11.6.1.2. Sensing Other Vehicles

Primarily for use in longitudinal control to maintain safe intra- and inter-platoon spacing, and in combined longitudinal and lateral control to coordinate maneuvers.

- Sensors to detect neighboring vehicles in the same lane and sensors to find distance and relative velocity from a preceding vehicle in the same lane, are needed. Possible choices are Doppler Radar, Sonar, two cameras mounted on the vehicle, etc. Sensing of the distance and relative velocity from the vehicle behind may also be needed/used in designing robust control laws and also during emergency situations.
- Sensors to detect neighboring vehicles in the adjacent lane.

11.6.1.3. Vehicle-to-Vehicle Communication

- *Control:* Infrared communication (e.g., on-off keying with clock encoding). However, the size and spacing of vehicles, radius of roadway curvature, height and reflectance of barriers, and so on affects the effectiveness, in terms of line-of-sight constraints for infrared communication devices.
- *Maneuver:* Pulse (i.e., frequency hopping spread spectrum) or WaveLAN (i.e., direct sequence spread spectrum) radio systems, along with the use of a mobile Internet protocol. FCC allocation of the frequencies for AHS remains an unresolved issue.
- *Advisory/Navigation:* Advisory and navigation information can be transmitted within and between platoons in a daisy-chain manner. Packet loss and delay of advisory and navigation information are non-critical. However, channel access is random in source, destination, and time, and communication distances are very long.

11.6.1.4. Vehicle-to-Infrastructure Communication

- *Control:* Broadcast communication medium. Cellular-based technologies are not a viable option since there will be more vehicles per 6 mi radius (effective range of cellular communication devices) than there are cellular channels to allocate. The infrastructure shall broadcast position information and each vehicle must provide an acknowledgment. The infrastructure provides the central coordination function. The technical questions to be answered are how to provide for position information and acknowledgments.
- *Maneuver:* Broadcast communication medium, for the same reason as described above. The same issues also apply here.
- *Advisory/Navigation:* Broadcast communication medium, for the same reason described above. The same issues also apply here.

11.6.1.5. Vehicle Identification Tag

One or more vehicle identification tags can be used for activities such as check-in, toll collection, and maneuver coordination.

11.6.2 Infrastructure

11.6.2.1. Low Level Modifications

- *Lateral Position Sensing:* Indirect road reference system (e.g., energy source, reflectors, etc.). Specific examples of this type of technology are acoustic resonance reflectors and magnets.
- *Barriers:* Barriers between the automated lanes and manual lanes.
- *Ramps:* Dedicated on and off ramps.
- *Macroscopic Traffic Condition:* Infrastructure-based sensors to collect traffic flow data (e.g., loop detectors).

- *Microscopic and Traffic Condition:* Infrastructure-based sensors to collect system performance data and determine the movements of individual vehicles.
- *Roadway Impediment Sensing:* Infrastructure-based sensors for detecting stationary or moving obstacles on the highway.

11.6.2.2. Intermediate-level modifications

- Short-range roadside transmitters that provide information to vehicles. The communication is in terms of radio broadcast (approximately one every 1.6-3.2 km.).
- Roadside controllers that get the flow data from roadside flow sensors as well as flow data from a few sections down the road to generate commands/ information to be passed on to vehicles
- Communication network between different sectional controllers.
- Communication network between TMC and each sectional controller.

These last two communication networks do need high bandwidth as the frequency of updates received from TMC will be of the order of 10's of minutes whereas the frequency of update of information to vehicles will be in the order of 1--2 minutes.

11.6.2.3. High Level Infrastructure modification

Network level TMC controller and two way communication between each sectional controller and the network controller.

11.6.3 Rural Highway

One possibility is to neither provide platooning nor transportation management center (TMC) services for routing.

11.6.4 Urban Highway

As described in Section 11.3.

11.6.5 Deployment

The minimum deployable system consists of the following:

- one or more automated lanes,
- physical barriers between the automated and non-automated lanes,
- at least one entry and one exit lane,
- check-in and check-out facilities at each entry and exit lane, respectively,
- full automation of vehicles, and
- partial automation of the infrastructure, including command, control, and communication capabilities

The degree to which command, control, and communication functions are shifted to the roadway infrastructure impacts the cost to develop, manufacture, and deploy automated vehicles. Too little or over reliance on infrastructure support can result in high-priced automated vehicles; for example, at either extreme, the complexity of the in-vehicle automation systems can be high and thus, costly to design, manufacture, and maintain.

There are some disincentives to deploying an this concept AHS. The more prominent disincentives are as follows:

- cost to build dedicated entry and exit lanes: these will have to be long enough to permit both small and large vehicles to accelerate or decelerate sufficiently to safely enter or exit the automated lane, and
- in some locales, no land is available—without razing existing structures, purchasing right-of-way, or having a significant environmental impact—for construction of dedicated entry and exit lanes

The incentives of such an architecture are that:

- dedicated entry and exit lanes and inter-lane barriers may be perceived by the public as necessary and sufficient safety features, and

- depending on the infrastructure design, in some cases it may be possible to upgrade the roadway infrastructure, especially in terms of communication, but less so for the physical roadway (e.g., resizing entry and exit ramps)

11.7 GENERAL ISSUES AND CONSIDERATIONS

11.7.1 Failure modes

As the intelligence is distributed between roadside and vehicle, the two types of control systems can back up each other. Different types of sensors and communication devices are used on the vehicle and the roadside to gather information of the world as well as for coordination. These systems can be used to back up other subsystems in case of a failure. Most of the vehicle failures (sensors, communication devices, etc.) will have a localized effect. Infrastructure failures will only result in reduced throughput and will not be safety critical. As the driver will not be able to drive in a platooned environment, the control should not be passed to the human driver while the vehicle is on AHS.

11.7.2 Sensing weather conditions

Adverse weather conditions such as limited visibility, snow, ice, etc. will be sensed by the on-board vehicle sensors and communicated to the infrastructure. They may also be sensed by roadside sensors placed at specific locations on the roadside for that purpose. The infrastructure communicates this information to the upstream traffic. The infrastructure may also advice the vehicles to slow down.

