APPENDIX H—DESCRIPTIONS OF CANDIDATE CONCEPTS

H.1. INTRODUCTION

As an intermediate step in the C1 effort, leading to the development of six preferred concepts for Automated Highway System to be carried into the C2 effort, 23 system concepts were defined and fleshed out. This appendix is a compilation of the 23 system write-ups.

These 23 concepts were all defined by selecting one option from each of six concept dimensions, as described in 3.1 of the main report. The concept dimensions, and their alternatives, are:

Distribution of intelligence

- Autonomous — The vehicles are driven entirely by on-board automatic control, but vehicles do not coordinate with each other.
- Cooperative — The vehicles are equipped as above, but share data and negotiate decisions. This is a natural allocation for functions involving multiple vehicles in a small area, such as a lane change.
- Infrastructure Supported — Similar to cooperative, but infrastructure provides general or location specific, non-vehicle specific, dynamic information and static information.
- Infrastructure Managed — Like infrastructure supported, but the infrastructure sends specific commands to individual vehicles.
- Infrastructure Controlled — The infrastructure directly commands individual vehicles, controlling their moment by moment trajectories.

Separation Policy

- Free Agent — Vehicles maneuver as individual units.
- Platooning — Coordinated groups of vehicles travel with very tight spacing, but long spacing between groups
- Slotting — Time or space is divided into sections which individual vehicles are assigned to and travel in.

Mixing of AHS and Non-AHS

- Dedicated Lanes with Continuous Physical Barriers — AHS highway is physically isolated along its entire length.
- Dedicated Lanes with Some Gaps — AHS lanes are physically isolated on a highway, with gaps in the barriers allowing traffic to flow between AHS and manual lanes.
- Dedicated Lanes with Virtual Barriers — only AHS vehicles are allowed on the automated lanes, but nothing physically prevents manual vehicles from intruding.
- Full Mixing — AHS vehicles travel fully automated while mixed with manual traffic.

Mixing of Vehicle Classes in a Lane

- Mixed — Multiple AHS vehicles in different classes (e.g., cars, trucks) allowed in the same lane at the same time.
- Unmixed — AHS vehicles in different classes do not travel in the same lane at the same time.

Entry/Exit

- Dedicated — The entry and exit of vehicles to and from AHS lanes is through ramps and other dedicated structures.
- Transition — The entry and exit of vehicles to and from AHS lanes is through transition lanes running parallel and between manual and AHS lanes.

Obstacle

- Automated sensing and automatic avoidance maneuver if possible — AHS, without requiring driver assistance, detects obstacles in the roadway, and attempts to automatically maneuver the vehicles to avoid the obstacles.

- Automatic Sensing, Stop and Manually Avoid — AHS, without requiring driving assistance, detects obstacles in the roadway. When an obstacle is detected, the vehicle is brought to a halt, and the driver takes over temporarily to manually circumvent the obstacle.
- Manual Sensing and Avoidance of Obstacles — The driver is responsible for seeing and avoiding obstacles. Sensors may assist the driver.

The Table below summarizes each of the concepts. After the meeting establishing the initial set of concepts, it was recognized that concept 7 was identical to concept 14, so concept 7 was dropped. Part way through the analysis of these concepts, the consortium decided that infrastructure controlled concepts were unfavorable. Since the only slotted concept in the initial set of 22, was infrastructure controlled, but non-infrastructure controlled slotted concepts are possible, concept 3a was created to give slotting a fair chance to make its case. Both concepts are described in this appendix.

Twenty-Three Candidate Concepts

Candidate Concept Identifiers	**1a**	**1b**	**2**	**3**	**3a**	**4**	**5**	**6**	**8a**	**8b**	**9**	**10**	**11**	**12a**	**12b**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Distribution of Intelligence																							
Autonomous	X	X																					
Cooperative						X	X													X	X		
Infrastructure Supported								X	X	X	X						X		X				X
Infrastructure Managed					X							X	X	X	X	X		X				X	
Infrastructure Control			X	X																			
Separation Policy																							
Free Agent	X	X	X			X		X	X	X		X		X	X			X	X		X		X
Platooning							X				X		X			X	X			X		X	
Slot				X	X																		
Mixing AHS & Non-AHS Vehicles in Same Lane																							
Dedicated lanes with continuous physical barriers			X	X	X				X	X	X			X	X	X					X	X	X
Dedicated lanes with some gaps in the physical barriers						X	X	X				X	X				X						
Dedicated lanes with virtual barriers																			X	X			
Full Mixing	X	X																X					
Mixing Vehicle Classes in Same Lane																							
Mixed	X	X	X			X	X	X	X		X	X	X	X			X	X	X	X	X	X	
Not Mixed				X	X					X					X	X							X
Entry/Exit																							
Dedicated			X	X	X				X	X	X			X	X	X					X	X	X
Transition	X	X				X	X	X				X	X				X	X	X	X			
Obstacle																							
Manual sensing and avoidance of obstacles	X																						
Automatic sensing, stop or manually avoid																					X	X	X
Automatic sensing and automatic avoidance maneuver if possible		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

2. CONCEPT 1A: ADAPTIVE CRUISE WITH LANE MONITORING

2.1 OVERVIEW

Adaptive cruise is the simplest of the concepts considered. Its main advantages are that it is a necessary step in the deployment of several of the other concepts, it requires little infrastructure investment, and its early implementation can aid in technical development of a full scale obstacle detection system.

Another way to consider this concept is as the way we would like an AHS vehicle to operate on a non-AHS roadway.

2.2 DIMENSION ALTERNATIVES

- autonomous, free agent vehicles
- mixed vehicle classes and mixing of AHS/non-AHS vehicles
- no special entry/exit for AHS vehicles
- full longitudinal control
- must rely on human for full obstacle detection/avoidance (although limited obstacle detection through longitudinal control sensors)

2.3 OPERATIONAL CONCEPT

Entry/exit is done as a non-AHS vehicle. Once the vehicle is in the lane, driver sets automatic cruise. Forward looking sensors allow vehicle to maintain up to posted speed without colliding with forward vehicles (or most forward obstacles). In addition, road curvature and grade information is coded in the roadway or by a DGPS system in conjunction with a map. This information is used by the longitudinal sensors to avoid false obstacle detection. Lateral position sensors will monitor the vehicle's position in a lane although automatic lane keeping may not be implemented (for reasons below).

The driver can override the system at any time. Most obstacles are detected by the forward-looking sensor but some will be missed (eg. dropped loads, pavement holes, objects moving laterally toward lane). The driver is required to be alert for obstacles not detected by the vehicle sensors.

Driver alertness is a major problem for this concept. One way to handle it would be to utilize a driver alertness sensor. If a sleeping driver is detected, an alarm is sounded and the vehicle slows. An alternative option would be to require the driver to steer the vehicle (i.e. no automated lane keeping). This would help keep the driver awake by giving him a task to do.

2.4 FUNCTIONAL ALLOCATION

- check in/out—none
- transition from manual to auto control-human
- sensing of roadway—human
- sensing of vehicles and obstacles—human and vehicle (mainly by vehicle sensors but backup provided by human)
- sensing of hazards—human
- lane keeping—human (alternatively vehicle)
- headway keeping—vehicle
- maneuver planning and execution—human
- transition from auto to manual control—human (instantaneous)
- flow control—none
- malfunction management—human
- emergency handling—human

2.5 IMPLEMENTATIONS

The following are two of many possible implementations:

2.5.1 Vehicle

Implementation #1:

- forward-looking FMCW radar
- throttle, steering, and brake actuators

- magnetic nail sensors

Implementation #2:
- fused radar/vision forward-looking sensor
- DGPS and accurate map
- throttle, steering, and brake actuators

2.5.2 Infrastructure

Implementation #1:
- magnetic nails

Implementation #2:
- DGPS reference stations (1 per approx. 100 miles)
- radar reflective roadway markings

Note, there is no difference in rural vs. urban operation.

2.5.3 Deployment

A minimal system could be implemented without any infrastructure modifications. This system would have headway sensors but no lane keeping or absolute positioning.

The next step from minimal is the addition of DGPS capabilities. This requires reference stations in the infrastructure. (DGPS will aid the headway control system in recognizing false obstacles at curves and road grades.)

A third step can either be modification of roads (magnetic nails or special pavement markings) to add lateral control, or an improvement in sensing capabilities toward full fledged obstacle detection. (The concept would then evolve to 1b.)

2.6 GENERAL ISSUES

Navigation is not automated although DGPS can provide trip planning and exit notification.

The most critical failure mode is non-detection of a dangerous obstacle by both the vehicle sensors and by a sleeping or distracted driver.

The system relies totally on human backup. The driver can take control of the vehicle on demand.

This concept has no roadway sensing and no special handling (or sensing) of limited visibility conditions (snow, ice, etc. ...)

Speed is not a critical issue—should be no problem handling 65 mph or possibly faster.

This concept (except for lateral control) can work on a conventional roadway.

This concept has no connection with other transportation modes.

Freight carriers may find this concept convenient for long trips (in fact, there exist adaptive cruise control systems for freight use today).

The concept provides no increase in throughput.

Forward-looking sensors increase safety by helping avoid front end collisions.

The concept is cost effective in the sense that it requires minimal investment in infrastructure.

Vehicle maintenance requirements are expected not to be any greater than normal maintenance schedules of today's vehicles.

The main demand for (and the user's view of) this concept will be as a smart cruise control device for long distance travelers (eg. freight carriers).

Another advantage of this concept is in its use as an evolutionary deployment aid for more complex concepts. In fact, any concept requiring full vehicle-based obstacle detection must implement this concept.

Besides helping perfect the obstacle detection capabilities, this concept will get drivers used to the idea of smart vehicle headway control.

A disadvantage of this concept is that it does not represent a "brain-off" driving situation. The driver must always be alert for obstacles. This could project a bad image of AHS if this concept is touted as an early example of AHS.

3. CONCEPT 1B: AUTONOMOUS FREE AGENT VEHICLES MIXING WITH NON-AHS TRAFFIC

3.1 OVERVIEW

This concept, which mixes AHS and non-AHS traffic on the same freeway lanes, requires few or no infrastructure changes to implement. This concept is characterized by autonomous vehicles which have the ability to maneuver appropriately given the following information: number of lanes on the freeway, which lane the vehicle is in, where the vehicle is within that lane, where other vehicles and obstacles are, and lastly, what the relative velocity of these objects are. By eliminating the driver from the loop, a gain in throughput will be realized even without platooning capabilities. Safety gains will also be realized because of the added vigilance of the AHS system. No communications technology is required, although a minimal communications capability would significantly add to this concept.

3.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Distribution of Intelligence: Autonomous vehicles with no infrastructure intelligence
Separation Policy: Free agent vehicles that do not travel in platoons

Mixing of Vehicles: Full mixing of AHS and non-AHS vehicles in lane

Mixing of Vehicle Classes: Full mixing of all vehicle classes

Entry/Exit: Transition lanes

Obstacle: Automatic sensing and collision avoidance maneuvering

Region Specific Options:

1. Although this option is intended to mix fully automated AHS vehicles with non-AHS vehicles on the same lane, dedicated AHS lanes could be created in order to maximize the benefits of AHS technology.
2. This technology can be used as a requirement for use of HOV lanes in order to encourage car-pooling.

3.3 OPERATIONAL CONCEPT

3.3.1 Check In

Once a vehicle has entered a freeway and the driver wishes to utilize the AHS features, a brief systems check is performed by the vehicle. If all required systems are operational, the on-board AHS system will gracefully assume control of the vehicle. At the point where the vehicle is successfully integrated into the traffic flow, the computer will prompt the driver for destination information. The driver will specify one of three options: that he will manually assume control a later point in time, that the vehicle will transition control to the driver after a certain number of miles, or that the vehicle will transition control to the driver in time for the driver to leave the freeway at a particular exit.

3.3.2 Normal Operations, Including Obstacle Detection

The vehicle will determine its location on the highway either through vision data or GPS used in conjunction with an on-board database. The vehicle will be able to determine the number of lanes on the freeway and which lane the vehicle is in. The vehicle has 360 degree obstacle detection sensors that detect other vehicles and obstacles. The vehicle will also be capable of detecting the relative velocity of these objects. The on-board logic uses the above information to maneuver the vehicle so that it travels with the flow of the traffic and maintains a safe distance from other vehicles. A gain in throughput is achieved because intelligent vehicles can use smaller headways due to faster reaction times to received information. Even given mixed traffic flow, increases in flow rates are predicted to improve. In the event that the AHS vehicle is closing on another object, be it a stationary obstacle or a slower moving vehicle, the AHS system will determine if it is safe to maneuver around the object by passing in another lane. The vehicle will automatically signal its intentions by using the turn signal. If a space is available for safe passing, the vehicle will do so. If a safe opportunity does not present itself, the vehicle will decelerate and potentially stop in order to avoid a collision. In severe emergencies, it will be possible for the vehicle to gracefully maneuver onto the shoulder.

A potential technology used to detect the relative motion of surrounding objects could be a non-vision based technology such as Doppler radar. A secondary, vision-based system may have sensors to detect the brake lights of vehicles around them. If a brake light is detected, the AHS vehicle will brake in a timely and appropriate manner or maneuver out of the way. The integration of cyberlight technology (whereby the brake light flash frequency can be detected by the vision system) may be required so as to determine the degree of braking required.

Additional vision system benefits include the ability of AHS vehicles to detect turn signals on other vehicles. They will have the logic to automatically create a space for a vehicle in another lane that has signaled its intention to merge into its own lane. This kinder, gentler vehicle will either accelerate past that vehicle or slightly decelerate in order to create a space.

