 (I13)—GPS to Pseudolites

This is merely the Pseudolite receiving the GPS signal, so that it can carry that signal, or to support the Pseudolite in generating its own signal. Note, the pseudolites may need extended antennas in some locations to reach Line of site to the GPS satellites.

9.4.14 Interface 14 (I14)—Local "GPS" Beacon to Pseudolites

Similar to I13, this interface is merely the receipt by a Pseudolite of the GPS signal sent out by any Local "GPS" Beacon in the region.

9.5 FUNCTIONAL ALLOCATION

9.5.1 Check-In

AHS vehicles enter and exit the system on dedicated transition lanes, going through check-in via communications with a local beacon, the local traffic, or on its own if entering at an isolated entry with no traffic nearby.

Check-in would ordinarily performed jointly by the infrastructure and the vehicle. A Local Vehicle-to-Vehicle Communications Beacon will control a particular entrance. While driving in the transition lane, the vehicle will establish communications with the beacon, and the beacon will check the vehicle's signal, including its ability to receive and properly process GPS. As a local option the beacon might also pose one or more tests to the vehicle's processor. The vehicle will also go thought a built-in test of its systems, to assure that they are functioning properly. If all of this is successful, the beacon will approve the vehicle for entry. If not, then the beacon will direct the vehicle to an "entry denied" lane, which will bring the vehicle back into manual traffic.

As a local option the Beacon might control a physical barrier to help make sure that unapproved vehicles do not enter the system.

As a local option, there might be an uncontrolled transition lane. In this implementation, the vehicle would establish communications with other vehicles already in the AHS. These vehicles would conduct a simple check-in procedure with the entering vehicle, to assure that it is acting compatibly. In this local option, if there is no nearby traffic, there is no formal check-in, and the vehicle simply enters and drives on the AHS.

9.5.2 Transition from manual to automatic control

This function is performed by the vehicle and the driver, while the vehicle is going through check in. The driver must command the vehicle go to automatic driving, before the vehicle will initiate check-in. If approved, the vehicle will announce that success, and that it is taking over driving control. It will then do so, and drive the vehicle into traffic.

During check-in, and as desired thereafter, the driver must inform the vehicle of the desired exit.

If check-in is refused, the vehicle will inform the driver, and remind the driver do maintain manual control, and exit the AHS roadway.

9.5.3 Automated driving

Automated driving is controlled by individual vehicles, using information provided by other vehicles, and a supporting infrastructure.

9.5.3.1. Sensing of roadway, vehicles, and obstructions

The vehicles carry inexpensive sensors which observe coded, cooperative passive markings on the other vehicles and the roadway. Deliberate obstructions (e.g., traffic cones) have their own machine readable passive markings.

The physically isolated roadway is meant in part to minimize unauthorized obstructions. In general, obstructions are sensed when the sensors sense something that is not coded with a proper passive marking, or which is not behaving as something with that passive marking should. Any such item is taken as an obstruction to avoid. Vehicles alert each other of obstructions they see. Vehicles use the ITS Mayday function to call in any particularly large on long-standing obstruction to local authorities. In an immediate area with some particular issue of sudden obstructions, an infrastructure sensor can be deployed, and broadcast the location of any obstructions sensed, using the vehicle-to-vehicle communications protocol.

Vehicles also sense each other indirectly through mutual communication. All the vehicles broadcast their GPS data, and differential GPS between vehicles allows them to develop dynamic maps of the dynamic traffic structure in their immediate vicinity. As part of this indirect sensing of other vehicles, messages would include (at a very low rate) information on the characteristics of the vehicles (dimensions, brick-wall stopping distance, preferred braking rate, preferred acceleration, etc.).

As a local option, localities may establish a stationary, GPS-like broadcast. This would be a fixed beacon sending out signals must like a GPS satellite. The signals would be used by vehicles to support more precise relative positioning and traffic navigation. It is anticipated that this could be an attractive option to support denser traffic flow in urban areas.

As a local option, localities may establish roadways with regular beacons. These beacons would act like stationary vehicles, transmitting their local GPS information, along with the geometry of the local roadway. This would allow the vehicles, which already calculate there relative positions to also determine their position relative to the roadway, and thus, keep within their lanes. Roadways certified to this higher level could be authorized to carry less expensive vehicles which rely solely on communications and forego sensors.

To the extent any vehicles have other sensors (e.g., for adaptive cruise control on non-automated highways), information from those sensors are also broadcast to the local community of vehicles.

One concept would be to provide some continuous, machine-readable pattern, the interruption of which would be taken as an obstacle.

9.5.3.2. Lane and headway keeping

Vehicles use sensors and vehicle-to-vehicle communication to determine their position within lanes and their headway. They maneuver under automated self-control to stay in lanes and maintain headway.

Each vehicle communicates back its brick-wall stopping distance. Vehicles maintain headway so that within their own brick-wall stopping distance they will not hit a vehicle which suddenly stops within its brick-wall stopping distance, plus a margin. If a vehicle gets closer than brick-wall stopping distance to where another vehicle could stop (which is not supposed to happen), then it's "brick-wall stopping distance" is calculated to be the distance until it would hit the next vehicle because of that vehicle's brick wall stopping distance.