11.7.3 Vehicle functionality

Typical users will travel at the speed limit.[4] Due to infrastructure support functions, highway speeds are fully tailorable.

The vehicles equipped to drive in this AHS will be able to perform feet-off driving using Adaptive Cruise Control (ACC) capabilities on the conventional roads. They can also use most of the ATIS information for route selection.

11.7.4 Throughput and Safety

The *platooning* feature of this concept contributes most to increasing traffic flow. In fact, platooning allows one to realize maximum achievable increase in capacity. Infrastructure support is also critical in optimizing the traffic flow.

The safety of the system is increased because of automated obstacle detection and avoidance and due to distributed intelligence between infrastructure and vehicle.

11.7.5 Cost

As vehicles and infrastructure both have sensors, controllers and communication systems, regular maintenance of vehicles and infrastructure is required.

The dedicated entry/exit option requires construction of dedicated on-off ramps to the AHS.

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[4] Typically in the range of 65-70 MPH. Although one can design a system to operate at a higher speed such as 80-85 MPH. Beyond certain speed, the gain in throughput will be offset by the large inter-platoon spacing required for safety and the cost of associated sensors.

12. CONCEPT 10: INFRASTRUCTURE MANAGED FREE AGENTS ON DEDICATED LANES WITH GAPS

12.1 OVERVIEW

This concept is infrastructure-managed, has dedicated lanes with gaps in the barriers, mixed vehicle classes in the same lane, a transition lane, and no platooning. Unusual features of this concept are:

1) no direct vehicle-to-vehicle communication;
2) only one side-looking sensor;
3) Using the transition lane like a railroad siding to allow faster-moving traffic to pass slower-moving traffic.

12.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

- Distribution of intelligence—infrastructure managed
- Separation policy—free agent
- Mixing of AHS and non-AHS vehicles in the same lane—dedicated lanes with some gaps in physical barriers.
- Mixing of vehicle classes in a lane—Yes. When two or more AHS lanes are available, local options include limiting heavy vehicles to the right hand lane.
- Entry/exit—transition lane.
- Obstacles—automatic sensing and automatic avoidance maneuver if possible.

12.3 OPERATIONAL CONCEPT

The vehicle does autonomous lane-keeping and headway maintenance using on-board sensors. It performs obstacle detection using its forward-looking sensor, and position determination using its lane-keeping sensors (see Issues for more details). It senses velocity, computes acceleration, and measures range to any vehicles or objects ahead of it or to the right. The sensor on the right side of the vehicle is primarily for merging into the transition lane (which may have some non-AHS traffic) from the AHS lane(s), and for lane changes prior to stopping when communication with the roadside processor has failed. Vehicle position and dynamics, and range measured by the two sensors are periodically reported to the roadside processor.

The roadside processor tracks the position of vehicles within its area of responsibility, and orders speed changes for individual vehicles to manage traffic flow. It selects local routes for vehicles based on their destination, and orders lane changes as appropriate. It plans and executes any maneuvers needed to deal with unforeseen conditions. The roadside processor uses sensors in or on the roadway to monitor environmental conditions, and it validates the IDs of vehicles requesting entry into AHS. Reports of incidents and obstacles are forwarded to the TOC along with statistics on average traffic speed and throughput.

The Traffic Operations Center provides speed and route guidance information to the roadside processors to allow them to manage local traffic flow in a manner consistent with conditions in nearby regions. The TOC also manages all reported incidents. The master vehicle ID database is updated here before being sent to the roadside processors and high-level statistics on AHS performance are kept here.

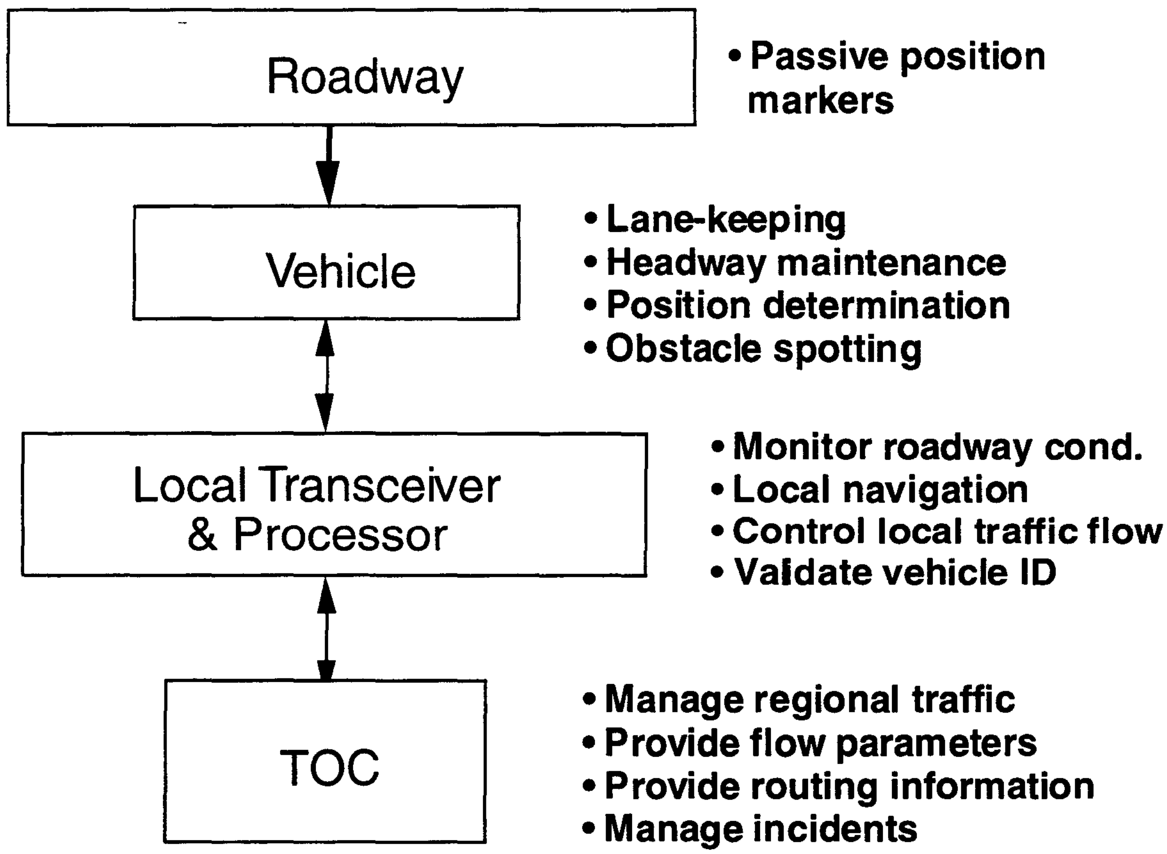

Figure H.12.3-1. Operational Concept

12.4 SYSTEM DIAGRAM

The system diagram is shown in Figure H.12.4-1. The vehicle coverage diagram is in Figure H.12.4-2.