AHS vehicles will also have sensors capable of detecting hazard signals for stalled or very slow vehicles. This information will also feed into the maneuvering and braking algorithms on-board, and will supplement the vehicle/obstacle and relative velocity information obtained.

Integration of a very simple, locally directed communications system would greatly simplify this concept. The vision system concept has significant technical concerns due to latency issues and non-functioning brake lights on non-AHS vehicles. By integrating a basic communications "beacon" that signals AHS capability and motion intentions, this system would be greatly simplified. It is also possible that all non-AHS vehicles be required to install a communications system that signals motion intention (lane changes and braking) so as to further enhance safety.

The backwards looking sensors will be continually scanning for vehicles which are approaching with a problematic delta v. The vehicle can signal the approaching vehicle by "flashing" its brake lights to gain the attention of the on-coming vehicle. If this is unsuccessful and a collision is imminent, the AHS vehicle will maneuver out of the lane to avoid a collision.

3.3.3 System Tailoring and Aggressive Driver Avoidance

Algorithms will be developed so that highly aggressive, manually driven vehicles do not "work the system" so as to run AHS vehicles out of the lane or off the road.

There will be a limited number of options to tailor the vehicle to the driver's preferences. For example, if an elderly driver prefers to stay in the right hand land regardless of the speed of travel, he will be able to do so. The driver can also insist that the vehicle never exceed a certain speed for personal comfort considerations or in order to torment his teenage children. Other items of user comfort, such as headway tolerance, could be specified within a range determined by the AHS. Lastly, the "kinder, gentler" feature that allows other vehicles to merge into your lane could be turned off at the option of the driver.

3.3.4 Use of AHS Technology for Rural and Inner-City Driving

Certain features of the AHS system, such as lane-keeping and headway maintenance, can be used independent of other features. This will provide additional safety benefits during inner-city driving as well as rural roadway driving. Partial-use of AHS features will be terminated manually.

3.3.5 System Transition from Automated to Manual Control

Terminating the full use of the AHS features will be done in one of two ways. In the first method, the vehicle will signal the driver via visual and audio cues that the desired exit is approaching or that the specified number of miles have been traveled. Transition from AHS to manual use will be done in steps, ensuring that the driver is physically responding to necessary cues. First, the AHS system will ensure there is sufficient headway distance between itself and the lead vehicle for the transfer to manual control. It will then return control of the accelerator to the driver. When the system determines that the driver has adequate control of the velocity and acceleration of the vehicle, it will return control of the braking and maneuvering functions as well. In the rare instance that the vehicle is slowing to a stop because the driver has not assumed control of the accelerator, the AHS system will regain all automated functions and safely pull to the side of the freeway.

3.3.6 Manual Termination of AHS Capabilities

The second method of transitioning an AHS vehicle from automated to manual control is through driver-initiation. This method also requires a graceful transition, however this transition period could be shorter and may even be immediate for emergency situations.

3.4 FUNCTIONAL ALLOCATION

In this concept, all intelligence is assigned to the vehicle. No infrastructure changes have been implemented to support AHS. Additional functional allocation information is summarized under "3.3. Operational Concept."

3.5 IMPLEMENTATION

Implementation of intelligence is strictly placed in the vehicle. No infrastructure support will be required.

3.5.1 Vehicle

The following technologies will be examined in order to achieve this concept:

- Forward and backward looking Doppler Radar
- GPS
- Side looking proximity sensors
- Infrared technology
- Vision system technology

3.5.2 Infrastructure

There will be no infrastructure support in this concept other than already existing GPS infrastructure. No TOC will be necessary or available. If communications are added to this concept, this statement is subject to review.

3.5.3 Deployment

This system will have tremendous appeal because of the safety advantages, early implementation of technology, and wide applicability of technology. Vehicles can be equipped with AHS technology as soon as it is proven and requires no timely and costly infrastructure changes. AHS capability can not only be utilized on freeways but can also be used, at least partially, in the city and on rural roadways. This provides significant and immediate benefit to the consumer.

3.6 GENERAL ISSUES AND CONSIDERATIONS

Were basic communications capability integrated into this concept, significant benefits would be realized. By allowing vehicles to electronically signal their intentions and/or braking data, the system architecture could be greatly simplified. Visual detection, with the associated latency problems and the complicated algorithms that are required to support a variety of detection features, would not be necessary.

4. CONCEPT 3: SPACE/TIME SLOT SEPARATION [INFRASTRUCTURE CONTROLLED]

4.1 OVERVIEW

Space/Time Slot Control is a configuration which allows synchronous control of all vehicles within a specific moving space on the AHS roadway. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for the slot control concept is the slot, which corresponds to a single vehicle. Synchronous control refers to the system wide coordination of the motion of vehicle slots. This form of control can be referred to as point following.

The desired local vehicle speed or timing is controlled by the infrastructure, as is the spacing. Slot dynamics can be modified based on vehicle performance capabilities or current traffic densities. The vehicle adjusts its speed to track the slot dynamics commanded by the infrastructure. The merge decisions for each vehicle are determined by the infrastructure at the time the vehicle is assigned to a slot; the vehicle follows infrastructure commands to reach merge speed and adjust its position to merge into its assigned slot.

This concept has been selected for discussion due to its unique approach to the traffic flow problem. Other concepts featuring free agents and platoon architectures are asynchronous, in that the dynamically changing distribution of vehicles within the system is not coordinated in a global manner, but is managed within the coordination unit at the vehicle or platoon level. The slot or point-following architecture provides a concept in which the distribution and flow of all the vehicles within a region are managed in time synchronization. This approach requires processing (intelligence) at the regional and zone level. The slot architecture can be implemented in a manner which places the majority of processing and sensing in the infrastructure, theoretically minimizing the extent of vehicle instrumentation. The advantage of this approach is that a larger percentage of vehicles may be compatible with AHS retrofit in the early stages of deployment and the cost of AHS specific instrumentation will not be prohibitive in new car models which feature AHS equipment.

4.2 DIMENSION ATTRIBUTES

4.2.1 Distribution of Intelligence: Infrastructure Control

Vehicle control loop commands are generated by the infrastructure. Slot positions are scheduled at the regional level and monitored at the zone level. Vehicle directives may be in the form of acceleration, deceleration and maneuver instructions, in which case the vehicle calculates the appropriate throttle, brake, and steering commands to vehicle actuators. Alternately, the infrastructure may perform the throttle, brake, and steering calculations and transmit these commands to the vehicle. The vehicle instrumentation provides the ability to translate commands into corresponding input to actuators. The vehicle also is capable of monitoring on-board measurement systems and adjusting vehicle performance to meet command requirements.

4.2.2 Separation Policy: Slot

The slot attribute provides unique slots in space and time for individual vehicles. The separation between vehicles is determined by the size of the slot. Smaller slots correspond to higher lane density. The ability to maximize density will depend on the ability to safely monitor and maintain vehicle headway in closely spaced slots. This will depend on the ability of infrastructure instrumentation to accurately determine on a continuous basis the position of all slots in its vicinity. A single vehicle is the coordination unit, the goal of the infrastructure control is to maintain individual vehicles in their assigned slot, and no interaction between vehicles occurs.

4.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Continuous Physical Barriers

Continuous physical barriers will prevent access of unauthorized vehicles into spaces between slots. Unqualified vehicles which breach the entry facility can be detected by the infrastructure instrumentation at the zone level as slot spacing is monitored. This information can be relayed to the regional slot allocation function and slot spacing around intruders or travel speed can be adjusted to allow operation to continue until the non-AHS vehicle can be removed.

4.2.4 Mixing of Vehicle Classes: Not Mixed

The preliminary attribute assignment specified no mixing of vehicle classes. This will permit maximum passenger vehicle density and travel speed within a single lane. Slot allocation will be determined based on the lowest common denominator of vehicle performance of the set of vehicles allowed on a certain lane. Slots will be allocated at a certain spacing for passenger cars based on the slowest accelerating and longest braking distance of allowed cars. Slots in a commercial vehicle lane will be spaced at greater intervals, corresponding to the performance of vehicles authorized for that lane.

An option for rural or less congested areas might allow mixing of vehicle classes. The regional allocation of slots could take into account vehicle performance factors when assigning slots to vehicles requesting entry to the automated lanes. Slot spacing could be adjusted to accommodate lower performing trucks or buses, or several slots could be assigned to a single vehicle as another approach.

4.2.5 Entry/Exit: Dedicated

Vehicles will access the automated lanes via entry facilities. The infrastructure will regulate access to the AHS as slots are available. A vehicle may need to wait in the entry facility for an empty slot to arrive in a highly congested lane. Alternately, the regional controller may reassign slots within a zone to accommodate entering vehicles more quickly.

Vehicles will exit the automated lanes through a dedicated exit facility. The infrastructure will generate maneuver commands which allow the vehicle to separate from the assigned slot and demerge from the automated lane at a point which corresponds with the requested exit location.

4.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

The vehicle control loop for this concept is closed in the infrastructure. Acceleration, deceleration, and maneuvers are coordinated by the infrastructure at the zone level. Obstacle detection can be performed by the vehicle or by the infrastructure. Resolution and accuracy are key performance factors in determining the ability to deploy infrastructure detection of obstacles. Vehicle detection of obstacles must be coordinated with the infrastructure generation of vehicle control loop commands. The vehicle must be able to communicate the obstacle information to the infrastructure, increasing the response delay time before an avoidance maneuver can be commanded and performed.

4.3 OPERATIONAL CONCEPT

Slot separation is based on the concept of a virtual string of continuously moving points in an unbroken chain. The distance between points in the chain is referred to as the slot. The slot between points in the chain can be measured in time or space, generating the title space/time slot. Figure H.4.3-1 illustrates the relationship of the TOC, the zone controller, and the chain of points moving through space and time. The vehicle must maintain its position relative to its assigned point in space within the required tolerance in close following modes. The rationale for maintaining the position in the slot relative to a specific point can be shown by imagining a leading vehicle positioned at the back edge of its slot, and the following vehicle at the front edge of its slot. A vehicle will encroach on the assigned slot of another if the longitudinal position error exceeds the slot length minus the length of the vehicle.

The regional TOC is responsible for slot assignments. Zone controllers monitor vehicle position relative to its assigned slot position. The infrastructure must sense vehicle position at intervals equivalent to the slot length within the local zone. The sensor spacing will depend on the capability to pinpoint location of multiple targets at the required resolution over a given range. There is also the requirement to update the vehicle position information at up to 50 msec rate.

Vehicles will request entry to the automated lanes from a dedicated entry facility. The regional traffic operations center (TOC) hasa dynamic map of available slots and assigns a slot to the entering vehicle which corresponds to his entry point. A region is envisioned to encompass a metropolitan area in urban environments. Rural regions may encompass a single county or several counties, depending on the traffic density, geographic separation of population centers, and level of infrastructure instrumentation. The relative positions of slots is constant in steady state operations. The zone controller gives the entering vehicle maneuver commands and monitors the vehicle's position relative to the assigned slot location and updates the acceleration/deceleration and turning commands as necessary to allow the

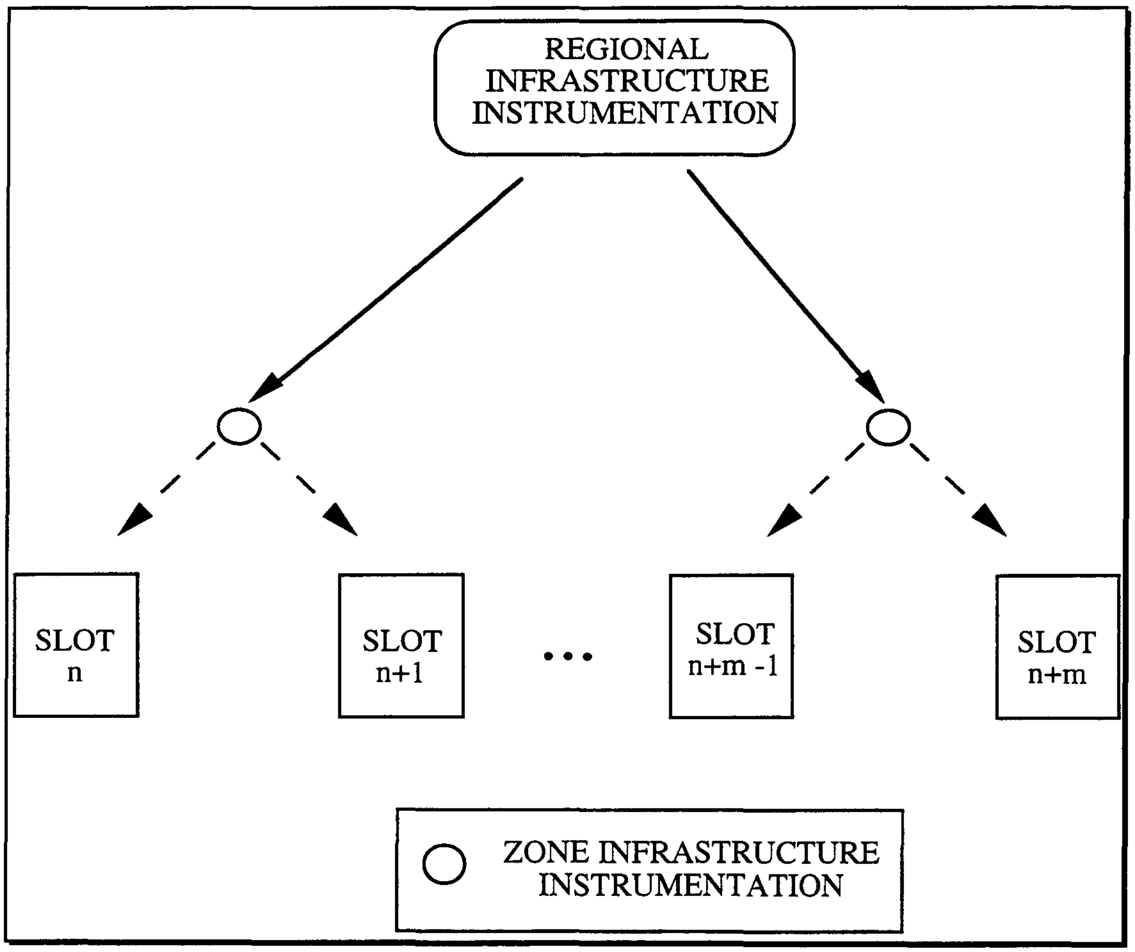

Figure H.4.3-1. Slots are the distance in space or time between points in a continuous chain

vehicle to merge into the moving slot. Zone controllers may encompass the local area surrounding an entry/exit facility. The field of responsibility of zone controllers must overlap to some extent to allow transfer of control as slots move through local zones.