As a local option, the infrastructure may broadcast driving parameters for vehicles to follow in order to smooth out roadway conditions, or otherwise optimize traffic flow. Example parameters include preferred speed, allowed spacing margin, preferred acceleration rate, preferred deceleration rate, nominal headway correction factor, and restricted class lanes.

9.5.3.3. Detection of hazards

When hazards exist they should ordinarily be detected by the vehicle's on-board sensors, or communicated to the vehicle by other vehicles.

In an immediate area with some particular issue of sudden hazards, an infrastructure sensor can be deployed, and broadcast the location of any hazards sensed, using the vehicle-to-vehicle communications protocol. Less elaborately, local officials could deploy a "virtual traffic barrier" that used the vehicle-to-vehicle communications protocol to inform other vehicles of an area of roadway to avoid, that was programmed into the device.

The ultimate detection of hazards occurs when a vehicle strikes a hazard. As part of the vehicle's panic response, it immediately broadcasts its position and any understanding of the hazard it struck.

9.5.3.4. Maneuver planning (normal or emergency)

Normal maneuver planning is distributed between vehicles. If a vehicle wishes to merge right, and there is adequate room, then it announces the maneuver, and merges. If there is not room, then it requests a space. Adjacent vehicles open up a gap when safe, and the vehicle merges into that gap.

Stereotyped emergency responses are pre-programmed into the vehicle, and defined in the communications specification. This allows a vehicle responding to an emergency to announce their responses using very little bandwidth, and rapidly coordinate during the emergency maneuvers.

The system might be designed so that vehicles negotiate various contingency plans as part of their communications overhead, and thus, are in a position to execute such plans if suddenly needed. The set of basic contingency plans might be incorporated into the AHS standard, making this negotiation overhead very small.

9.5.3.5. Maneuver execution

Maneuvers are executed by the vehicle, which uses its on-board processor and actuators to control the throttle, steering position, etc.

9.5.4 Transition From Automatic to Manual Control

As the driver's requested exit approaches, the vehicle alerts the driver, and asks for an acknowledgment.

9.5.5 Check-Out

The check-out function is performed in the vehicle, in cooperating with the human. This function occurs once on-board navigation decides that the desired exit is approaching. It could also start if the vehicle receives operator requests to exit the automated system. The vehicle then initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely (including the driver's ability and readiness to retake control) and maneuvers to the exit transition lane. The vehicle will maneuver through the transition lane and the operator will be resume manual control.

Vehicles which fail the check-out process will remain in automated control and will be moved to a safe location. The driver will be informed of the failure of the check-out.

9.5.6 Flow Control

To the extent there is flow control, it is managed by the infrastructure.

On long travel distances where there is only one lane, perhaps on interstates for example, the automated roadway would periodically expand to two lanes to allow passing.

9.5.7 Malfunction Management

Vehicles have built in test, and continually assess the abilities of vehicle systems. The on-board process takes this further by using trend analysis to predict when a failure might occur. When a malfunction is expected, the driver is warned, and the vehicle is ordinarily directed out of the AHS system. When an on-board failure is detected, the vehicle goes through a pre-programmed failure response, which depends upon the nature of the failure detected.

9.5.8 Handling of Emergencies

Vehicles respond to emergencies, generally using pre-programmed emergency responses (including "Brake hard to a stop"). When a vehicle senses an emergency, it broadcasts that fact. Note: the Communications protocol may have to change modes during an emergency.

Vehicles might continually negotiate contingency plans for various emergencies using the slack communications bandwidth during ordinary operations

9.6 IMPLEMENTATIONS

Following is a potential implementation of the concept, specifically what will be in the vehicle, the roadside and the AHS TOC, above and beyond the standard and ITS.

9.6.1 Vehicle

- Forward looking sensor
- Passive marker sensor (May be the forward looking sensor)
- Differential GPS (receiver and communications)
- Transmitter/Receiver integrated with processor (Short range RF vehicle-to-vehicle communications)
- [Other sensors, optionally]

It might be argued that a no-sensor version of this concept would be feasible, using roadside beacons to convey road geometry information. In this implementation, vehicles would not require forward looking sensors, nor passive marker sensors.

9.6.2 Infrastructure

Passive markers marking the edges of the roadway, possibly the lanes, and maybe other vehicles. If the edges of the roadway are marked, they must be coded to indicate the distance to the nearest lane, the default lane width, and the default number of lanes.

The roadway must also have continuous physical separation. This can be a specially-built road, or by modifying existing roadway, for example using Jersey barriers.

9.6.2.1. <u>Rural Highway</u>

Long section of highway, a single lane wide, separated from main road by Jersey Barriers, or poured permanent barriers. Entry/Exit lanes would be many miles apart, and the Rural AHS would be intended for long travels, both rural to distant rural locations, and inter-urban trips.