12.5 FUNCTIONAL ALLOCATION

12.5.1 Check-In

An AHS-equipped vehicle in the transition lane requests permission to enter AHS. Local transceivers relay this request to the roadside processor, which checks the database, and queries (vehicle) on-board status indicators for vehicle status. If the vehicle is registered, and all systems are operating, the vehicle is signaled that it is logged into AHS.

12.5.2 Transition From Manual to Automatic Control

When an AHS vehicle traveling in the transition lane receives a "logged-in" signal, the driver pushes a button transferring control to AHS. If the driver fails to push the button within a certain time, the signal is repeated; if the driver still does not push the button, a message on the user interface instructs him on his options (including returning to manual operation in the conventional lanes). When the driver signals that he is ready to give up control of the vehicle, it is then automatically guided into the AHS lane. A vehicle crossing into the AHS lane under manual control triggers local alarms (bells, lights) from a sensor located on the lane divider, and a camera photographs the license and transmits the image to a dedicated roadside processor to relay to the TOC during a low demand time.

Concept #10 Data Flows

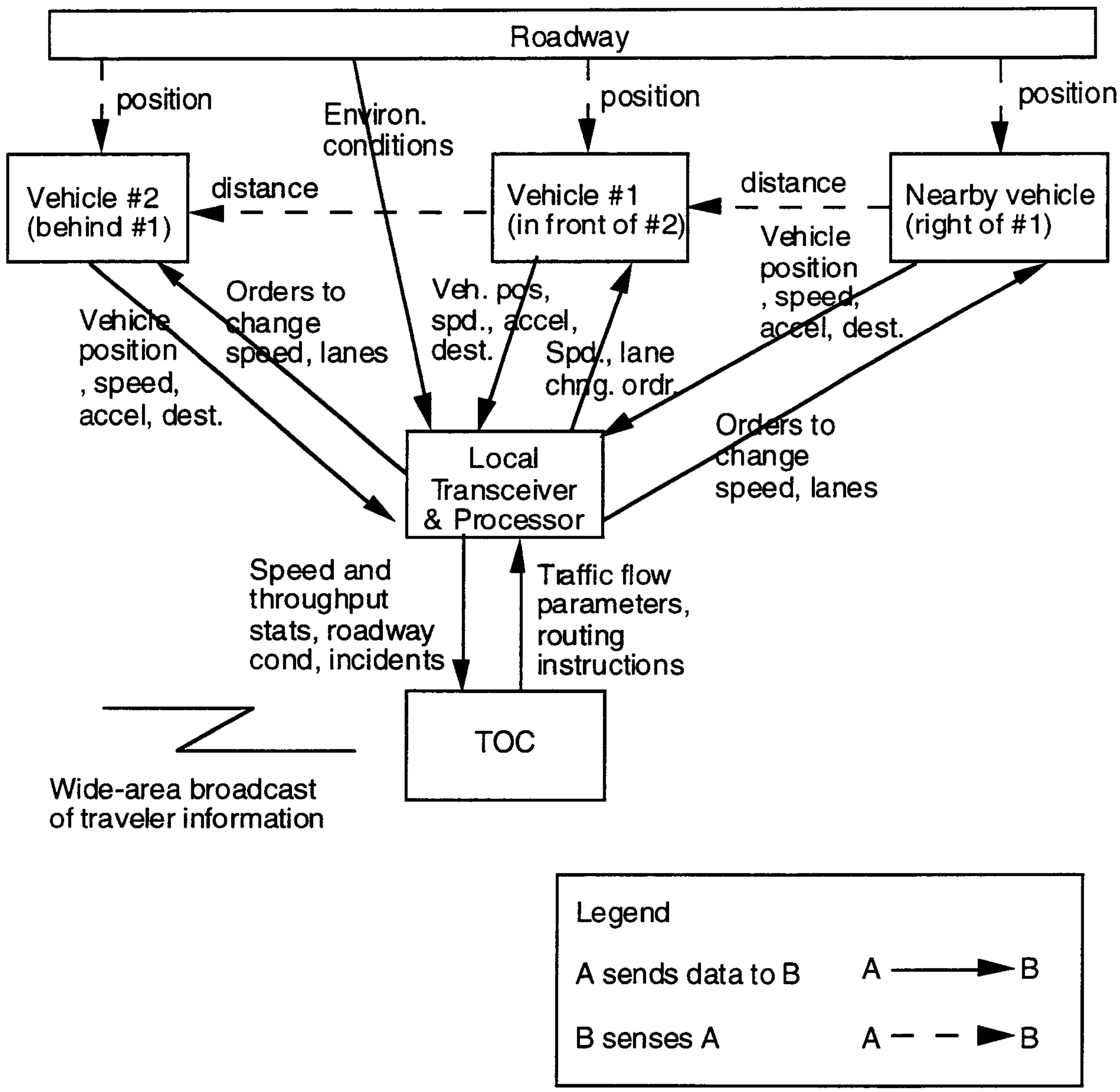

Figure H.12.4-1. Data Flows

12.5.3 Sensing of Roadway, Vehicles, and Obstructions

Other vehicles and large obstructions are sensed by the vehicle's forward-looking sensor. If technologically feasible, this is also used to spot all roadway hazards that can damage the vehicle. If this is not possible, it is necessary to add one of the following to this concept: 1) a second vehicle-mounted sensor optimized for obstacle detection; 2) roadway-mounted obstacle detection sensors; 3) use of the driver as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance (see Deployment for more on this). Roadway obstacles are reported to the roadside processor to divert traffic around them and forward the report to the TOC.