Infrastructure instrumentation is required to monitor the location of vehicles within the assigned slots. Vehicle position will be detected using infrastructure based instrumentation, such as loop detectors or infrared sensors. The infrastructure will monitor the position of passing vehicles relative to their assigned slot position, and compare with expected time synchronization. The infrastructure will generate maneuver commands and transmit information addressed to the vehicle traveling in slot n. Commands will include data necessary for the vehicle to maintain its position within its assigned slot. Vehicles will monitor infrastructure commands and respond to data that is addressed to their assigned slot.

A vehicle is assigned a slot at the entry point that is associated with an absolute position in space or time. The motion of the slot is defined by the infrastructure, so the expected position of the vehicle is known by the infrastructure. The infrastructure knows where each slot should be at any point in time and periodically senses the position of the vehicles and maps this against the expected position of vehicles based on slot assignments. Vehicles detected out of tolerance in the assigned position are commanded to adjust speed until the correct position is attained.

Longitudinal position is adjusted by the vehicle responding to infrastructure speed commands until the infrastructure senses that the vehicle within slot n is positioned correctly. Lateral position is adjusted relative to a lateral control reference, such as magnetic markers. The vehicle lateral control system maintains the vehicle in the center of its assigned lane unless a maneuver command over rides the lateral control algorithm. The vehicle uses its lateral position relative to the lateral control reference and responds to infrastructure lateral commands which define a lateral rate of change in terms of a delta from the lane reference to accomplish lane changes and merges.

The spacing of infrastructure instrumentation within each zone must be sufficient to update vehicle commands to slots in its domain at an adequate rate to support safe and comfortable headway maintenance. Regional traffic operations centers will map and assign slots at the regional level and subdivide slot assignments to the local zone level. Zone based traffic controllers will transfer slot assignments to the vehicles and provide updates of slot control commands. Monitoring of vehicle position relative to its assigned time synchronization must be coordinated between zone controllers. Slots move continuously through time and space, passing from one local zone control range to the next.

The chain of points which define the slot spacing must also be coordinated at the global level. Chains associated with intersecting highways must merge at the intersection of the highways. The intersection of chains at highway interchanges can be thought of as teeth in a zipper which mesh when the paths intersect and separate when the paths diverge. The chain of points must continue into infinity, and a vehicle is associated with a single point throughout its journey within a region. Vehicles are transferred to slots in a separate chain when vehicles merge to another highway. As slots move out of the control of a specific TOC, the vehicle within the slot is assigned a slot in the next TOC. The virtual slot then joins the chain of moving slots at the starting point of the control area of the TOC. The coordination of slots at the TOC level is shown in Figure H.4.3-2.

The regional TOC is responsible for coordinating the merge of slots at highway interchanges. Slots n through n+m are assigned to Route A. Slots j through j+k are assigned to Route B. The TOC must ensure that if Route A and Route B merge to one lane, slots assigned to vehicles on Route A interleave with slots assigned to vehicles on Route B. Vehicles in Route A remain associated with their slot n+m assignment unless the vehicle is transferring to route B. When a vehicle on Route A is transferred to Route

B, the slot n+m assignment is transferred to a slot j+k assignment. The TOC must ensure that the chain of slots is timed correctly to allow a smooth transition from one chain to another. The processing required to maintain this type of coordination is significant. The TOC must plan slot assignments and synchronization on a network wide basis, coordinating slot availability with route plans for all vehicles on all routes under regional control. Failure to coordinate the slot assignments could result in adjusting slot assignments on the routes or modifying the slot motion on route A, delaying traffic flow to allow a vehicle to transfer to the next available slot on Route B.

4.4 SYSTEM DIAGRAM

4.4.1 TOC to Zone Controller Interface

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

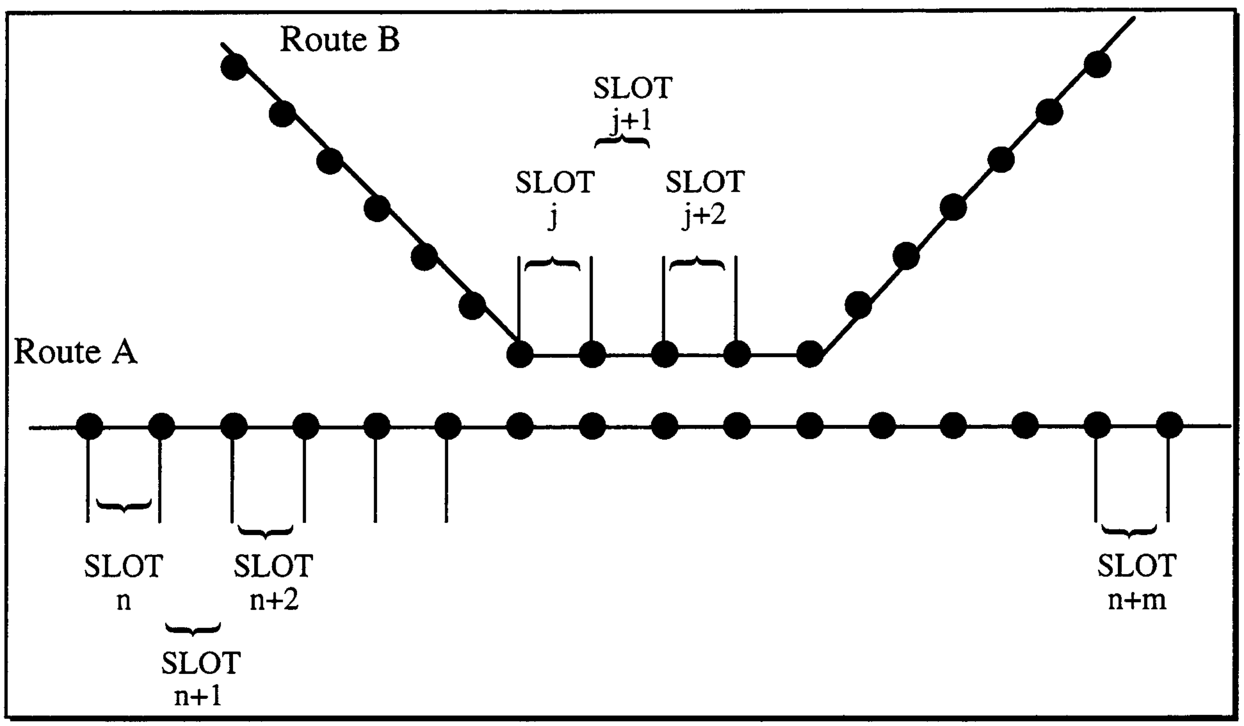

Figure H.4.3-2. Coordinating Chains of Slots at Interchanges

4.4.3 Roadway Condition Sensors to Roadway

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

4.4.4 Zone Controller to Range Detection Sensors

The range condition sensors pass information to the zone controllers concerning the position of vehicles relative to their assigned slot.

4.4.5 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.

4.4.6 Zone Controller to Vehicles

The zone controllers transmit slot addresses to vehicles requesting entry to the automated lanes based on slot assignments made by the TOC. The zone controllers transmit speed and lateral adjustment commands based on range calculations and maneuver requirements.

4.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

4.5 FUNCTIONAL ALLOCATION

Figure H.4.5-2 provides a graphical representation of a preliminary functional block diagram of the slot concept. The following text describes where each functional block is located and the tasks the functions are responsible for.

4.5.1 Position Control

Infrastructure control of the slot spacing is based on maintaining the relationship of vehicles within its assigned moving slot. Measurement of the longitudinal position is made by infrastructure sensors. The sensor information is processed by zone controllers which generate position control commands for each slot in its authority. Lane assignments are incorporated into the slot assignments. The vehicle senses its lateral position with respect to its assigned lane position. Lane changes and other lateral position adjustments are made when the infrastructure provides lateral control instructions containing lateral position increments relative to the assigned lane position.

The position control function is performed in the vehicle based on longitudinal control instructions obtained from the infrastructure, and vehicle-generated lateral reference information combined with incremental lateral movements commanded by the infrastructure. The longitudinal control subsystem receives acceleration/deceleration commands from the maneuver coordination function and generates throttle and brake signals to adjust the longitudinal position. The lateral control subsystem receives turning commands from the maneuver coordination function and generates steering signals to implement lateral changes commanded by the infrastructure.