9.6.2.2. <u>Urban Region</u>

Dedicated lanes on existing urban highways, with roadside markers, and dedicated entry/exit locations, spaced more widely than regular highway entrances and exits.

9.6.3 Deployment

Since the roadway has the large per mile expense of total physical isolation (even if just achieved by deploying continuous Jersey barriers), the minimal deployable roadway is probably in an urban area.

It is taken to be a dedicated lane on a commute corridor, isolated by Jersey barriers, with city transit along that corridor fitted for AHS use, and AHS capability available as a factory option and/or as an aftermarket option for private vehicles. Equipped private vehicles are allowed on the AHS lane.

Given this minimal deployment, incentives are as follows. Those who commute along the modified corridor have an incentive to buy or retrofit a vehicle to operate in the AHS system. This will earn the driver a "brain-off" commute, and a probably a much faster commute. The local transit authority has some incentive to extend the AHS lanes to more of the local transit lines, and to concurrently transition its fleet to AHS capable vehicles. This earns the greater use and more flexibility with its AHS-capable vehicles, faster transit runs (hopefullydrawing more customers), and reduced accident risk with a given driver skill level. It might reduce driver costs, or not, depending on union rules, and it might increase maintenance costs.

If the local base of AHS-capable vehicles builds up, this provides added incentive to build infrastructure.

9.7 GENERAL ISSUES AND CONSIDERATIONS

The questions listed in the outline are answered below.

What degree of automation is there in the navigation function?

The navigation function is done fully automatically by the vehicle, which must know the highway map at a gross level, and the desired exit.

What are the obvious failure modes for the concept?

GPS goes down. Vehicle-to-Vehicle Communications Airspace is jammed.

What major systems or subsystems can back one another up in case of failure?

Sensors and roadway markers can back up GPS/Comm-based navigation (and vice versa). Sensors on the whole set of vehicles can back up any one vehicle's sensor which goes out.

Under what circumstances (if any) is control passed to the driver?

Control is passed to the driver during check out. In the event of a total, system-wide shut-down (e.g., GPS goes down), control would eventually be passed to the driver. In general, the driver cannot take control during travel when in substantial traffic. a driver always has control, however, to the extent of being able to specify a new exit (including the next exit coming up).

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?

There may be ITS services, or sensors in the road which inform the infrastructure, either of which could inform the vehicles.

Vehicles sense traction, and thus, have some sense of poor road conditions, and can pass that information upstream. Limited sensor visibility is directly sensed by the inability to see the roadway markers. Note, this would be taken as an obstacle, and substantially shut the road down. (This suggests using an all-weather sensor, such as radar.)

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

The maximum user speed is an open design issue, but could be very high. Once the maximum user speed is set, lower speed limits would be possible as local options. This would be very tailorable with Local Vehicle-to-Vehicle Communications Beacons. Speed limits could also be put in machine-readable format and read from passive markers, but the code would lead to a quantization limit of only a finite number of speeds.

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

These vehicles could always do adaptive cruise control when following other AHS vehicles. The vehicle specification could be extended so that these vehicles could always do adaptive cruise control. On roadways with the passive lane markers, the could also do automated lane keeping. (Note: these passive markers might be traditional reflective lane markers.)

When more than one of these vehicles are traveling within the vehicle-to-vehicle communications network length, they could communicate with each other. This communication could include local traffic patterns, and hazard, roadway and other information that would improve the safety of traveling. This network could carry many other possible secondary signals (e.g., Pong).

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

Buses could run on the AHS lanes, gaining the same travel time benefits. AHS entry/exit points could be collocated with multi-mode transition points (airports, train terminals, park and rides, etc.). Greater throughput on AHS might slightly reduce the traveler load on other travel modes.

What additional services would the concept provide for freight carriers?

Much greater detail of truck activities could be monitored via ITS fleet management. The AHS equipment could also provide safety sensors (e.g., brake warning/adaptive cruise control) on non-automated highways. Convoys (groups of trucks traveling together) could interlink their traffic surrounds while on non-automated roads, which should greatly increase their aggregate safety.

What features of this concept will most contribute to increasing throughput over the present system?

The very detailed information on very local traffic, provided via redundant vehicle sources, will allow the vehicles to travel rapidly and at higher densities, while still maintaining safety.

What features of this concept will most contribute to increasing safety over the present system?

Enhanced situational awareness of surrounding traffic, including very rapid recognition of sudden changes in non-Line-of-Site vehicles.

What features of this concept will most contribute to making it cost-effective?

The vehicles exploit the ongoing historical trend in decreasing cost for performance.

What will be the required vehicle maintenance?

Repair/replacement of vehicle-to-vehicle communications and processor (should be very rare, solid-state device).

Regular maintenance of control/actuators.

Regular maintenance of forward looking sensor.

Continual inspection in use of AHS in vehicle equipment.

What will be the required infrastructure maintenance?

Continual maintenance on passive markers, replacing damaged/worn ones.

Pseudolites repair/replace damaged Pseudolites. (Including regular examination schedule, which can be drive-through.)