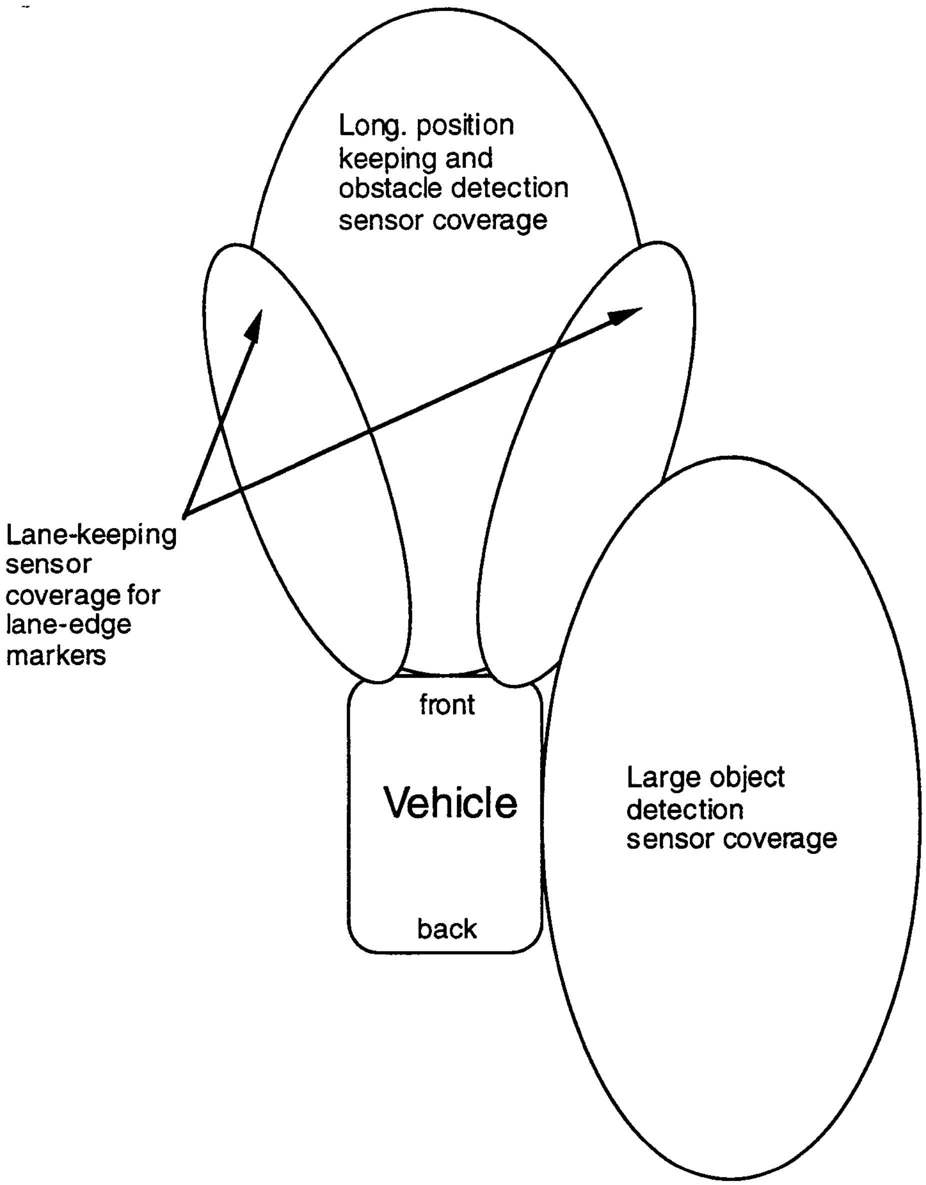

Figure 12.4-2. Vehicle Sensor Coverage

12.5.4 Lane and Headway Keeping

Lane-keeping and longitudinal positioning are vehicle-based. Lane-keeping is performed with reflective markers on both sides of the lane which will also be encoded with a sequence number used for positioning (see Issues). These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. The lane-keeping sensors measure range and can therefore estimate vehicle position relative to the markers. Vehicle speed is ordered by the roadside processor, but the vehicle can override this if needed to maintain an appropriate distance from the vehicle in front, judged by the forward-looking vehicle-based sensor.

12.5.5 Maneuver Planning

Lane change requests can originate with the driver ("I want to get a hamburger") or the infrastructure ("the middle lane is blocked ahead"); in either case, the roadside processor identifies the vehicles (if any) that must speed up or slow down to accommodate the lane change, and calculates speed changes for all vehicles concerned.

12.5.6 Maneuver Execution

The vehicles involved in the maneuver receive a command from the roadside processor to change speed or lane, and confirm receipt. The vehicles execute the command(s); the roadside processor can track the maneuver through the vehicle's regular position and speed updates.

12.5.7 Transition From Automatic To Manual Control

A vehicle preparing to exit AHS remains under automatic control until it is in the transition lane. The roadside processor signals the driver via the operator interface to take control, and the driver confirms that he is ready by pushing a sequence of buttons. If he fails to do this, he is instructed on his options via the user interface and asked to make a selection. If he fails to do so, the vehicle remains under AHS control until it can be stopped in a breakdown lane or area. The vehicle is checked out of AHS at the same time.

12.5.8 Check-Out

Check-out is performed at the same time as the transition from automatic to manual control. Fees are computed at this time by the roadside processor, and the vehicle is dropped from the list of those active in the region.

12.5.9 Flow Control

The infrastructure monitors traffic density and flow rate, and chooses routings which keep travel time low while taking overall traffic flow into consideration. The TOC does this at the global level, and passes traffic flow and speed parameters to the roadside controllers to optimize local traffic flow. In regions where only one lane can be dedicated to AHS, the transition lane is used like a railroad siding. If faster vehicles are being held up by slower vehicles (e.g., trucks ascending a grade), the infrastructure will order the slower (or perhaps faster) vehicles to switch to the transition lane at the next barrier opening. They remain under AHS control in the transition lane, and are ordered back onto the dedicated AHS lane once the faster traffic has passed.