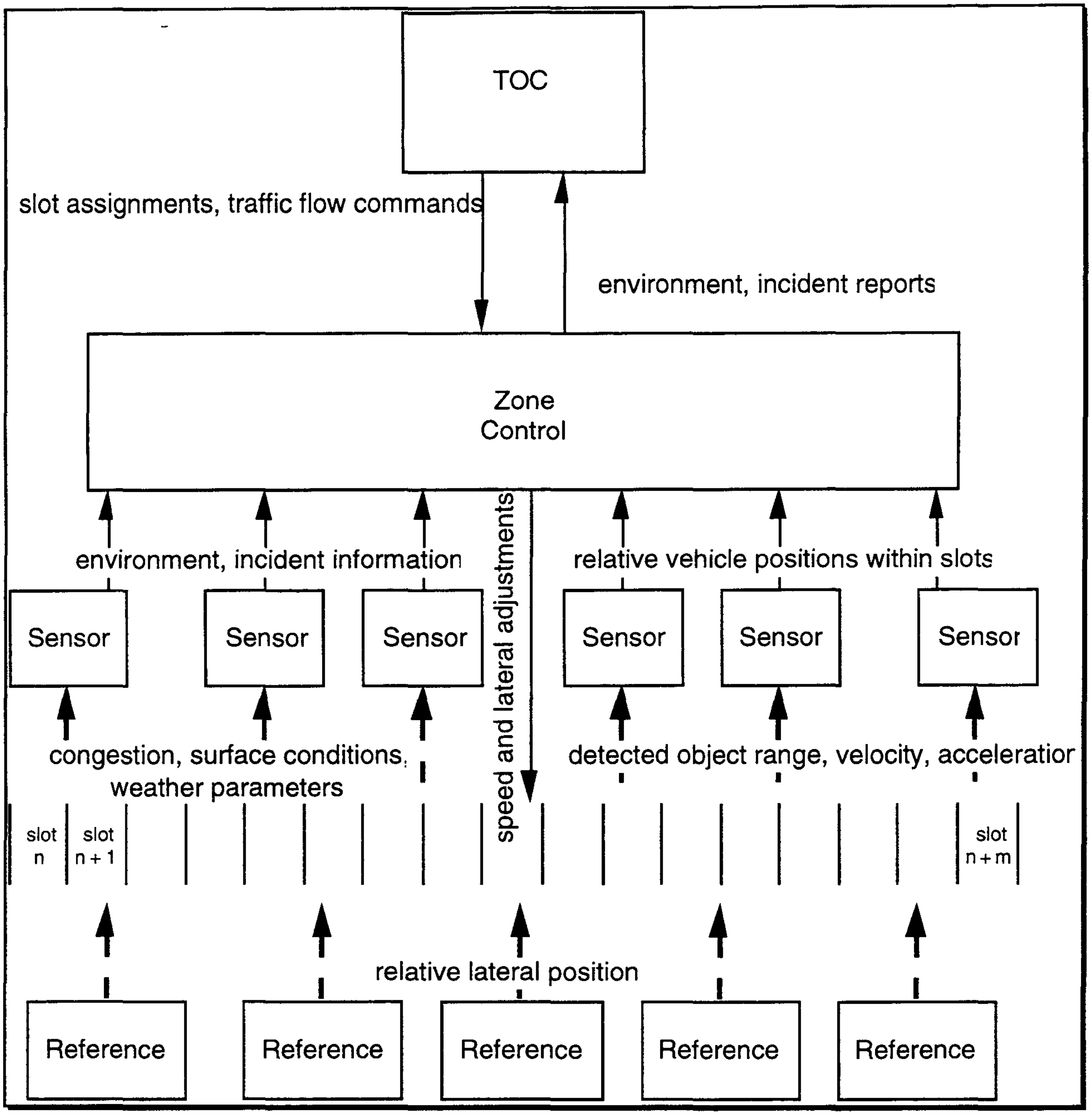

Figure H.4.4-1. Slot Control Interface Diagram

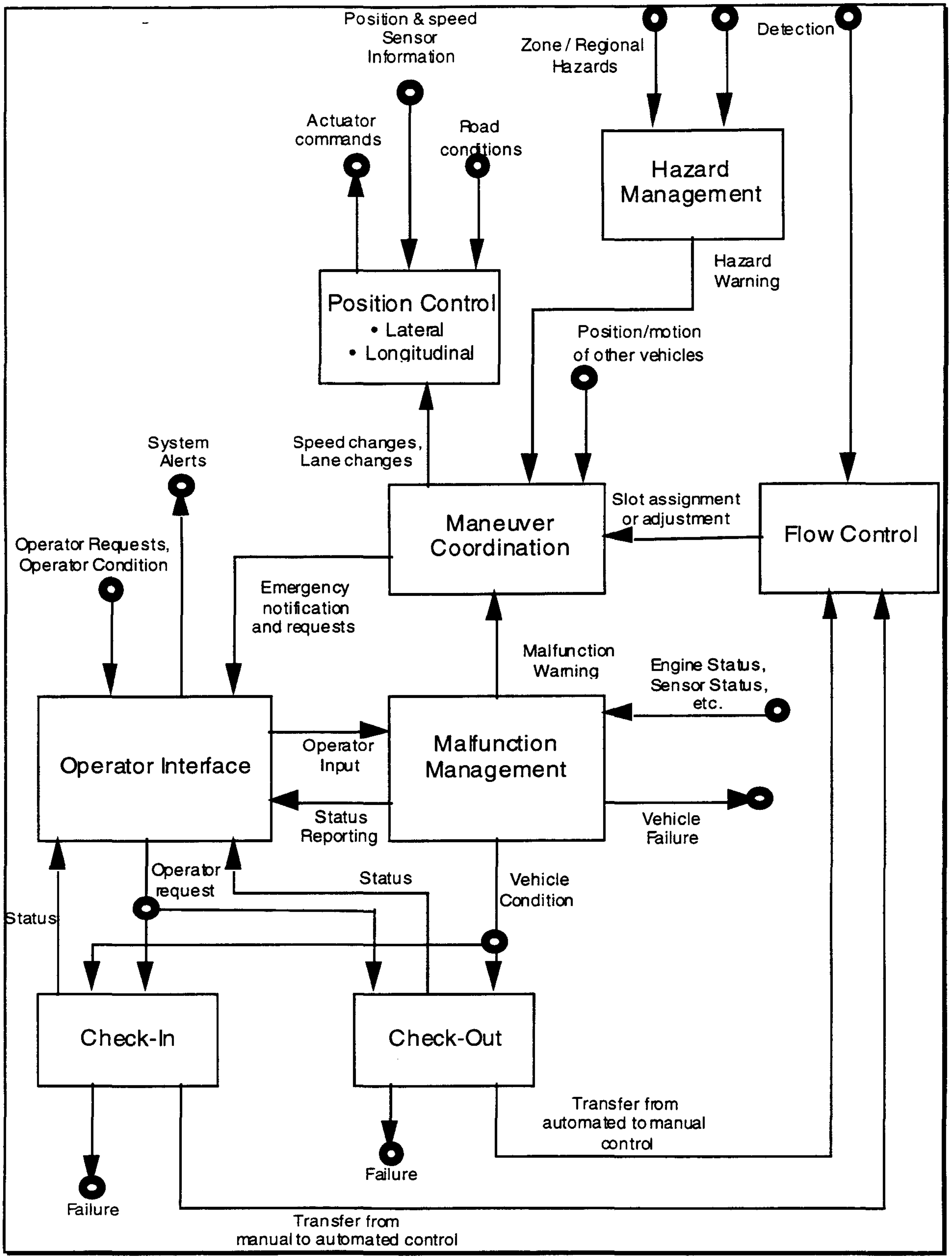

Figure H.4.5-2. Functional Block Diagram

position and speed. The vehicle performs The position control function processes sensor input regarding steady state vehicle steady state adjustments to longitudinal and lateral position using sensor inputs to generate actuator signals.

4.5.2 Maneuver Coordination

The maneuver coordination function is performed in the infrastructure. The maneuver coordination function receives maneuver requests from the flow control function, hazard warnings concerning obstacles or other traffic incidents from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function. This function receives information concerning the position and motion of vehicles at the zone level.

The maneuver coordination function responds to maneuver commands received from the flow control function by generating acceleration, deceleration, and turning commands which allow vehicles to enter or exit the automated lane in the slot assigned by the flow control function. The maneuver coordination function responds to hazard and malfunction warnings by generating acceleration, deceleration, and turning commands 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.

4.5.3 Hazard Management

The hazard management function is performed in the infrastructure. The hazard management function receives incident information and detects obstacle using sensors deployed in the infrastructure. The hazard management function generates a hazard warning message which is passed to the maneuver coordination function for appropriate action.

4.5.4 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 failure information to the traffic operations center and provides status messages to the operator.

The vehicle does not have a direct communications link with the infrastructure to advise the zone controller of vehicle malfunctions. The infrastructure will be capable of sensing irregularities in the position of vehicles relative to their assigned slot and may adjust slot velocity or size when it is determined that a vehicle is not maintaining the correct position relative to the slot. The vehicle must also be capable of detecting when an infrastructure failure prevents slot adjustment commands from occurring at the expected rate. A default operating mode must be available to allow vehicles to maintain safe control when infrastructure management fails.

4.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function receives requests to enter the automated lane from the check-in function, and requests to exit the automated lanes from the check-out function. The flow control function generates maneuver commands at the regional level. This function assigns slots to entering vehicles based on slot availability and entry location. The flow control function keeps track of unused slots following exit of a vehicle and reassigns slots or adjusts slot spacing based on current traffic flow.

4.5.6 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.

4.5.7 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 flow control function to request a slot and initiate entry to the automated lane. The transfer from manual to automated control is performed on the entry ramp. Once the transfer of control is completed, the vehicle begins to adjust speed in response to infrastructure commands and merges to the automated lane under automated control.

Vehicles which fail the check-in process will not be assigned a slot and 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 initiates the process for returning to the conventional lanes.

4.5.8 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 flow control function to initiate exit from the automated lane. The transfer from automated to manual control is performed on the exit ramp. The vehicle demerges from the automated lane under automated control and adjusts speed to allow the transfer of control to occur at a safe speed.

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.

Vehicles which fail the check-out process will remain in automated control and moved to a safe position as close as possible to the requested exit. 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. Slot assignments are released as vehicles exit the facility, and the TOC updates the database of available slot assignments. The released address can then be assigned to the next vehicle which enters the continuous chain of virtual slots.

4.6 IMPLEMENTATION OPTION(S)

4.6.1 Vehicle Electronics

Obstacle detection (option): the vehicle may be responsible for obstacle detection. Implementation of this option would require an interface between the vehicle obstacle detection subsystem and the position control subsystem to allow avoidance maneuvers if necessary. A communications link with the zone processor is an option to provide obstacle information to the local flow controller. This option would require a two way vehicle-infrastructure channel.

Maintain position: update actuator control signals as necessary

Sense lateral position: the vehicle is assigned its longitudinal position in space/time so there is no need for determination of absolute position. This concept could use a vision based or passive marker type lateral control approach.

Receive slot information messages: The communications device could be receive only, with the ability to screen messages to determine commands addressed to the assigned slot.

Process slot control commands: based on current speed, calculate acceleration/ deceleration parameters required to adjust slot position in response to infrastructure commands.

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

4.6.2 Infrastructure Instrumentation

TOC: manage global traffic flow. Generate slot assignments and update slot directory as vehicles enter and exit the system. Collect incident information from zone controllers and modify slot spacing as necessary.

Zone controller: collect incident information, transfer to TOC as necessary.

Slot sensors: monitor slot spacing. Generate slot control messages as necessary to regulate vehicle spacing within slots.

Broadcast slot information: transmit addressed slot messages. Unique addresses permit broadcast RF to be used. Only vehicles assigned with unique slot address respond to flow control commands.

Incident detection: sense local traffic congestion.

Obstacle detection (option): The infrastructure can be assigned the responsibility for obstacle detection. Radar ranging may be used to determine the relative spacing, velocity, and acceleration of vehicles traveling in slots. A roadside radar can determine the position of numerous targets by converting the time delay of the echo signal received from each target into a distance measurement and pinpointing the location relative to the radar. Resolution to a fraction of a meter may be necessary. The locations of expected targets known from system slot assignments may be mapped against the radar picture. Obstacles can be identified as targets which do not correlate with the known occupied slots. The ability of the radar ranging technique to discriminate legitimate obstacles from echoes such as background clutter and volume clutter caused by rain is an issue.

Lateral markers (option): passive markers in the roadway can be used as the lateral control reference.

4.6.3 Roadway Infrastructure

This concept requires conversion of a conventional lane to a dedicated AHS lane with a barrier separating the conventional and AHS lanes. An alternate approach

4.6.3.1. <u>Rural Highway</u>

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 this approach. The transition lane may consist of no more than a ramp merging from the conventional lane to the automated lane. 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.

4.6.3.2. Urban Region

Modify gap spacing to optimize capacity

Restrict heavy vehicles to off-peak hours

Limit frequency of access points for heavy vehicles to encourage longer trips

4.6.4 Deployment

This concept contains a high degree of infrastructure electronics. The efficacy of instrumenting long stretches of rural highway is a concern. The ability to serve larger numbers of vehicles per lane mile of instrumentation will improve the cost benefit ratio.

4.7 ISSUES

A very high level of real-time processing of sensor data and generation of vehicle commands will be required. The update rate of commands from the infrastructure to the vehicles is expected to be very high. Update rates on the order of 50 msec may be necessary to support close-vehicle following. Limitations in position sensing accuracy from the roadside of vehicles within expected time/space synchronization slots will determine maximum lane densities. The spacing of infrastructure instrumentation to support tracking of vehicle slots in a zone will depend on roadside sensor capabilities. The roadside sensors must accurately detect the position of vehicles at a rate sufficient to maintain the slot spacing. Tight slot spacing will require greater accuracy in position determination and higher update rates. Less capable sensors may be required to be spaced at very close intervals.

5. CONCEPT 3A: SPACE/TIME SLOT SEPARATION [INFRASTRUCTURE MANAGED]

In the preliminary assessment of the 22 concepts, it appeared that infrastructure control was a more expensive, less safe, less flexible alternative than any other. There was considerable sentiment to discard infrastructure control as an option.

Slot's, however, still seemed like a somewhat viable concept. In order to fairly assess slots, without biasing the results with the weaknesses of infrastructure control, concept 3a was created, which is concept 3 modified to be infrastructure managed, rather than infrastructure controlled. Thus, much of chapter 5 is repeated from chapter 4.

5.1 OVERVIEW

Space/Time Slot Control is a configuration which allows synchronous control of all vehicles within a specific moving space on the AHS roadway. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for the slot control concept is the slot, which corresponds to a single vehicle. Synchronous control refers to the system wide coordination of the motion of vehicle slots. This form of control can be referred to as point following.

The desired local vehicle spacing is determined by the infrastructure. Different vehicle classes can be accommodated by increasing the separation distance between the point assigned to a truck and a passenger vehicle, for example. Slot synchronization may be modified in preparation for merges. The vehicle adjusts its speed to track the slot dynamics coordinated by the infrastructure. The merge decisions for each vehicle are determined by the infrastructure at the time the vehicle is assigned to a slot; the vehicle adjusts control loop parameters to reach merge speed and maintain its position to merge into its assigned slot.

This concept has been selected for discussion due to its unique approach to the traffic flow problem. Other concepts featuring free agents and platoon architectures are asynchronous, in that the dynamically changing distribution of vehicles within the system is not coordinated in a global manner, but is managed within the coordination unit at the vehicle or platoon level. The slot or point-following architecture provides a concept in which the distribution and flow of all the vehicles within a region are managed in time synchronization. This approach requires processing (intelligence) at the regional and zone level. The primary advantage of the synchronous system is in facilitating merging and coordination of highway network interchanges.

There has been some debate concerning the potential capacity of a synchronous system. A single corridor may not benefit from synchronized coordination of traffic flow. A complex highway system with interchanges can be more efficient if the flow of vehicles is coordinated at the regional level. The more congested a channel is in steady (non-bursty) loads, the more benefit to be gained from synchronized management to regulate flow system wide. The spacing of vehicles is expected to be on the same order as free agents, providing comparable potential capacity with free-agent, infrastructure managed concepts.

5.2 DIMENSION ATTRIBUTES

5.2.1 Distribution of Intelligence: Infrastructure Managed

The infrastructure assigns vehicles entering the system to a moving point in space or time which the vehicle must track. The relative position of points or spacing is scheduled at the regional level and monitored at the zone level. The vehicle monitors its speed and position relative to its assigned slot and adjusts control loop parameters to maintain headway and lateral position.

5.2.2 Separation Policy: Slot

The slot attribute provides unique slots in space and time for individual vehicles. The separation between vehicles is determined by the size of the slot. Smaller slots correspond to higher lane density. The ability to maximize density will depend on the ability to safely monitor and maintain vehicle headway in closely spaced slots, similar to the constraints of free agent spacing. The coordination of traffic flow will depend on the ability of infrastructure instrumentation to track the status of all slots in its vicinity on a continuous basis, and to hand-off control of slots as they pass from zone to zone. Vehicles do not communicate directly, the infrastructure provides slot assignment updates as necessary to allow merging.

5.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Continuous Physical Barriers

Continuous physical barriers will prevent access of unauthorized vehicles into spaces between slots. Unqualified vehicles which breach the entry facility can be detected by the infrastructure instrumentation at the check-in facility as slots are assigned. This information can be used to by the zone controller to provide a buffer between the rogue vehicle and the next vehicle permitted to enter. Vehicles following a rogue vehicle may be assigned to another slot or travel speed can be adjusted to allow operation to continue until the non-AHS vehicle can be removed.

5.2.4 Mixing of Vehicle Classes: Not Mixed

The preliminary attribute assignment specified no mixing of vehicle classes. This will permit maximum passenger vehicle density and travel speed within a single lane. Slot allocation will be determined based on the lowest common denominator of vehicle performance of the set of vehicles allowed on a certain lane. Slots will be allocated at a certain spacing for passenger cars based on the slowest accelerating and longest braking distance of allowed cars. Slots in a commercial vehicle lane will be spaced at greater intervals, corresponding to the performance of vehicles authorized for that lane.