Roadside V-V Beacons, repair/replaced damage. Remote test. (Including regular examination schedule, which can be drive-through.)

General maintenance on any local "GPS" beacons.

What does this concept assume in the way of support from the external world (e.g., enforcement, safety checks, ...)?

It assumes periodic equipment checks on the vehicle. More significantly, it assumes that where a failure in use is identified, the vehicle is identified, and given a "fix it ticket." This ideally occurs primarily at Check-In.

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)?

Induced demand, comparable to that demand which would be induced if the highway was simply widened to the same level of capacity that AHS will offer. Special categories of induced demand are not currently foreseen.

10. CONCEPT 8B: ISACADO

This is a description of a design concept for the Automated Highway System. This particular concept is defined by:

- an infrastructure supported intelligence distribution,
- free agent vehicle separation architecture,
- dedicated lanes with continuous physical barriers,
- vehicles of the same class in a AHS lane,
- with dedicated entry/exit lanes, and
- comprehensive obstacle detection and avoidance.

This concept is given the mnemonic name *Isacado*.

10.1 OVERVIEW

The Isacado concept provides an outstanding solution for many urban traffic systems. Excellent throughput and a high level of safety is realized, while allowing regional specific implementation tailoring.

With dedicated lanes coupled to dedicated entry/exit access for single classes of vehicles, Isacado provides outstanding throughput. Vehicle flow can be optimized to the acceleration and braking characteristics of the single vehicle class, whether it be two axle automobiles; heavier, two axle busses or trucks; or heavy articulated vehicles.

The physical barriers, dedicated access, homogenous vehicle class, and obstacle sense and avoid approach provided by Isacado is the optimum combination of design architectures for safety. Physical barriers and dedicated access inhibit rogue vehicles and reduce the probability of random obstacles in the AHS lanes. The statistical distribution of vehicle control and responses, especially braking and steering, is small since all vehicles in a lane are of the same class. And finally, any obstacles that do encroach on the traffic flow are sensed and avoided without driver intervention.

The Isacado concept is adaptable to the urban traffic needs. Similar in design to many of the high occupancy vehicle (HOV) lanes used everyday in large cities, Isacado is a natural evolution. Isacado can be customized by the local implementing agency for time of day and direction of travel. Since the command, communication, and control intelligence (C^3I) is infrastructure supported, the implementation costs are lower than other infrastructure managed or infrastructure controlled designs.

10.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

The six concept dimensions are explored in the following paragraphs.

10.2.1 Distribution of Intelligence

The Isacado concept is based on cooperative vehicle intelligence supplemented by infrastructure information. The individual vehicles maintain lane keeping control; cooperatively, vehicles determine and maintain safe headway distance and perform merge maneuvers. The vehicles are provided traffic information, such as:

- congestion—slower traffic from mile 215 through mile 219, maximum speed 80 km/h;
- exit 211 at capacity, alternate exit 213 is open;
- lane damage at mile 212.5, slow to not greater than 70 km/h for bump;

10.2.2 Separation Policy

The Isacado concept is a "free agent" architecture. Safe headway spacing is a function of the class of vehicles in the lane, braking distance (a function of velocity and road condition), and the frequency, resolution, and accuracy of vehicle to vehicle communication (if any). The headway between vehicles can be minimized if the vehicles communicate with each other, rather than relying solely on sensing distance to the preceding vehicle.

10.2.3 Mixing of AHS and Non-AHS Vehicles in Same Lane

The Isacado concept is predicated on maintaining complete physical separation of non-AHS vehicles from the AHS vehicles. This can be satisfied by:

- continuous physical barriers, e.g. jersey barriers;
- physically separated roadway, e.g. elevated or below grade similar to some HOV lanes;
- specifically dedicated AHS roadway, e.g. new roadbed constructed in newly acquired or existing right-of-way, or dedication of existing roadway as an AHS highway.

10.2.4 Mixing of Vehicle Classes in a Lane

The Isacado concept is predicated on a single class of vehicles in a lane. Individual lanes must be provided to accommodate two or more classes of vehicles (traveling at the same time). The selection of which class, or classes, of vehicles to accommodate is a regional specific option.

10.2.5 Entry/Exit

Entry and exit to and from the AHS travel lanes for the Isacado concept is via dedicated lanes. The entry lanes include the vehicle inspection operation. In providing for higher throughput, increased safety, reduced emissions, and a favorable return on investment, the regional implementing agency will be encouraged to strategically locate entrance and exit lanes. It is expected that in order to make the AHS operate smoothly, the distance between access lanes cannot be as short as currently exists on some urban "expressways", where some entrance/exits are separated by less than two kilometers.

10.2.6 Obstacle

The vehicles will sense and avoid hazardous obstacles. Each vehicle will sense the presence of obstacles, complemented by the cooperative communication between the vehicles. Additionally, if a change in traffic conditions occurs as a result of obstacle avoidance maneuvers, the supporting infrastructure intelligence will sense and inform approaching vehicles. However, the likelihood of encountering dangerous obstacles is relatively low for the Isacado concept, (as compared to many other concepts) given the physical segregation of traffic.