12.5.10 Malfunction Management

If a vehicle does not respond properly to messages from the infrastructure, or does not report position and speed at appropriate intervals, the driver is notified and given the option of taking over manual control once the vehicle is in the transition lane. If the driver does not respond affirmatively to this, the vehicle will be kept under automatic control and shunted to a breakdown lane or area at the first opportunity. The vehicle processor is also programmed so that if no messages or confirmations are received from a roadside processor within a pre-determined time period, and no response to a special query is received, a communications failure will be assumed and the driver is alerted. He is given the option of taking over control of the vehicle; if he fails to do so, the vehicle will continue to move ahead and right, using on-board sensors, until it can be safely stopped in a breakdown lane or area. If the AHS senses a vehicle malfunction, other nearby vehicles are controlled to increase the spacing around (and in an emergency, avoid) the malfunctioning vehicle.

12.6 IMPLEMENTATIONS

12.6.1 Vehicle

- Processor,
- Short-range roadside to vehicle communication (2-way),
- Forward-looking sensor for range to vehicles and obstructions,
- Ranging sensor (for large objects) on right side only, and
- Lane-keeping sensors capable of reading encoded position information on specially designed reflectors, and measuring range to reflector.

12.6.2 Infrastructure

- Short-range roadside transceivers, sufficient density for continuous coverage,
- Traffic Operations Center spaced at pre-determined intervals,
- At least one dedicated AHS lane and one adjacent lane equipped with reflective lane markers compatible with the lane-keeping sensors,
- Physical barrier with gaps separating dedicated AHS lane(s) from transition lane,
- Breakdown lane (or areas) accessible from either the AHS lane or the transition lane. If not continuous, spaced at pre-determined intervals, and
- Cameras and unauthorized entry sensors at each entry zone.

12.6.2.1. Rural Highway

(See Flow Control for concept to allow mixed vehicle types on a single AHS lane.) Regular traffic lane can double as the AHS transition lane if this is dictated by cost or space limitations.

12.6.3 Deployment

If the lane-keeping sensors can be made compatible with existing rectangular reflectors, then a stepping-stone to implementing this concept could be installation of the on-board vehicle sensors, with no modifications to the infrastructure. The vehicle performs lane-keeping and longitudinal position-keeping under normal circumstances. The driver has the power to override when he desires, and is expected to take over under unusual circumstances. Driver monitoring techniques such as the one described in the next paragraph, are used to periodically check driver alertness.

If a satisfactory hazard detection sensor is not available at the time of initial AHS deployment, the driver can be used as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance. When the driver pushes an alert button, he also enters a code (roadway obstruction, fire, medical emergency, etc.). This information, along with the vehicle's position, is broadcast by the vehicle to a roadside receiver to relay to the TOC. If the driver pushes a button indicating a possible hazard in his lane, the roadside processor orders his vehicle and others near it to immediately slow and increases spacing in preparation for stopping or maneuvering. The driver must volunteer to perform this "spotter" function; reduced tolls represent a possible incentive. Where there are two or more dedicated AHS lanes a speed "bonus" could also be used as an inducement, with vehicles where the driver wants to read or sleep being limited to a lower speed in the right lane(s). Driver alertness and response time could be monitored by periodically projecting an image focused in the distance onto a windshield heads-up-display; the driver must respond by pushing a button within a prescribed time interval; if he fails several times, the vehicle is "demoted" to the lower speed right-hand lane.

12.7 ISSUES

12.7.1 Obstacle Detection Sensor

Obstacle detection could be performed a) by the vehicle-mounted headway sensor; b) by a separate vehicle-mounted sensor designed to detect small objects on the roadway; c) by sensors mounted on the roadway and designed for this purpose; d) by the headway sensor assisted by the driver (see previous paragraph). This is a technology issue that needs further investigation.

12.7.2 Vehicle Position Determination

This concept proposes that the vehicle calculate its position from a known position when it entered AHS, a count of the number of markers passed since entry, and measured range to the current markers. To do this the lane-keeping sensor must measure both range to the lane markers, and read a three to four bit sequence number encoded on the markers. These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. They are, however, spaced at regular intervals, machine-readable, and encoded with the sequence number of the marker. The vehicle counts markers, and uses the code on the marker as a check in case it misses a few. Where snow falls regularly, the markers must be designed or placed so that they are not damaged by snowplows. The feasibility of this position determination method is not critical to this concept; other methods can be substituted.

13. CONCEPT 11: INFRASTRUCTURE MANAGED MIXED PLATOONING WITH TRANSITION LANES

13.1 OVERVIEW

This chapter is based on concept number 11 given in AHS concept matrix. That system is defined as infrastructure managed mixed platooning with transition entry/exit and dedicated physically barriered gaped lanes.

Among several concepts available in the AHS concept matrix, concept 11 has definite advantages over the others. This concept allows the use of existing freeway on and off ramps. The driver passes through non AHS lanes to reach AHS lane. This option is very cost effective as no new on and off ramps have to be designed and built. Building new on and off ramps is not only very expensive, but they take a long time to build.

Since mixing of different class of vehicles is allowed in this option, only one AHS lane is required to pass all kinds of traffic. Non mixing of different classes of traffic calls for either separate lanes or the system is only implemented for one class of traffic. Again this option is clearly a cost saver.

This concept restricts mixing of AHS and non AHS traffic by using a physical barrier between AHS and non AHS lanes. Since dedicated entry/exits are not allowed in this concept design, gaps are provided at certain distances for AHS traffic to merge/separate from AHS lane. Even though this lane is not allowed for non AHS users, there is a possibility of a rogue driver entering AHS lane. This likelihood is taken care of by the design and is discussed in section 13.5.1.2.3 of this report.

Allowing platooning in this option allows high throughput in a given time as traffic is more compact.