An option for rural or less congested areas might allow mixing of vehicle classes. The regional allocation of slots could take into account vehicle performance factors when assigning slots to vehicles requesting entry to the automated lanes. Slot spacing could be adjusted to accommodate lower performing trucks or buses, or several slots could be assigned to a single vehicle as another approach.

5.2.5 Entry/Exit: Dedicated

Vehicles will access the automated lanes via entry facilities. The infrastructure will regulate access to the AHS as slots are available. A vehicle may need to wait in the entry facility for an empty slot to arrive in a highly congested lane. Alternately, the regional controller may reassign slots within a zone to accommodate entering vehicles more quickly.

Vehicles will exit the automated lanes through a dedicated exit facility. The infrastructure will notify the vehicle to separate from the assigned slot and demerge from the automated lane at a point which corresponds with the requested exit location.

5.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

Obstacle detection can be performed by the vehicle or by the infrastructure. Resolution and accuracy are key performance factors in determining the ability to deploy infrastructure detection of obstacles. Obstacle detection by the infrastructure may increase the response delay time before an avoidance maneuver can be performed by the vehicle. Vehicle detection of obstacles must be coordinated with the infrastructure processor monitoring slot positions. The vehicle must be able to communicate obstacle avoidance information to the infrastructure to allow the infrastructure to adjust slot position or timing to accommodate emergency vehicle maneuvers.

5.3 OPERATIONAL CONCEPT

Slot separation is based on the concept of a virtual string of continuously moving points in an unbroken chain. The distance between points in the chain is referred to as the slot. The slot between points in the chain can be measured in time or space, generating the title space/time slot. Figure H.5.3-1 illustrates the relationship of the TOC, the zone controller, and the chain of points moving through space and time. The vehicle must maintain its position relative to its assigned point in space within the required tolerance in close following modes. The rationale for maintaining the position in the slot relative to a specific point can be shown by imagining a leading vehicle positioned at the back edge of its slot, and the following vehicle at the front edge of its slot. A vehicle will encroach on the assigned slot of another if the longitudinal position error exceeds the slot length minus the length of the vehicle.

Vehicles will request entry to the automated lanes from a dedicated entry facility. The regional traffic operations center (TOC) has a dynamic map of available slots and assigns a slot to the entering vehicle which corresponds to his entry point. A region is envisioned to encompass a metropolitan area in urban environments. Rural regions may encompass a single county or several counties, depending on the traffic density, geographic separation of population centers, and level of infrastructure instrumentation. The relative positions of slots is constant in steady state operations. The zone controller monitors information transmitted by the entering vehicle concerning the vehicle's position relative to the assigned slot location as the vehicle merges into the moving slot. Zone controllers may encompass the local area surrounding an entry/exit facility. The field of responsibility of zone controllers must overlap to some extent to allow transfer of control as slots move through local zones.

Infrastructure instrumentation is required to track the location of vehicles within the assigned slots. Vehicles will transmit position information, and the infrastructure will compare the position of passing vehicles relative to their assigned slot position. The infrastructure will generate updates containing relative slot position information addressed to the vehicle traveling in slot n as necessary to manage the slot spacing. Vehicles will monitor infrastructure commands and respond to data that is addressed to their assigned slot.

A vehicle is assigned a slot at the entry point that is associated with a moving position in space or time. The motion of the slot is defined by the infrastructure, so the expected position of the vehicle is known by the infrastructure. The infrastructure knows where each slot should be at any point in time and periodically compares the transmitted position of the vehicles and maps this against the expected position of vehicles based on slot assignments. Vehicles which are out of tolerance in the assigned position are directed to adjust speed and are given a targeted longitudinal delta. This is necessary to maintain precise slot position in the absence of a vehicle to follow in the adjacent slot.

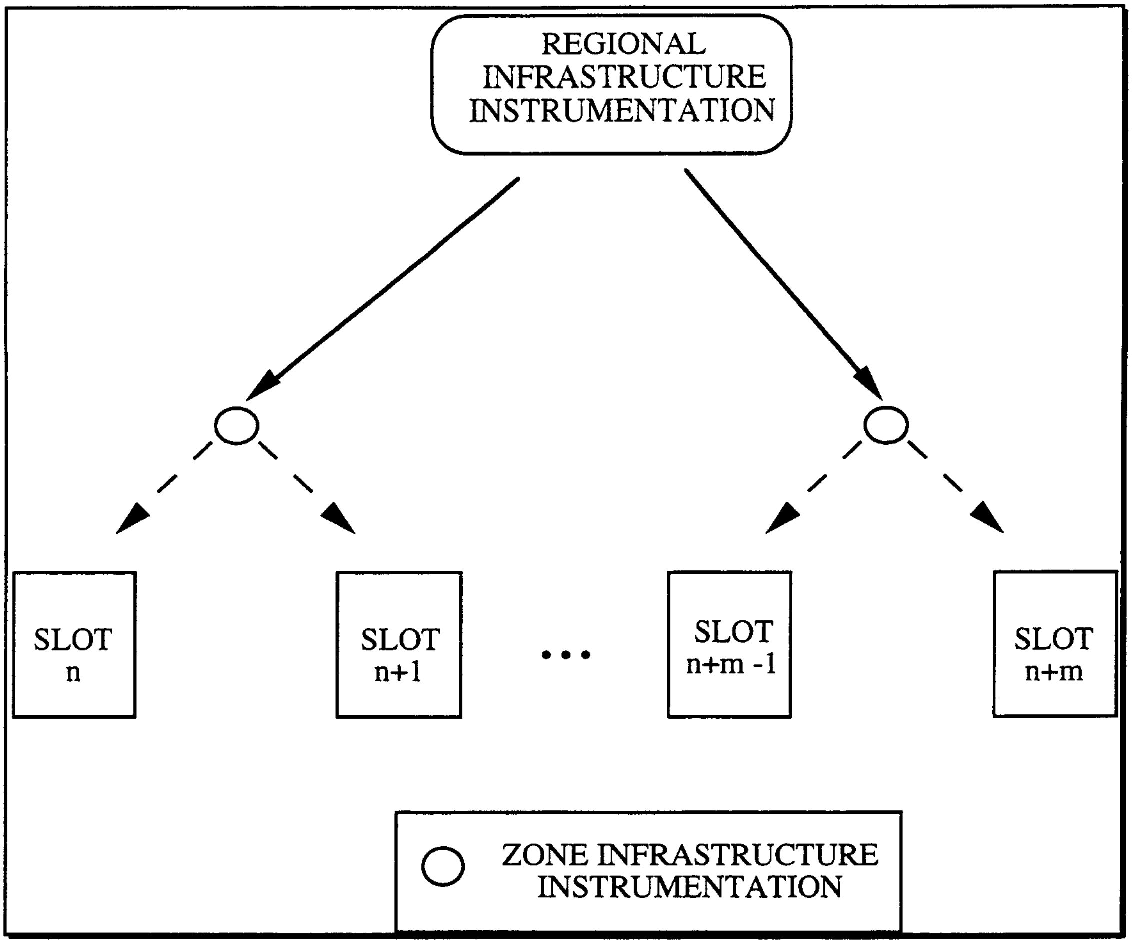

Figure H.5.3-1. Slots are the distance in space or time between points in a continuous chain.

Lateral position is adjusted relative to a lateral control reference, such as magnetic markers. The vehicle lateral control system maintains the vehicle in the center of its assigned lane unless a maneuver command over rides the lateral control algorithm. The vehicle uses its lateral position relative to the lateral control reference and responds to infrastructure lateral commands which define a lateral rate of change in terms of a delta from the lane reference to accomplish lane changes and merges.

The spacing of infrastructure instrumentation within each zone must be sufficient to update vehicle commands to slots in its domain at an adequate rate to support safe and comfortable slot position maintenance. Regional traffic operations centers will map and assign slots at the regional level and subdivide slot assignments to the local zone level. Zone based traffic controllers will transfer slot assignments to the vehicles and provide updates of slot position commands. Monitoring of vehicle position relative to its assigned time synchronization must be coordinated between zone controllers. Slots move continuously through time and space, passing from one local zone control range to the next.

The chain of points which define the slot spacing must also be coordinated at the global level. Chains associated with intersecting highways must merge at the intersection of the highways. The intersection of chains at highway interchanges can be thought of as teeth in a zipper which mesh when the paths intersect and separate when the paths diverge. The chain of points must continue into infinity, and a vehicle is associated with a single point throughout its journey within a region. Vehicles are transferred to slots in a separate chain when vehicles merge to another highway. As slots move out of the control of a specific TOC, the vehicle within the slot is assigned a slot in the next TOC. The virtual slot then joins the chain of moving slots at the starting point of the control area of the TOC. The coordination of slots at the TOC level is shown in Figure H.5.3-2.

The regional TOC is responsible for coordinating the merge of slots at highway interchanges. Slots n through n+m are assigned to Route A. Slots j through j+k are assigned to Route B. The TOC must ensure that if Route A and Route B merge to one lane, slots assigned to vehicles on Route A interleave with slots assigned to vehicles on Route B. Vehicles in Route A remain associated with their slot n+m assignment unless the vehicle is transferring to route B. When a vehicle on Route A is transferred to Route B, the slot n+m assignment is transferred to a slot j+k assignment. The TOC must ensure that the chain of slots is timed correctly to allow a smooth transition from one chain to another. The processing required to maintain this type of coordination is significant. The TOC must plan slot assignments and synchronization on a network wide basis, coordinating slot availability with route plans for all vehicles on all routes under regional control. Failure to coordinate the slot assignments could result in adjusting slot assignments on the routes or modifying the slot motion on route A, delaying traffic flow to allow a vehicle to transfer to the next available slot on Route B.

5.4 SYSTEM DIAGRAM

5.4.1 TOC to Zone Controller Interface

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

5.4.2 Zone Controller to Roadway Condition Sensors

The roadway condition sensors pass congestion and environment information to

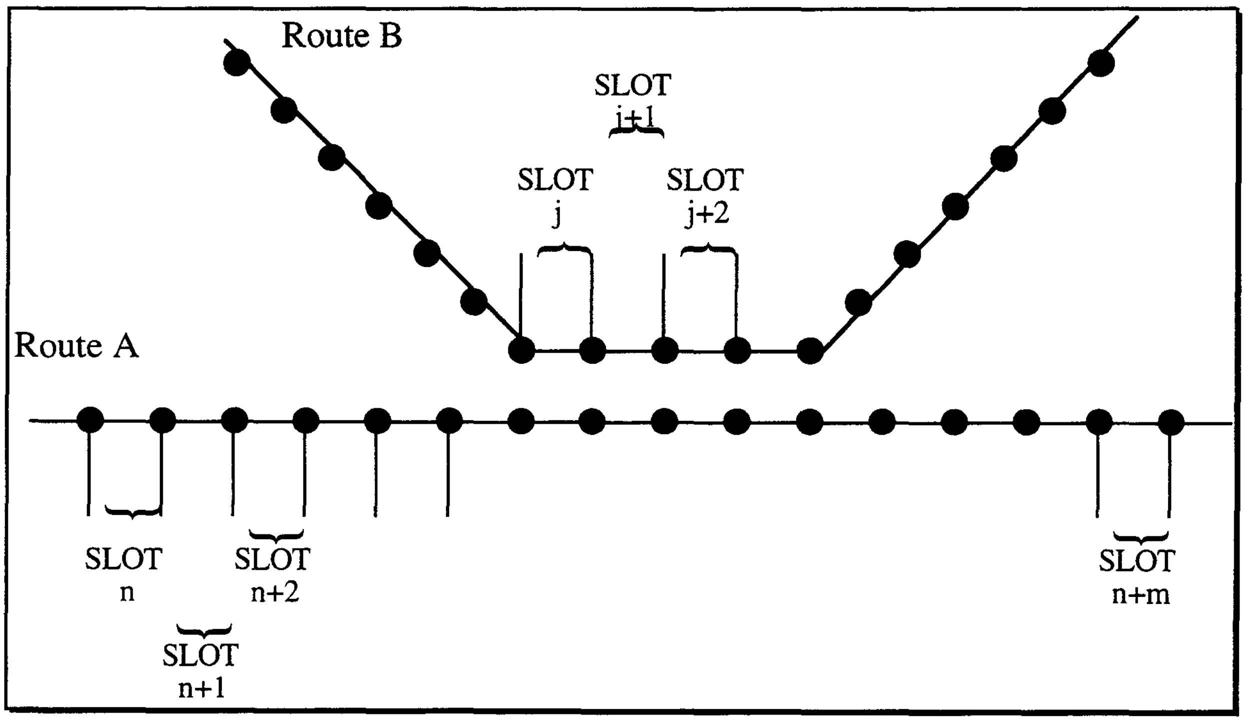

Figure H.5.3-2. Coordinating Chains of Slots at Interchanges

the zone controllers.

5.4.3 Roadway Condition Sensors to Roadway

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

5.4.4 Zone Controller to Range Detection Sensors

The vehicles transmit absolute position and detected obstacle information to the zone controllers.

5.4.5 Range Detection Sensors to Vehicle

Range sensors detect the distance between vehicles and relative speed of adjacent vehicles. Range detection can be supplemented with known slot assignments to identify objects not in an assigned slot as an obstacle.

5.4.6 Zone Controller to Vehicles

The zone controllers transmit slot addresses to vehicles requesting entry to the automated lanes based on slot assignments made by the TOC. The zone controllers transmit relative position corrections based on known assigned slot position and actual vehicle position transmitted from the vehicle.