10.3 OPERATIONAL CONCEPT

The Isacado concept, an excellent bias of intelligence distribution (most intelligence within the vehicles), coupled with the closed nature of the system, is a deployable, operable system. The system is defined in three possible conditions: normal, degraded, or failed.

10.3.1 Normal Operating Condition

The Isacado design would operate almost exclusively in the normal condition.

10.3.1.1. Access

The Isacado AHS design concept provides safe and efficient traffic flow. Entrance lanes are instrumented and gated to inspect and permit, or prohibit, access to the AHS travel lanes. The driver passes gate one, entering a portal analogous to a man-trap. As the vehicle travels toward gate two, vehicle-infrastructure cooperative telemetry verifies the vehicle equipment meets the minimum operation conditions (sensors, communication, and controls working properly). Given satisfactory results to the interrogation, vehicle control is assumed by the AHS and the vehicle passes gate two and merged into the AHS traffic. If the vehicle fails the interrogation, the driver is advised that entrance to the AHS is denied (and given a reason), and instructed to drive the vehicle out of the access system (via a posted egress). Note that the gate designs must prevent vehicle passage; the specific solution could be something as unobtrusive as the tire puncture devices installed at car rental agencies and parking garages.

10.3.1.2. Exit

The Isacado design provides a simple and efficient exit operation. Given an indication from the driver of an exit preference, the vehicle will be guided from the travel lane to the dedicated exit lane—unless the vehicle has received a notification from the infrastructure that the exit is not available. The infrastructure monitors the travel and exit lane conditions and advises the vehicles of the availability of exits. Once in the exit lane, the vehicle enters a portal, similar to the access system described above; whereas for the exit portal, the release from the system is predicated by confirmation of the driver's ability to resume vehicle control. If the driver does not pass a competency screening, the AHS guides the car to a wayside station, and notifies highway authorities.

10.3.1.3. Normal Travel

> *"The building blocks of the Isacado concept are sufficiently flexible and modular to become the cornerstone of the national architecture. The implementation of the concept elements can be tailored to regional needs—while still maintaining configuration commonality."*

The vehicle, having been certified for the AHS and under autonomous control, is merged into the AHS travel lane. Through cooperative intelligence between the merging vehicle and the traveling vehicles (if any are in the vicinity coincident with the merge event), the vehicle accelerates and steers to a safe position between traffic in the travel lane. The vehicle travels along the highway as defined by the cooperative intelligence process, supplemented by traffic and roadway information through the infrastructure supported architecture. The vehicles, being of the same class, in a physically separated lane, can move at relatively high speeds, as compared to other design concepts. The speed limitation is driven by the class of vehicles, their performance characteristics (efficient operating speed, braking distances, handling characteristics), the roadway condition (type of pavement, condition of pavement, turn radius and bank), weather (rain, snow, wind), and system volume (number of vehicles, spacing between vehicles).

Incidences along the Isacado AHS are extremely rare. The high degree of containment: physical barriers separating the AHS traffic from other lanes, all vehicles cooperating, supported by infrastructure data, and all vehicles being with a class; reduces the likelihood of accidents to near zero.

10.3.2 Degraded AHS Condition

In the event of extreme weather, high congestion, roadway surface problems, vehicle accident, or AHS subsystem malfunctions, the AHS operates in a degraded mode. This mode may result in less than optimum throughput, and may require some driver participation. Note that since Isacado is an infrastructure *supported* design, and therefore not dependent on communication through the infrastructure for vehicle control, the likelihood of a degraded AHS as a result of an AHS subsystem or component malfunction is near zero (and may actually be shown to be zero, after design is complete and analyzed).

10.3.3 Failed AHS Condition

In the event of natural disaster, lane blockage, AHS failure, or other extreme event, the AHS will bring the vehicles to a safe transition to the driver. The driver may be instructed to exit the system or given some option to continue under manual control, depending on the nature of the problem. Note again, that since Isacado is an infrastructure *supported* design, and therefore not dependent on communication through the infrastructure for vehicle control, the likelihood of a failed AHS as a result of an AHS subsystem or component failure is near zero (and may actually be shown to be zero, after design is complete and analyzed).

10.4 FUNCTIONAL ALLOCATION

Table H.10.4-I defines the allocation of baseline functions for the Isacado design to vehicle, infrastructure, human, or combination. The allocation is presented as a distribution summing to 100%; i.e. check-in is shown to be allocated 75% to the vehicle, 25% to the infrastructure.

10.5 IMPLEMENTATIONS

In the Isacado design, the vehicles are sufficiently instrumented to cooperate a free agent separation policy supplemented with minimal infrastructure data.

10.5.1 Vehicle

The vehicle AHS subsystems include sensors to detect leading, following, and near adjacent vehicles and obstacles; processing logic to provide acceleration, braking and steering commands; communication equipment to communicate with neighboring vehicles, and actuation components to execute maneuver commands.