Infrastructure management creates a uniform signal structure, as every manufacturer has to comply with a single standard. Infrastructure management also streamlines the traffic since it can sense the traffic in a wider area than the vehicle itself.

13.2 TRADE OFFS

One of the very obvious feature of this report is that this concept calls for physical barriers with gaps to segregate the AHS lane from the non AHS lane. Jersey barriers or a permanent wall is required to achieve this concept. Gaps are required in these physical barriers in order to enable AHS vehicles to merge/separate form AHS lane. Existing freeways have to be modified in this fashion. AHS vehicles will use non AHS lanes and existing on/off ramps to access AHS lane.

Mixing of all classes of vehicles is allowed through the AHS lane. To achieve this local tailoring is not required to implement this trade off. This trade off is built in to this concept of AHS. Its implementation is described in section 3 of this report.

Platooning is called for in this concept. No local tailoring is required, as it is built in to this concept of AHS. This concept is described in section 5.1.2.1 of this report.

Roadside stations have to be installed along the freeway. To monitor roadside controllers, regional traffic management centers have to be erected. The implementation of roadside controllers and regional traffic management centers is discussed in section 6.2 of this report.

13.3 SYSTEM DIAGRAM

The AHS concept is shown in Figure H.13.3-1. Looking at the diagram one notices that there is no vehicle-to-vehicle or platoon-to-platoon communication. The only communication allowed is between the vehicle and roadside controller. A roadside controller is a bridge between traffic and regional traffic management center. Most of the traffic managing intelligence is located in the regional traffic management center. Even in case of roadside controller failure or complete destruction, local traffic will not be

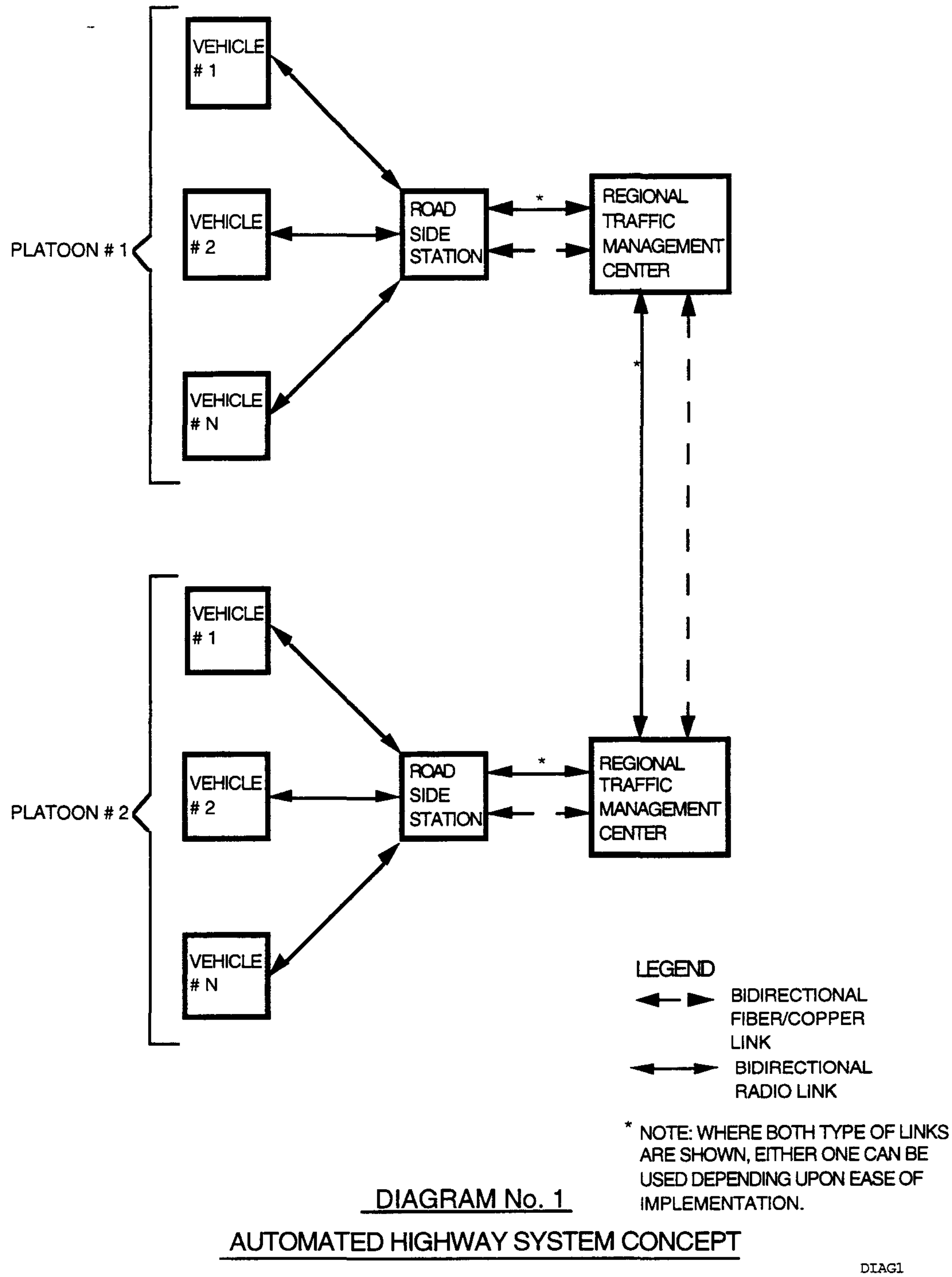

Figure H.13.3-1. Automated Highway System Concept

harmed and adjacent roadside controllers will take over the control.

Roadside controllers communicate with individual vehicles as well as regional traffic management centers simultaneously. The communication link between roadside controller and regional traffic management center shall either be a high speed radio or a fiber/copper link. Roadside controllers shall have the capability of collecting weather data and optional capability of video camera.

All these signals, if available, help personnel at the regional traffic management center to have better control over the traffic.

The regional traffic management center communicates with roadside controllers continuously. All the information about the traffic is passed to other regional traffic management centers to be shared. This distribution of information helps regional traffic management centers have better control over the traffic.