5.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

5.5 FUNCTIONAL ALLOCATION

Figure H.5.5.4 provides a graphical representation of a preliminary functional block diagram of the slot concept. The following text describes where each functional block is located and the tasks the functions are responsible for.

5.5.1 Position Control

The position control loop is closed within the vehicle. Absolute position is determined by the vehicle. The vehicle transmits position data to the zone controller which compares actual vehicle position with expected position for each slot in its authority. Longitudinal position adjustments are made when the infrastructure provides position increment data relative to the assigned slot position. Lane assignments are incorporated into the slot assignments. The vehicle senses its lateral position with respect to its assigned lane position. Lane changes and other lateral position adjustments are made when the infrastructure provides lateral position increments relative to the assigned lane position.

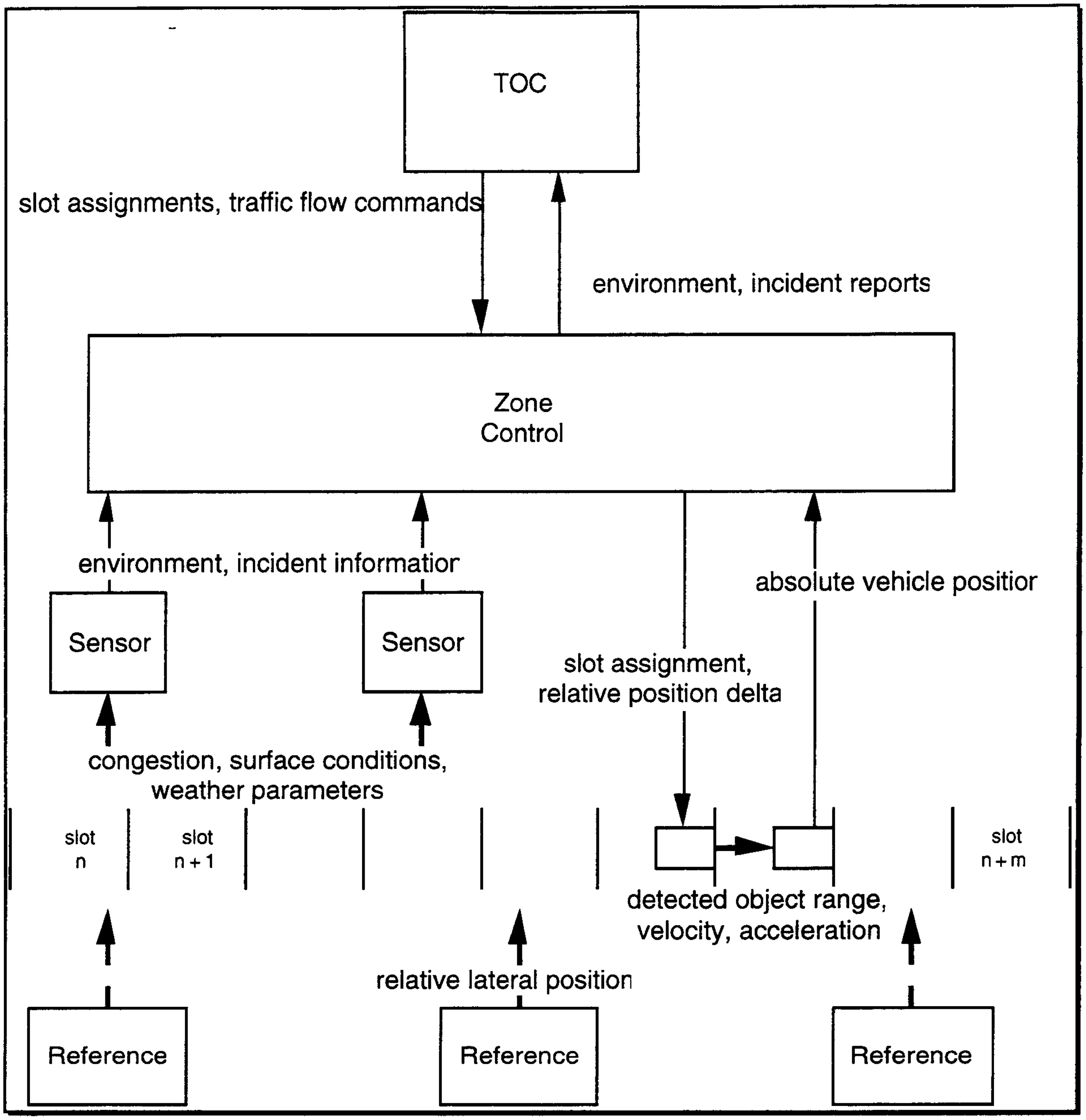

Figure H.5.4-3. Slot Control Interface Diagram

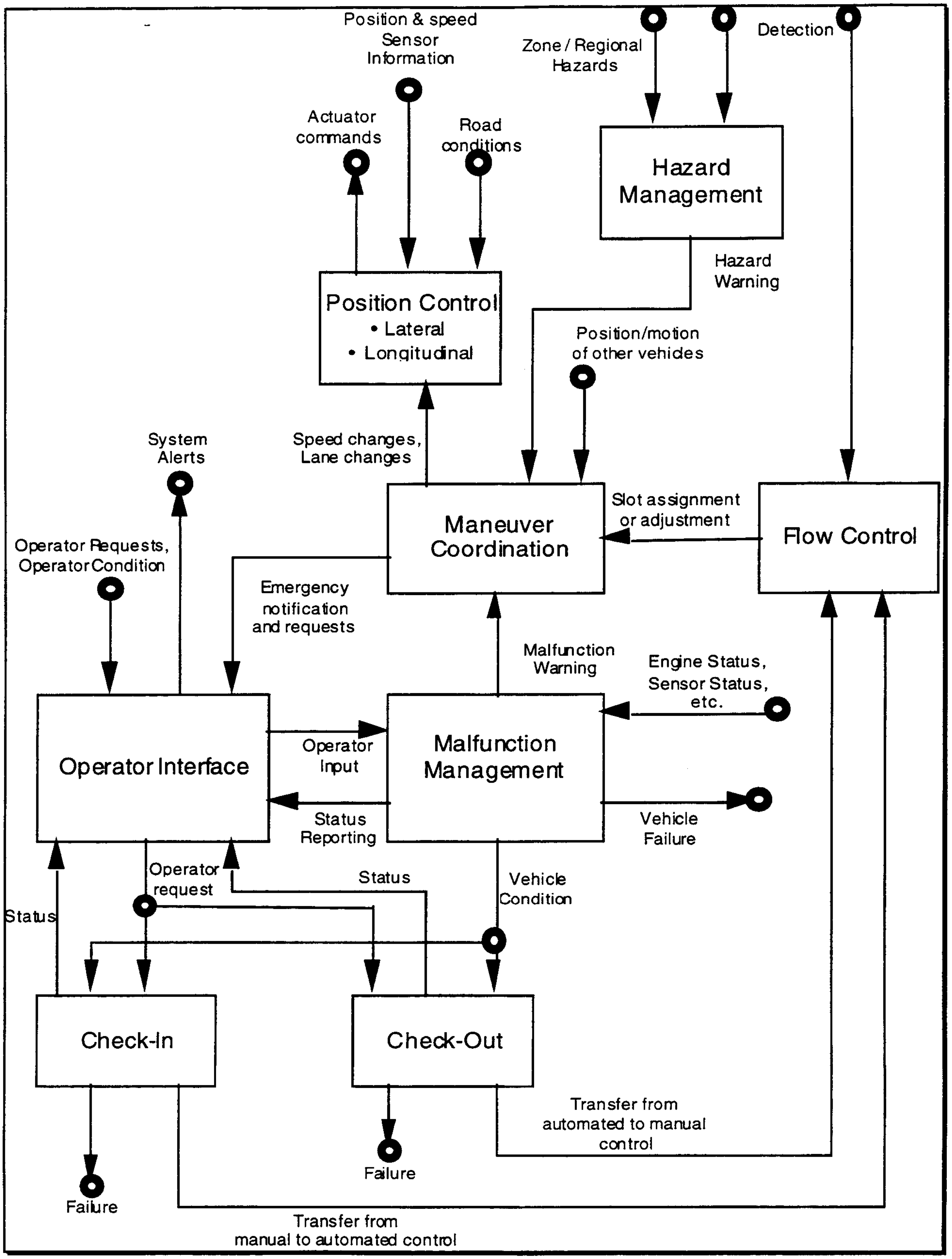

Figure H.5.5-4. Functional Block Diagram

5.5.2 Maneuver Coordination

The maneuver coordination function is performed in the infrastructure. The maneuver coordination function receives maneuver requests from the flow control function, hazard warnings concerning obstacles or other traffic incidents from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function. This function receives information concerning the position and motion of vehicles at the zone level.

The maneuver coordination function responds to maneuver commands received from the flow control function by generating position offset commands which allow vehicles to enter or exit the automated lane in the slot assigned by the flow control function. The maneuver coordination function responds to hazard and malfunction warnings by generating changes to slot assignments or spacing which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits maneuver information 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.

5.5.3 Hazard Management

The hazard management function is performed in the infrastructure. The hazard management function receives incident information from roadside sensors and obstacle data from individual vehicles. The hazard management function generates a hazard warning message which is passed to the maneuver coordination function for appropriate action.

5.5.4 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 failure information to the traffic operations center and provides status messages to the operator.

A default operating mode must be available to allow vehicles to maintain safe control when infrastructure management fails. Vehicles can degrade to a free agent operating mode when the roadside-vehicle communications link is lost, for example. The vehicle may default to independent obstacle avoidance and headway maintenance based on safe stopping distances to adjacent vehicles.

5.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function receives requests to enter the automated lane from the check-in function, and requests to exit the automated lanes from the check-out function. The flow control function generates maneuver commands at the regional level. This function assigns slots to entering vehicles based on slot availability and entry location. The flow control function keeps track of unused slots following exit of a vehicle and reassigns slots or adjusts slot spacing based on current traffic flow.

5.5.6 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.

5.5.7 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 flow control function to request a slot and initiate entry to the automated lane. The transfer from manual to automated control is performed on the entry ramp. Once the transfer of control is completed, the vehicle begins to adjust speed in response to infrastructure commands and merges to the automated lane under automated control.

Vehicles which fail the check-in process will not be assigned a slot and 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 initiates the process for returning to the conventional lanes.

5.5.8 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 flow control function to initiate exit from the automated lane. The transfer from automated to manual control is performed on the exit ramp. The vehicle demerges from the automated lane under automated control and adjusts speed to allow the transfer of control to occur at a safe speed.

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.

Vehicles which fail the check-out process will remain in automated control and will move to a safe position as close as possible to the requested exit. 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. Slot assignments are released as vehicles exit the facility, and the TOC updates the database of available slot assignments. The released address can then be assigned to the next vehicle which enters the continuous chain of virtual slots.

5.6 IMPLEMENTATION OPTION(S)

5.6.1 Vehicle Electronics

Obstacle detection: vehicle based sensors are required to detect obstacles.

Sense lateral position: vision based or magnetic sensors are required to determine lateral position.

Determine absolute position: the vehicle must know its position relative to the assigned slot in space/time. Absolute position may be determined using GPS.

Transfer position data messages: Two-way vehicle-roadside communications is required to support transmission of vehicle position information to the roadside processor, and transmission of slot offset messages to the vehicle from the processor. The communication system must provide address capability to direct unique offsets to vehicles in assigned slots.

Process slot control commands: based on current speed, calculate acceleration/ deceleration parameters required to adjust slot position in response to infrastructure commands.

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

5.6.2 Infrastructure Instrumentation

TOC: manage global traffic flow. Generate slot assignments and update slot directory as vehicles enter and exit the system. Collect incident information from zone controllers and modify slot spacing as necessary.

Zone controller: collect incident information, transfer to TOC as necessary.

Slot sensors: monitor slot spacing. Generate slot control messages as necessary to regulate vehicle spacing within slots.

Broadcast slot information: transmit addressed slot messages. Unique addresses permit broadcast RF to be used. Only vehicles assigned with unique slot address respond to flow control commands.

Incident detection: sense local traffic congestion.

Obstacle detection (option): The infrastructure can be assigned the responsibility for obstacle detection. Radar ranging may be used to determine the relative spacing, velocity, and acceleration of vehicles traveling in slots. A roadside radar can determine the position of numerous targets by converting the time delay of the echo signal received from each target into a distance measurement and pinpointing the location relative to the radar. Resolution to a fraction of a meter may be necessary. The locations of expected targets known from system slot assignments may be mapped against the radar picture. Obstacles can be identified as targets which do not correlate with the known occupied slots. The ability of the radar ranging technique to discriminate legitimate obstacles from echoes such as background clutter and volume clutter caused by rain is an issue.

Lateral markers (option): passive markers in the roadway can be used as the lateral control reference.

5.6.3 Roadway Infrastructure

This concept requires conversion of a conventional lane to a dedicated AHS lane with a barrier separating the conventional and AHS lanes. An alternate approach

5.6.3.1. 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 this approach. The transition lane may consist of no more than a ramp merging from the conventional lane to the automated lane. 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.

5.6.3.2. Urban Region

Modify gap spacing to optimize capacity

Restrict heavy vehicles to off-peak hours

Limit frequency of access points for heavy vehicles to encourage longer trips

5.6.4 Deployment

This concept contains a high degree of infrastructure electronics. The efficacy of instrumenting long stretches of rural highway is a concern. The ability to serve larger numbers of vehicles per lane mile of instrumentation will improve the cost benefit ratio.