10.5.2 Infrastructure

The roadway supports vehicle lane keeping sensing with magnetic, optical, or other lane marking guides. The infrastructure also senses the access, exit and travel lane conditions to evaluate safe traveling speeds, prevent congestion, and support obstacle detection. The information is broadcast along the appropriate section of roadway; the vehicle operating systems respond accordingly.

10.5.2.1. Rural highway

The basic subsystems of the Isacado concept supports AHS applications in a rural environment. Assuming that rural agencies could not afford dedicated, physically segregated AHS travel and access lanes, the cooperative, fully instrumented vehicles required by the Isacado concept could also be operated in a rural environment where physical traffic segregation, both vehicle class and lane barriers, is nonexistent. The design concept dimensions for this application are:

- infrastructure supported, cooperative, or autonomous C^3I,
- free agent separation policy,
- full mixing of AHS and non-AHS traffic,
- transition lanes for entry and exit, and
- automatic sensing and avoidance of obstacles.

Note that the hand-off to/from manual and autonomous control and the merge process will differ from the Isacado concept for a rural application. Also, improvement in throughput will not be great; but, it is presumed that increasing throughput is not a significant need in a rural environment. The subsystems in the vehicles, supplemented by some form of lane marking guides, can provide substantial improvement in the safety and comfort of the rural traveler. The building blocks of the Isacado concept are sufficiently flexible and modular to become the cornerstone of the national architecture. The implementation of the concept elements can be tailored to regional needs—while still maintaining configuration commonality.

10.5.2.2. Urban Region

The Isacado concept is inherently envisioned for a urban region. Dedicated, physically separated access and travel lanes, providing segregated travel based on vehicle class, is a design specifically aimed at improving throughput and safety for congested urban traffic systems. The Isacado concept can be implemented for one, two, or more classes of vehicles. The regional transportation agency can designate lane use restrictions by time of day to certain classes of vehicles, or more likely, could establish AHS lanes for each class of vehicle warranted in a given area (e.g. one lane for busses, one for automobiles).

Table H.10.4-I. Allocation of Baseline Functions

Baseline Function	Vehicle (%)	Infrastructure (%)	Human (%)	Comment
Check-in	75	25		Infrastructure may facilitate inspection
Transition from Manual to Automatic	100			
Sensing of Roadway	100			
Sensing of Vehicles	70	30		Infrastructure senses vehicles to monitor traffic, facilitate flow control, identify availability of exits
Sensing of Obstacles	90	10		Infrastructure supports through monitoring traffic flow.
Lane Keeping	100			
Headway Keeping	100			Vehicles cooperative
Detection of Hazards				
Normal Maneuver Planning	100			Vehicles cooperative
Emergency Maneuver Planning	100			Vehicles cooperative
Maneuver Execution	100			
Transition from Automatic to Manual	90		10	Human acknowledges readiness to assume vehicle control
Check-Out	70	30		Infrastructure supports identification of availability of exits and may facilitate hand-off to driver.
Flow Control	50	50		
Malfunction Management	50	50		Infrastructure can broadcast advice to the vehicles

10.5.3 Deployment

The Isacado AHS design concept is a natural evolution for the traveling public, freight carriers, transit operators, and transportation management agencies. The vehicle subsystems are a natural evolution of the emerging intelligent vehicle components and the infrastructure requirements can be tailored to the region unique needs.

10.5.3.1. Vehicles

The vehicle is equipped with the necessary AHS instrumentation and controls. These vehicle unique components and subsystems are standard equipment on most automobiles, and readily available for buses and trucks. The ascendancy from cruise control, to adaptive cruise control, collision warning systems, et cetera, to the AHS equipment has been anticipated by the vehicle marketplace.

10.5.3.2. Infrastructure

The regional (national, state, county, urban authority) agencies modify their HOV lanes, where required, or establish new roadways, where desired, to provide dedicated entry/exit for physically segregated AHS traffic. The AHS lanes can be collocated with existing highways or constructed in other existing or acquired right-of -way.

10.6 GENERAL ISSUES AND CONSIDERATIONS

10.6.1 Implementation Flexibility

The Isacado concept, with dedicated lanes and access, does not have to be collocated to existing highway right-of-way. As in the Pittsburgh example, where railroad beds were acquired and converted for bus service, AHS lanes could be established in locations where right-of-way could be acquired for the lowest cost and would decrease motor vehicle congestion at existing highway and surface street intersections.

10.6.2 Cost

The Isacado concept has much lower infrastructure costs versus any infrastructure managed or infrastructure controlled designs. Given that the vehicles will need to provide sensors, processing and actuation systems for any concept, the additional costs for the infrastructure *supported* Isacado concept are relatively small: roadway sensors to monitor traffic, data processing equipment, and roadside beacons. Also, the Isacado concept could be modified to satisfy rural transportation needs (see 6.2.1), at even lower cost.