Figure H.13.3-2 shows vehicle on-board systems which are explained in detail in section 6 of this report.

13.4 OPERATIONAL CONCEPT

Before entering an AHS lane, each vehicle transmits its vehicle code, class identification code, and intention to merge into an AHS lane. The regional traffic management center registers this vehicle as a valid user. Vehicles are registered with the closest roadside controller. Each roadside controller has its operating zone based on its signal strength. As long as this vehicle remains in a zone, the roadside controller keeps all its information. Once the vehicle leaves a zone all the information is passed to the next roadside controller through the regional traffic management center. The regional traffic management center displays this information on a monitor.

After registering the vehicle, the regional traffic management grants or denies permission to enter the AHS lane. If permission is granted, the regional traffic management center sends speed and headway distance parameters. At this point the vehicle merges into the AHS lane. The merging procedure is discussed in section 5 of this report.

Allowing mixed classes calls for classification of vehicles. Vehicles are classified by their dynamic characteristics. Each vehicle is preprogrammed with a headway distance based on its class. Since heavy vehicles are slower in response (acceleration and braking) as compared to light vehicles, headway distance will vary for each class of vehicle. Heavy vehicles are preprogrammed with a higher headway distance then light vehicles.

Each segment of the AHS lane transmits speed and headway distance parameters to each vehicle. These parameters are weather and freeway condition dependent. The regional traffic management center computes these parameters and passes them to roadside controllers for a certain segment of freeway. Once a vehicle gets these parameters it maintains that speed in AHS lane. Headway distance is a slight different case. Since each vehicle is preprogrammed with a headway distance, the headway distance computed by the regional traffic management center is added by the vehicle on-board computer to preprogrammed headway distance.

In case the condition of the AHS lane is good, the regional traffic management center computes a higher speed and zero headway distance. In case of poor AHS lane conditions, the regional traffic management center computes a lower speed and a higher headway distance.

Each regional traffic management center handles up to a fixed number of roadside controllers. This creates a uniformity in design. Thus, rural areas end up with few regional traffic management centers with larger areas to cover since in rural areas roadside controllers can be installed with greater spacing.

In contrast, urban areas end up with more regional traffic management centers with smaller areas to cover since the number of roadside controllers per regional traffic management center is fixed. Roadside controllers in urban areas have low power transceivers to reduce interference between each other as the transceivers use the same frequency and bandwidth.

In normal conditions, AHS vehicles merge into the AHS lane by registering with roadside controllers. The roadside controller has the data about vehicle identification, vehicle class, number of vehicles in a platoon and their speeds. This data is given to the regional traffic management center for processing. When a vehicle enters a new zone it communicates with the roadside

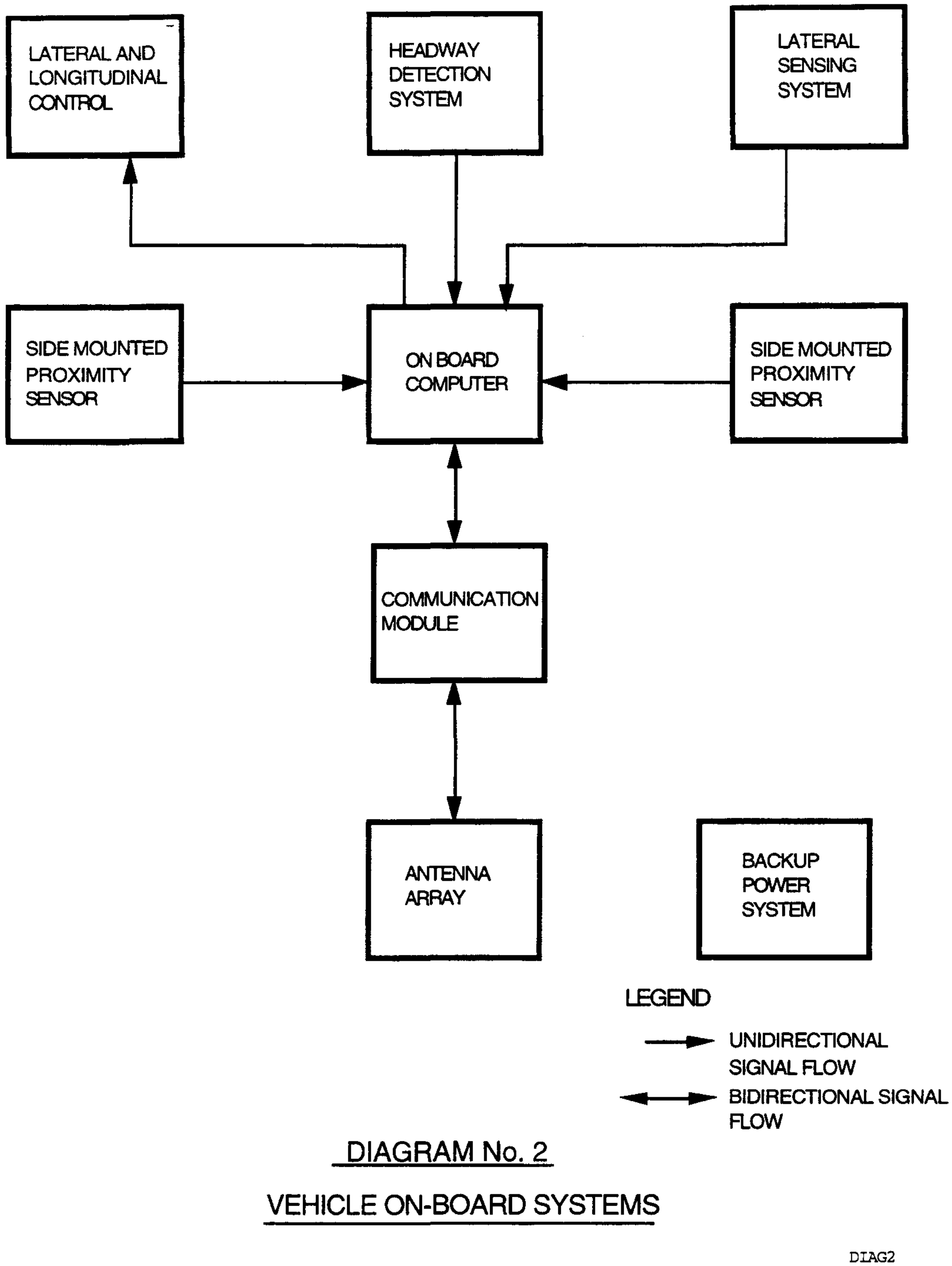

Figure H13.3-2. Vehicle On-board Systems

controller and all this data is given to the regional traffic management center for cross-checking against data provided by previous roadside controllers. Once a vehicle leaves, it informs the roadside controller and this data is again sent to the regional traffic management center to be processed and updated on the monitor.