5.7 ISSUES

A high level of real-time processing of vehicle position updates and calculation of offsets from assigned slot positions will be required. The update rate of slot offsets from the infrastructure to individual vehicles will be determined by the ability of the vehicles position control and navigation functions to maintain the vehicle's relative position within its assigned slot. Maximum lane densities will also be determined by the ability to maintain expected time/space synchronization. Tight slot spacing will require greater accuracy in position maintenance and possibly higher update rates. Infrastructure processors and beacons will be required at certain intervals to support tracking of vehicle slots and transfer of vehicle position data and slot offset updates.

6. CONCEPT 4: COOPERATIVE, FREE AGENT ON DEDICATED LANES WITH GAPS IN BARRIERS

6.1 OVERVIEW

Concept #4 takes all the best attributes from the trade space and is a unique example of a very flexible system: cooperative intelligence of free agents that can achieve platoon efficiency without enforcing platoons for mixed vehicles, dedicated lanes with numerous gaps to enter/exit through the transition lane on the fly, and autonomous obstacle avoidance that benefits from inter-vehicle communications. The final AHS system should have all of these characteristics. In this concept, the features tend to be balanced evenly. Mixed vehicle classes do not place unnecessary restrictions and limitations on the system. By being a free agent in the system, each vehicle (automobiles, buses, trucks) will establish and control its own separation distance. By doing so, the system could still behave like a platoon with all of its benefits. This pseudo platoon will have both close and far spacings based on individual vehicle's stopping distance, turning radius, acceleration capability, etc. that is communicated to adjacent vehicles (closest neighbors philosophy).

There is a feeling of safety based on having a dedicated lane with physical barriers. This is a leap over continuous barriers in the amount of flexibility the system can afford by having periodic gaps where one could enter and exit freely. This works well with the transition lane to enter and exit seamlessly on the fly. There is also a cost saving by not having a dedicated entry and exit facility/infrastructure. Concept #4 will provide the optimum throughput for the final AHS system. It is very important to the passengers to have automatic obstacle detection and avoidance. It is just another safety feature that is expected and provides a peace-of-mind feeling. Moreover by having inter-vehicle communications, some of the detection systems can be turned off to save power, add redundancy, or increase coverage.

6.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Concept #4 has the following alternatives from the concept space:

1) Cooperative Distribution of Intelligence—There is minimal infrastructure intelligence, but there is vehicle-to-vehicle communications. The infrastructure provides the basic ITS services, i.e. in-vehicle information and routing. The vehicle senses the lane and controls the vehicle.
2) Free Agent Separation Policy—The separation policy is free agent. Each vehicle (automobile or truck or bus) operates independently and freely. However, by acting freely and communicating with its nearest neighbor, the series of vehicles may act as a pseudo platoon in terms of throughput. The spacing between vehicles will vary depending on the type and performance of each individual vehicle.
3) Dedicated Lanes with some Gaps in the Physical Barriers—Dedicated lanes are desirable for safety concerns and to achieve maximum throughput. To gain maximum flexibility, there will be periodic gaps in the barriers from which to enter and exit via the transition lane. The gaps in the barriers complement the transition lane concept perfectly. Gaps will occur only on straight-aways. Length of gap will be such that the driver continuously sees both ends to know that this is a dedicated AHS lane and will be sufficient for merging and de-merging.
4) Mixed Vehicle Classes in a Lane—There will be a mix of light vehicles such as automobiles and small trucks and larger

vehicles such as buses and semi-trucks. Mix vehicles will be the most robust option analogous to current everyday traffic patterns. In some areas of the country, there will be more trucks than automobiles and vice versa. To platoon only "like" vehicles could cause long delays and ineffectiveness of the system.

5) Transition Lane for Entry/Exit—Transition lanes are desirable for transparency of using the system. Vehicles in the transition lane have a greater opportunity to merge and de-merge while communicating to oncoming vehicles on the AHS lane, timing the openings in the stream of vehicles, and accelerating to the appropriate speed to accomplish lane change. Dedicated lanes are usually associated with higher infrastructure cost and possible delays. With transition lanes, exit and entry would have to be done on the fly, a very desirable feature.

6) Automatic Obstacle Sensing with Automatic Avoidance Maneuver—Automatic sensing and avoidance is a necessity for a fully operational system. Manual sensing nor avoidance are not characteristics of an automated highway. Any manual functions are only steps towards an automatic system. Automatic sensing will be easier in this concept due to the dedicated lanes and augmented by the inter-vehicle communications.

6.3 OPERATIONAL CONCEPT

Mixed vehicles are traveling along the dedicated lane, each vehicle insuring its own safe spacing (longer space for buses and closer space for automobiles). Some vehicles are at its optimal spacing with respect to their neighbors while others are by themselves (singular free agents). There will be larger spaces between the pseudo platoons. A car turns onto the freeway and drives for a while on the manual lane. It wishes to enter the dedicated, automated lane. The car is manually driven into the transition lane, which is a buffer between the manual lane and the dedicated lane. The AHS lane is further protected by a physical barrier with periodic gaps. The gaps are only on straight-aways and designed to accommodate the large vehicles (buses, semi- tractor trailers, etc.).

While on the transition lane, it does a self check and communicates with the infrastructure for system compliance and permission to enter the AHS (only time the vehicles communicate with the infrastructure in addition to standard ITS features). At this point the vehicle is controlled in a shared mode, the car is driving itself , but the driver can still regain control and override its automated functions. It communicates with any "close" vehicles. If there is none, it enters through a gap in the barrier and accelerates to the proper operational speed that is set by the infrastructure. If there is a pseudo platoon (no more than 10-20 vehicles, size dependent on the mix) of vehicles at their optimum spacing (a function of individual turning, braking, acceleration, top speed, weather factor, etc.) on the AHS, the joining vehicle must cruise at a slower speed, waiting for the appropriate gap/time to enter. The vehicle enters through the gap and into the open space in the stream of automated vehicles. The head of a pseudo platoon or a single, free agent vehicle will have automated sensing and will be aware of entering vehicles and other potential obstacles. To regulate the throughput, the infrastructure may choose to raise or lower the operating speed of the dedicated lane.

When a vehicle needs to exit, it signals its neighbors of its intentions. The separation distances and speeds of the departing vehicle as well as its closest neighbors adjust for this upcoming maneuver. All the effected vehicles also sense the adjacent transition lane, looking for entering vehicles or manual vehicle and the like. Having a clear transition lane, the exiting vehicle makes its maneuver off of the automated lane. The remaining vehicles in the AHS stream return to their optimum mode, prior to the exiting vehicle. Checkout is done on the fly as it passes through the transition lane. If an obstacle is detected on the dedicated AHS lane, the stream must first slow down and take a cautious position. The vehicles could either come to a complete stop in the AHS lane or maneuver through a gap on to the transition lane and back on again for a swerve maneuver, avoiding that area of the road until the obstacle can be removed.

6.4 SYSTEM DIAGRAM

Since each vehicle is a free agent, each agent will have a low-level control layer, a mid-level local action layer, and a high-level global action layer. The servo loops in the control layer will have milliseconds update rate, the local action layer will also be real-time but slower, and the global action layer will have update rates in the seconds.

There is in-vehicle communications through the different layers of architecture. To accomplish this, there must be a standard message protocol and server resident in each vehicle. There is also vehicle-to-vehicle communications that is a function of the co-operative distribution of intelligence and is real-time. Vehicle-to-vehicle information includes speed, steering direction, any emergencies, possible obstacles and verifications, any coordinated maneuvers, and any relevant health & status/system condition data. At the highest level, there is no continuous vehicle-to-infrastructure communications, however, there is some sparing communications at this level for standard ITS features, i.e. routing requests or Mayday.

6.5 FUNCTIONAL ALLOCATION

Baseline Functions:

- Check-In—Check-In is allocated to the vehicle with a final output stating if it is acceptable or not for entry into the AHS lane. This simple "accept" or "reject" is communicated to the infrastructure as a standard ITS feature. The routing of the vehicle is also queried and tracked by the infrastructure.
- Transition from manual to automatic control—Transition is also in-vehicle. It is accomplished in the transition lane and merge into the dedicated lane is automatic. The transition is verified by some positive indication between the driver and the vehicle.
- Automated Driving—All driving functions are in-vehicle. Sensing of roadway, other vehicles, lane keeping, and headway keeping are all in-vehicle functions. There is also communications between the pseudo platoons where it is important for the lead and end vehicles to keep constant coordination for the safety of their special group. The intermediate vehicles could function as repeaters or relays to understand the actions of the group. Vehicle-to-vehicle communications in a pseudo platoon is

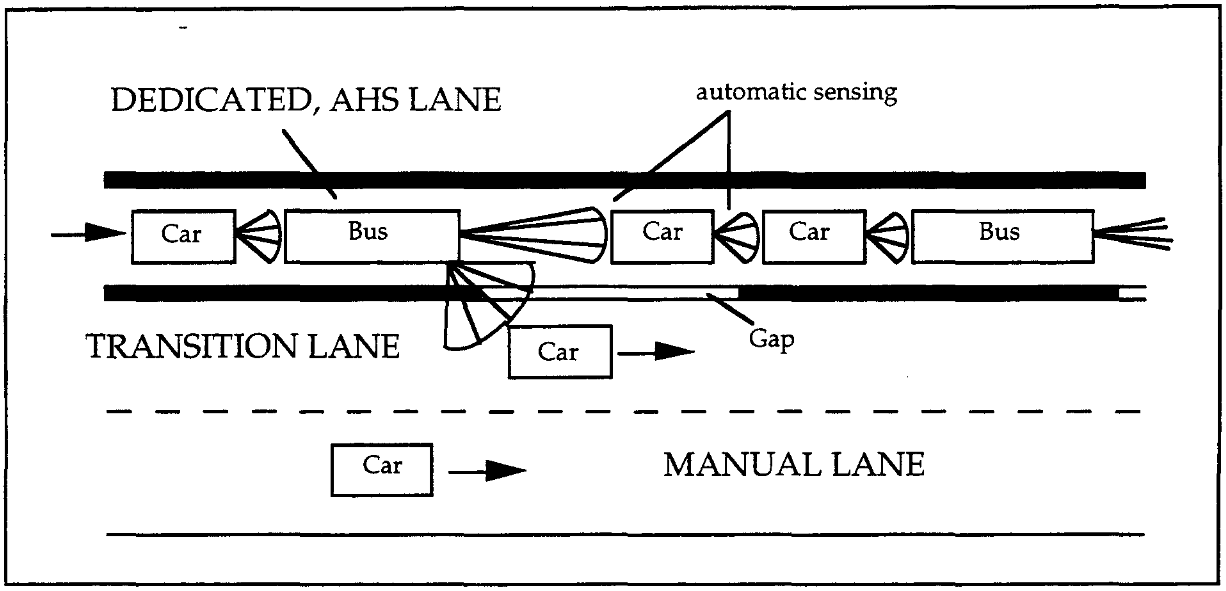

Figure H.6.4-1.

necessary for maneuver planning (normal and emergency), as well as maneuver execution. There is some communications between pseudo platoons for coordination issues on the system level. When it comes to the detection of hazards, everyone does obstacle detection (some for redundancy) and it is especially important for the lead vehicles.

- Transition from automatic to manual control—Transition is in-vehicle and accomplished again in the transition lane. Automatic control takes the vehicle from the dedicated lane into the transition lane. At this time, the automated vehicle insures that the driver is ready to accept control of the vehicle and the vehicle transitions control to the driver, insuring a positive hand-off.
- Check-out—check-out is allocated to the vehicle with just a ending message to the infrastructure to control accountability in the system. The details for check-out are done at the various levels of the architecture in the vehicle, i.e. statusing.
- Flow Control—At the macro level for routing purposes, flow is managed in the infrastructure. The infrastructure may chose to limit entrance into the dedicated lane to preserve flow or for some other logistical reason. There is also micro flow control when a vehicle is let onto the dedicated lanes and the size/average speed of the pseudo platoons. There may be no pseudo platoons, but all separate and independent agents, which is also an indicator of flow.
- Malfunction Management—Malfunction management is primarily in the vehicle. There is other options such as an obstacle in the dedicated lane, which becomes a joint vehicle, pseudo platoon, and infrastructure problem.
- Handling of Emergencies—Handling of emergencies is another joint problem between the individual vehicles, any impacted pseudo platoons, and the infrastructure.

6.6 IMPLEMENTATION

6.6.1 Vehicle

- Vehicle-to vehicle communications
- Adaptive cruise control or some type of headway control system
- Positive lateral control such as magnetic strip sensor with redundant vision system
- Forward looking radar and camera for obstacle detection

- Side looking radar for obstacle detection, especially during merging and splitting

6.6.2 Infrastructure

- Vehicle-to-infrastructure (and vice versa) communications for standard ITS features
- Magnetic strip for lateral control
- Infrastructure obstacle detection camera or radar
- Traffic Management Operations Center

6.6.2.1. Rural Highway:

There would not be a dedicated lane with gapped barriers. Rural lanes will be either one or two lanes in each direction with a high flow rate. The left most lane (if their is more than a single lane) will be a transition lane that can accommodate both automated and manual driving to some degree. Obstacle detection and adaptive cruise control will enhance any vehicle.

6.6.2.2. Urban Region:

The concept described with the dedicated lane, transition lane, and manual lane will be optimized in a urban and extended urban region where the flow is stagnated.