10.6.3 Freight Carriers

The Isacado design significantly reduces highway congestion, speeding the movement of freight. By improving traffic flow and reducing accidents, independent of whether a regional transportation agency has provided an AHS lane specifically for trailer truck rigs, the trip time will be improved for all highway users. And, of course, if a regional transportation agency dedicates a lane for freight class vehicles, trip time, trip time predictability and safety are improved; driver fatigue is eliminated.

11. CONCEPT 9: INFRASTRUCTURE SUPPORTED PLATOONING ON DEDICATED LANES, WITH MIXED CLASSES

11.1 OVERVIEW

Concept #9 considers *infrastructure supported platooning* of vehicles on the AHS while allowing *mixed vehicle classes in a lane*. The AHS and non-AHS lanes are separated with *continuous physical barriers* thereby requiring *dedicated entry-exit* facilities for the AHS lanes. 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. Vehicles on the highway are organized into platoons. Platooning can be used to increase highway throughput, minimize the delta-velocity between vehicles within a platoon,[1] and use line-of-sight communication technology for control purposes. Infrastructure support allows for central coordination in the form of supervisory control.

11.1.1 Distinguishing features

- Use of platooning to increase throughput and minimize the delta-velocity between vehicles.
- Low level of reliance on infrastructure support. 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 case features to the infrastructure other than those allowed by the definition of *infrastructure support.* The increased functionality will be required for two purposes: (i) entry/exit assistance which will be localized at the on-off ramps and (ii) vehicle specific communication capability used for dynamic routing and emergency notification.
- Distributed intelligence provides the opportunity to design an AHS that
  - optimizes system-wide performance via infrastructure-based controllers, and
  - provide for high levels of system availability: congestion due to faults/accidents avoided or eased through the use of infrastructure-based supervisory control.
- Infrastructure support can be used to broadcast safety-related information (e.g., reduced safe speed when it starts raining for example) to vehicles on specific sections of the automated highway.
- Dedicated lanes with continuous physical barriers mitigate hazards associated with intentional and unintentional mixing of vehicle types (i.e., manual and automated). However, continuous physical barriers also introduce hazards.
- Dedicated entry/exit ramps permits the hand-off-of-control in the presence of vehicles that are not equipped for automated vehicle control. If the queue of vehicles entering the dedicated entry ramp exceeds the ramp length, then the entry ramp will have a possibly negative impact on arterial roadway traffic flow. Similarly, if some interval of time the number of vehicles departing an automated lane via a dedicated exit ramp exceeds the capacity of the ramp, then some vehicles will be denied permission to exit until the next available exit ramp.

[1] By minimizing the delta-velocity between vehicles, it is possible to reduce the severity of collisions between vehicles.

11.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

11.2.1 Infrastructure Support

In this concept, infrastructure support is utilized to provide dynamic information to automated vehicles, such as:

- Suggesting lane changes and safe speeds.
- Announcing upcoming exit locations, lane drops, or hazards.
- Providing advice on 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.

11.2.1.1. 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.

11.2.2 Platooning With Mixed Vehicle Classes in a Lane

When automated vehicles of different classes are formed into platoons, the dynamics (e.g., 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 platted 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:

11.2.2.1. 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 agents. A particular design may

force the vehicles to join the appropriate platoon at the time of entry requiring a 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.

11.2.2.2 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 for use by buses/trucks during off-peak hours. In fact, it can be exclusively used for trucks at night. The infrastructure support allows the local authorities to exercise such control depending on time of the day.

11.2.3 Dedicated Lanes with Continuous Physical Barriers

This option 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. This option with dedicated entry/exit allows the AHS operators to strictly enforce the above separation. Physical barriers also prevent accidents by manual vehicles spilling over to AHS and vice versa. On the other hand, the risk of collision with a stationary barrier requires tighter sensing and control of vehicle steering.

11.2.4 Dedicated Entry-Exit

This option results in a smooth flow of AHS and non-AHS traffic as the two streams use separate entry/exit facilities. However, the necessary construction of dedicated on/off ramps for AHS increases the cost of deployment and maintenance.

11.2.5 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* with a minimal false alarm rate. These sensors should at least match the human sensing abilities. The design of an automated avoidance maneuver should at least match human intelligence.

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

11.3 OPERATIONAL CONCEPT

Normal operation scenarios for this concept are as follows. The vehicle under manual control decides to enter the AHS by manually entering the dedicated AHS entry. At the beginning of the entry ramp 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. At this point the vehicle control systems take control of all the vehicle systems and sends a message requesting entry to the infrastructure. The infrastructure will have the capability to perform a ramp-metering type of function. Thus, based on overall system conditions it decides at some time to allow entry. Once permission is granted the vehicle moves 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 from where the entering vehicle is waiting. These detectors 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, the vehicle is allowed to enter. If a platoon is detected in the entry zone, the infrastructure has 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 allow safe entry, the infrastructure requests the platoon to allow entry. If the platoon acknowledges, it is required to decelerate to a specified entry speed. After the platoon receives confirmation from the oncoming platoon, it provides the waiting vehicle with its target speed and asks 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 so, the vehicle sends lane-change requests until a platoon communicates its willingness to admit the vehicle in front of it. The vehicle uses 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, it changes lanes. Otherwise, it co-ordinates with the adjacent lane platoon that has agreed to accept the vehicle in front of it. The assisting platoon slows down till the required gap becomes available. Then a lane-change maneuver is executed. If there is no platoon in the adjacent lane in the *safe lane change distance*, the vehicle changes lanes 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, the vehicle sensors are used to detect the presence of a platoon that is close enough ahead to join with. If such a platoon is detected, 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, the join maneuver is executed. Thus, the new vehicle accelerates to merge with the platoon ahead. If no such vehicle is detected within a specified range, 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 safety while executing a maneuver. This ensures, for example, that during a join maneuver, another vehicle from an adjacent lane does not change lanes in between the two joining platoons. To maintain routing flexibility to individual vehicles, only free agents can change lanes in a multilane AHS. On the other hand, a follower in a platoon may 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 broadcasts 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 processes the advice of the infrastructure and acts 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 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, it must send its split request to the platoon leader who acknowledges the request by asking the vehicle to become a leader. Once the vehicle does so, it retards itself and all the vehicles 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, lane changes proceed as above. 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.[2] 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 possess vehicle-to-vehicle communication capabilities as required during join, split, lane-change, and entry maneuvers.

[2] 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, that is, 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.

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, to 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, target platoon size, velocity and distance setpoints. The role of the infrastructure will still be limited as an advisory controller. The safe execution of maneuvers is handled by individual vehicle controllers. Moreover since the infrastructure participates in check-in and collects destination information at the point of entry, 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 also provides 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 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 arise either due to the loss of infrastructure or loss of 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 possibly 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 according to passenger preference. 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 determines it by 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 its remaining capability along with help from neighboring platoons to exit 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 having the obstacle removed.

11.4 SYSTEM DIAGRAM

The system diagram is on the following page.

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 need only be in aggregate form since it is used 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.

11.5 FUNCTIONAL ALLOCATIONS

11.5.1 Check-In

The human indicates his or her willingness to enter the AHS by driving onto the dedicated entry ramp. The vehicle senses that it has entered the dedicated entry ramp. 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), the infrastructure broadcasts to platoons entering the roadway segments in proximity to the entry ramp that a rogue vehicle might enter the automated lanes.

11.5.2 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 broadcasts to platoons in proximity to the dedicated entry ramp 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), the infrastructure broadcasts to platoons entering the roadway segments in proximity to the entry ramp that a rogue vehicle will enter the automated lanes.

11.5.3 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.

11.5.4 Lane and Headway Keeping

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

11.5.5 Detection of Hazards

Detection of hazards is performed by both the vehicle and infrastructure. The vehicle and infrastructure fuse sensor data, with the objective of distinguishing between hazards (e.g., rogue vehicle or roadway obstacle) and non-hazards (e.g., shallow puddle of water or newspaper blowing across the roadway).

11.5.6 Maneuver Planning

Vehicles within a platoon communicate with each other in order to prepare for a maneuver. When two or more platoons are involved in a maneuver, inter-vehicle communication is used for coordination purposes. The infrastructure provides aggregate vehicle and roadway information, which the vehicles utilize in planning maneuvers.

11.5.7 Maneuver Execution

Maneuver execution is performed by vehicles, according to the maneuver plans developed by platoons.

11.5.8 Transition from Automatic to Manual Control

Same as for transition from manual-to-automatic control, only in reverse order.

11.5.9 Check-Out

Same as for check-in, only in reverse order. The infrastructure will provide aggregate information regarding the status of arterials at the exit point (i.e., intersection of the dedicated exit ramp and arterial roadway).

11.5.10 Flow Control

The infrastructure provides aggregate roadway and vehicle status information. The vehicles receive this information and make local decisions (i.e., decision specific to one or more roadway segments) regarding control actions which affect local and global traffic flow. That is, the information provided by the infrastructure is in the form of recommendations rather than commands.

11.5.11 Malfunction Management

The platoons and infrastructure coordinate with each other in managing malfunctions. The infrastructure provides position and other platoon status information to platoons in the vicinity of a faulty vehicle or roadway infrastructure. If the malfunction is within the infrastructure, the management coordination relies on vehicle-to-vehicle communication, planning, and execution. If vehicle-to-vehicle communication fails, each vehicle within a platoon performs malfunction management as a free agent.

11.5.12 Handling Emergencies

The infrastructure provides global commands for stopping or restarting movement on the AHS lanes. Vehicles provide the infrastructure with their status.

11.6 IMPLEMENTATION

11.6.1 Vehicle

11.6.1.1. Roadway Sensing

Used for lateral and possibly longitudinal control (e.g., if vehicle communication fails, calculate spacing and relative speed from beacon data). Such technology includes all types of indirect[3] road reference systems (e.g., energy sources, reflectors, etc.).

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[3] By indirect we mean there is no physical link between the sensor and the marker: the signal processor is responsible for determining the distance between the sensor and the sensed marker.