6.6.3 Deployment

- Dedicated lane with gaps in the barriers
- Transition lane

6.7 GENERAL ISSUES AND CONSIDERATIONS

- Navigation is independent, in-vehicle and autonomous with opportunities to do cooperative operations/maneuvers, i.e. pseudo platoons
- Failure modes are in matched performances, degradation of performances due to usage (function of all the concepts), etc.
- We can utilize redundant in-vehicle sensors for lateral control, longitudinal control, and obstacle detection. These sensors might also be able to do overlapping functions, e.g. forward obstacle detection and longitudinal control, side obstacle detection and lateral control, inter vehicle communications for headway sensing.
- Under no circumstances is control passed to the driver, only on the transition lane to change modes: automatic to manual control and from manual to automatic control
- Reduced visibility, ice, snow, rain impacts the overall effectiveness of the entire system. There is an impact to the infrastructure and traffic management operation center to reduce flow by decreasing the AHS set speed and increasing the spacing between vehicles.
- Typical users would travel at 120 km/hr or higher (~180 km/hr). It should be a significant increase over manual driving.
- It would have limited autonomy, a minimum of adaptive cruise control. The average free agent would be autonomous for limited and special situations where the driver would be supervisory. All safety systems will be in place and functional. On long, lonely stretches of highway, the vehicle will be virtually autonomous with a mode transfer capability for special situations, i.e. lack of definition in its assigned path, etc.
- This system is adaptable to forms of mass transit like buses and will also be connected in the information/scheduling sense to other ITS functions like trip planning, scheduling or tracking.
- This system has freight carriers designed into the system. It will further assist in on-time delivery and efficiency in transporting goods from start to destination.
- High speed, system flexibility, and insured safety will all contribute to increased throughput for the present system.
- Automatic obstacle detection and avoidance, together with vehicle-to-vehicle communications, will show conformity

to standards of travel that will increase safety.

- A robust vehicle that has been standardized (in terms of component interfaces) will make for a cost-effective vehicle. The infrastructure will also benefit from being mainly passive except for the gapped barriers and the standard ITS functions allowable for cooperative distribution.
- Vehicle maintenance will be similar to existing vehicles (safety through periodic maintenance).
- Infrastructure maintenance will be similar to existing infrastructure with added tasks like checking connectivity of metal strips for lateral control.
- Support from the external world include safety inspection and automated vehicle compliance during registration and enforcement in dedicated lanes through periodic law enforcement and video entrapment with strict penalty.
- Since the concept is flexible to support all users, demand should be the same as current traffic patterns.
- The system will be intuitive, easy, foolproof, and at the least, the safest mode of transportation available on the ground. The driver should be at ease when he/she relinquishes control. He should have automatic, normal updates and exception handling updates to make him/her and their passengers feel at ease and confident the system is safe.

7. CONCEPT 5: COOPERATIVE PLATOONING IN DEDICATED LANES WITH GAPS IN PHYSICAL BARRIERS

7.1 OVERVIEW

This concept considers a cooperative platooning configuration of vehicles for an automated highway system (AHS) together with the allowance of mixed vehicle classes in the same automated lane. The six fundamental components to each AHS concept, namely (1) distribution of intelligence, (2) separation policy, (3) mixing of AHS and non-AHS vehicles in same lane, (4) mixing of vehicle classes in same lane, (5) entry/exit configuration, and (6) obstacle detection handling, offer numerous combinations for feasible AHS concepts. This concept is being considered since it is a viable alternative that places the distribution of intelligence more heavily weighted on the vehicle and not the infrastructure. While it has the potential for achieving increases in capacity and safety to the automated facility by adding intelligence and obstacle detection and avoidance capability to the vehicle, upon more thorough examination, it will be revealed that relying too heavily on the vehicle without some minimum of infrastructure support for the communication of dynamic information, too many disadvantages result for this concept.

7.1.1. Distinguishing Features

- *Platooning* which will help to increase throughput, however, as will be discussed later, without the infrastructure support available to provide dynamic information, will not provide a system optimum relative to traffic flow control.
- *Minimal infrastructure involvement* resulting from the vehicle carrying most of the weight of the distribution of intelligence.
- *Very local level of authorized communication among platoons* which will lead to problems in trying to optimize traffic flow, coordinating the merging of vehicles into the automated lanes, and handling emergency situations.

7.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

7.2.1 Cooperative Intelligence Among Vehicles

In this concept, communication among adjacent platoons is utilized to provide dynamic information, to the extent that is possible, given the local nature of this communication protocol. Only static information will be communicated from the roadside to the vehicle, such as upcoming exit locations, posted speed limits, etc.

7.2.1.1. Local Tailorability

Because the vehicle coordination is local, possibly resulting in difficulties in achieving an optimal flow control for numerous functions, such as entry and exit, merging, and emergency maneuvers, variances to this local communication and coordination protocol may be allowed.

7.2.2 Platooning

Where traffic levels are high enough, vehicles will travel in platoons to increase throughput.

7.2.3 Dedicated Lanes With Gaps in Physical Barriers

Dedicated lanes will be for the use of automated vehicles only, that is, there is no permitted mixing of AHS-equipped vehicles driving in automated mode with non-AHS equipped manually driven vehicles or with AHS-equipped vehicles who fail check-in but want to enter the AHS lane nevertheless. There is a transition lane for entry and exit activities in which there will be permitted mixing of AHS-equipped vehicles in automated mode in the process of merging into the automated lane with AHS-equipped vehicles who have failed the check-in process and need to exit the transition lane to return to the manual lane. Thus, the mixing of automated and manual traffic is of a transitory and temporary nature. The three lane types, automated lane, transition lane, and manual lanes are separated by an intermittent physical barrier with openings to allow vehicles to enter from the manual or conventional non-automated lanes to the automated lanes via the transition lane.

7.2.4 Mixed Classes of Vehicles in a Lane

This concept allows for the mixing of vehicle classes in the same automated lane.

7.2.4.1. Local Tailorability

Local officials may choose, if there is available additional roadway space, to have separate automated lanes for the two major vehicle classes, namely, light-duty and heavy-duty vehicles (trucks and buses). In addition, the lane for light-duty vehicles may have a faster operating speed and narrower lane width than the other automated lane. Under such circumstances, such a lane for light-duty vehicles would be placed in the inner-most position, in which case light-duty vehicles would weave through the heavy-duty vehicle lane to access their lane.

7.2.5 Transition Lane Entry/Exit

The transition lane will be used by AHS-equipped vehicles to maneuver from the manual lane to the automated lane, possibly going through a check-in procedure in-motion after the vehicle enters the transition lane. Thus, all vehicular traffic will use conventional freeway on- and off-ramps to first access the freeway, then those AHS-equipped vehicles who want to use the automated lane(s) need to weave through all manual lanes to first enter the transition lane, then move over to the automated lane(s).

7.2.5.1. Local Tailorability

It may be the case that for implementation locations, at particularly heavily used entry/exit points that a variation of the transition lane entry/exit be allowed, that is, that a dedicated entry/exit area be added if feasible (sufficient right-of-way) and needed.

7.2.6 Automated Obstacle Avoidance

Obstacles will be detected automatically by the vehicles, which will automatically avoid them, if possible.

7.2.7 Options

The following options will be discussed in more detail in the remainder of the document, however, they are highlighted here:

- Transition lanes can be continuos or intermittent
- There may be a breakdown lane or area for use by automated vehicles
- If there are multiple AHS lanes, light-duty vehicles may have the option of traveling on a separate lane that is narrower and has a higher speed limit than for heavy-duty vehicles

7.2.8 Assumptions

The following assumptions were made during the course of this investigation of the cooperative platooning concept:

- *There is no mixing of vehicle classes in a platoon*-This assumption is made for safety reasons since not only do the (1) differences in speed among intra-platoon vehicles and (2) intra-platoon spacing have to be taken into account, but the differences in the masses that would exist if, for example, a truck or bus were leading or following a small light-duty vehicle.
- *If multiple AHS lanes exist and mixing of vehicle classes is transitory, then light-duty vehicles would travel on the innermost lane*

7.3 OPERATIONAL CONCEPT

The AHS system relies on the intelligence of vehicles without support or management from infrastructure. The vehicles are equipped with sensing and communication systems to exchange information and data among themselves. The sensing system on the vehicles allows the vehicles to detect and identify the existence of other vehicles and roadways. The on-board sensing system may also obtain information from components on the roadway or infrastructure but such components do not provide controlling signals. Communication among vehicles facilitates the exchange of information such as spacing, location, and vehicle dynamics. Such communication systems exist among vehicles of which the motions must be coordinated.

The AHS system adapts the concept of vehicle platooning. Vehicle platoons are formed with small spacing, in a range of 1 to 10 meters, among a group of vehicles, with a number from 2 to 20 for instance, in a lane. The small spacing between vehicles allows a higher highway throughput and reduces the speed difference in impacts if sudden deceleration or acceleration occur. Communication is required within a platoon to maintain the string stability and integrity of spacing control. Vehicles become free agents when they are not operating in platoons.

The AHS system does not allow mixing of non-AHS vehicles in automated lanes. The AHS lanes are separated from the manual traffic by physical barriers. Gaps exist in these barriers. Vehicles enter and exit AHS lanes through gaps in barriers. Barriers may or may not exist between multiple AHS lanes.

The entry and exit to the AHS lanes are accomplished through transition lanes. Manual traffic enters the transition lanes manually. In transition lanes, vehicles switch from manual to automatic modes. The automated vehicles then enter AHS lanes through gaps in barriers. Automated vehicles exit by moving into transition lanes through gaps in barriers. The vehicles switch from automatic to manual modes in transition lanes and drivers resume control.

Mixing of vehicle classes is allowed in a lane. Trucks, buses, and passenger cars may travel simultaneously on a lane in a transitional stage or in a regular operation. If there are multiple automated lanes, one class of vehicles may be advised to travel in the inside lanes while other classes are advised to travel in the outside lanes. The distribution of traffic classes will be accomplished through lane changes maneuvers in AHS lanes.

The vehicles in the AHS systems will sense and avoid obstacles automatically. The vehicles will detect the existence and determine the type of obstacles. The control systems on vehicles will then take appropriate actions to avoid obstacles to mitigate the consequences. Such actions may include the control of throttle, braking, and steering.

7.4 SYSTEM STRUCTURE

All vehicles sense the surrounding vehicles and roadways. Communication among vehicles is required if coordination is needed. Two-way communication is necessary in general but one-way transmission may be applicable in a broadcast mode.

In normal operations, vehicles within a platoon communicate by sending vehicle position number, speed, acceleration, and the speed and acceleration of the leading vehicles. The message transmission rate is in the order of 100kb/sec. A communication loop time below 20 msec is desired. In a join or split maneuver, a request is made and a consensus among affected vehicles is reached through communication prior to the activation of such maneuvers. Lane change maneuvers of single vehicles are typically preceded by a platoon split maneuver.

If a vehicle is separated from a platoon, it becomes a free agent. A free agent may or may not maintain communication with other vehicles. Without communication, the free agent will rely on the sensing system to perform functions of speed tracking, vehicle following, lane keeping, and lane changing. In lane changing maneuvers, vehicles must detect and identify the existence, position, and speed of vehicles in the adjacent lane.

7.5 FUNCTIONAL ALLOCATION

7.5.1 Check-In and Entry

Vehicles move from manual lanes into transition lanes manually. Drivers instructed vehicles to prepare entering AHS. Vehicles enter check-in stations or points. If vehicles successfully check in, vehicles switch from manual to automatic modes. Lane keeping and speed tracking are now automatically controlled. Vehicles communicate with the upcoming free agent or platoon in the adjacent lane to coordinate entry speed and timing. If a consensus is not reached, the entering vehicle waits for the next free agent or platoon. If the request to enter is permitted, the entering vehicle moves into the adjacent AHS lane in front of the communicated free agent or platoon.

7.5.2 Automatic Driving

A driver may indicate or change the destination before, during, or after the entry process. Vehicles automatically sense the roadway marker or sections and decide the proper merging, diverging, or exit points along the AHS infrastructure.

7.5.2.1. Platoon Join and Split

Once in the AHS, a free agent will communicate with the preceding free agent or platoon and request to join. If the request is granted, a join maneuver is made and the free agent becomes a following vehicle in a platoon. If the request is rejected, the free agent will wait to become a leader for the trailing vehicle or try to join a platoon later.

A vehicle in a platoon may need to change its path and depart from the platoon. Before the vehicle changes its speed or path, it needs to request a split maneuver within the platoon. If a consensus is reached, the platoon is split to make room for this vehicle to make its move. If the departing vehicle is the leader of a platoon, the 2nd vehicle in the platoon assumes the leader functions and the leading vehicle becomes a free agent. If the departing vehicle is a follower, the platoon is split before and after this vehicle to make room for this vehicle to make its move. The vehicle behind it will become the leader of a new platoon.

7.5.2.2. Lane Keeping, Speed and Vehicle Following

The vehicles perform its lane keeping function by an on-board sensing system. The sensing system provides information regarding the lane boundary, preview of roadway curvature, junctions, entry and exit locations, and absolute positions on a highway section. The vehicles are also equipped sensing system to measure the relative speed and distance between vehicles to provide inputs to its control systems to track speed or maintain spacing between vehicles.

If a vehicle becomes a free agent, the control system will regulate the vehicles to maintain its speed at the speed limit or a safe distance from the preceding vehicle. If a vehicle joins a platoon, it will maintain a proper spacing at the speed of the platoon leader through communication. The leading vehicle of a platoon will travel at the speed limit if the traffic, weather and roadway conditions allow it.

7.5.2.3. Lane Change

A free agent or the leader of a platoon may decide to make a lane change. Such decisions may result from the detection of an obstacle or slowing traffic, or the need to change its path. To make a lane change maneuver, the free agent or platoon must communicate with the upcoming free agent or platoon to coordinate such moves. Vehicles will use its sensing system to detect any potential hazards on the adjacent lanes even after the consensus with the upcoming vehicle is reached.

7.5.2.4. Obstacle Avoidance

If an obstacle is detected on the roadway ahead, a free agent or a platoon leader may decide to come to a stop or to change lanes.