The size of data communicated between vehicle and roadside controller is not more than a few hundred bytes. Also each vehicle communicates with the roadside controller only when it merges in an AHS lane or it enters a new zone. This does not burden the communication link between the vehicle and roadside controller. The update rate depends on speed and the distance between roadside controller and vehicle.

13.5 FUNCTIONAL ALLOCATION

This system allows communications between vehicles and roadside controllers only. Every request from the AHS vehicle is checked by the regional traffic management center. The regional traffic management center takes appropriate actions to manage the traffic. Roadside controllers serve as a bridge between AHS vehicles and regional traffic management centers.

13.5.1 Baseline Functions

Procedures for baseline functions are given below. Keep in mind that safety is the prime concern here.

13.5.1.1. Check-In

The driver uses an existing on-ramp to enter the freeway. After entering the freeway the driver transitions through non AHS lanes till he reaches the lane next to the AHS lane. The driver informs the infrastructure (roadside controllers) about his intention to enter the AHS lane by turning the AHS system ON. The on-board computer generates a signal and relays it to the nearest regional traffic monitoring center, through the roadside controller, requesting to enter the AHS lane. The regional traffic management center registers the vehicle as a valid user and grants permission to merge in the AHS lane. At this point, the vehicle is in a quasi automatic state. The on-board computer checks, using proximity sensors, for the physical barrier and for other vehicles in close proximity in the AHS lane. If the vehicle is passing by a gap in physical barriers and there are no vehicles present in close proximity in the AHS lane, the merging vehicle generates the proper lateral and longitudinal commands to merge in the AHS lane. After merging, the vehicle informs the roadside controller about its successful entry and engages the lateral and longitudinal control to follow the AHS lane (fully automatic mode).

13.5.1.2. Automatic mode of driving

Once the vehicle goes in the fully automatic mode, the on-board computer checks for the availability of any other vehicle in front using the front mounted headway detection system.

13.5.1.2.1. Joining the platoon

The regional traffic management center periodically checks a segment of the AHS lane for all the incomplete platoons. If there are any single vehicle platoons or incomplete platoons available, then the regional traffic management center manages the AHS vehicles to complete the platoons.

13.5.1.2.2. Separating from platoon

When the driver decides to separate from the platoon, he indicates this by entering a command on the key pad. The on-board computer generates commands to inform the regional traffic management center about the driver's intention. Permission is granted by the regional traffic management center to leave the platoon. The on-board computer uses proximity sensors to check a gap in the physical barrier and if there is no car in near proximity. Once both of the conditions are met, the on-board computer generates the proper lateral and longitudinal commands to leave the platoon and the AHS lane. After a successful exit from platoon the vehicle informs the roadside controller about its successful exit. The gap in this platoon is filled by the following cars as mentioned above until the platoon is full.

13.5.1.2.3. Sensing of roadway, vehicle and obstructions

Roadway sensing is done with a lateral sensing system. The system senses the roadway and processes this information using a dedicated CPU. All the processing is passed to an on-board computer for proper generation of lateral control commands.

The front mounted headway detection system computes the vehicle or platoon headway distance. The headway detection system has a dedicated CPU to process headway information. After this information is processed it is passed to the on-board computer for proper generation of longitudinal control commands.

Roadside controllers are equipped with surveillance equipment to monitor lane condition (oil spill, frost etc.) and any obstruction (dropped ladder, moving animal etc.) on the AHS lane. This information is passed to the regional traffic management center. In case of an unfavorable lane condition (oil spill, frost etc.), the regional traffic management center slows the AHS traffic speed and/or increases the headway distance. The regional traffic management center dispatches maintenance crews for cleanup. The case of obstruction on AHS lane is discussed in section 13.5.1.2.4

Roadside controllers check for any non AHS vehicles on the AHS lane. If a non AHS vehicle is detected on AHS lane, the regional traffic management center increases the distance between AHS and non AHS vehicle by either increasing/decreasing speed or increasing headway distance of AHS vehicles. The regional traffic management center also notifies the highway patrol to handle the situation.

13.5.1.2.4. Maneuver planning and execution

Normal maneuvering and execution was discussed above in sections 13.5.1.2.1 and 13.5.1.2.2.

Roadside stations detect any obstruction on AHS lane and relay this information to the regional traffic management center. This information is relayed by the regional traffic management center to all the previous roadside controllers, up to a specified distance. Roadside controllers relay this information to all cars and platoons within that specified distance from the obstruction. Roadside controllers also inform the on-board computer to leave the AHS lane and break the platoon. Once the vehicle exits the AHS lane, control is returned to the driver by the on-board computer, which also notifies the roadside controller about the successful exit of the vehicle from the AHS lane. Once AHS vehicles pass the obstructing point on AHS lane they are again given permission to merge in the AHS lane.

13.5.1.3. Check out

The checkout procedure is the reverse of the check-in procedure. The driver punches a command on the keypad to initiate the sequence. The on-board computer informs the roadside controller. The roadside controller relays this command to the regional traffic management center. The regional traffic management center grants permission to change the lane. At this point, the on-board computer uses the proximity sensors to check the feasibility of the lane change. If conditions are feasible (gap in physical barrier and no car in near proximity in the other lane), then the vehicle changes lane and goes into quasi-automatic mode. The driver is informed at this stage to take control and the roadside controller is informed of a successful lane change. After the driver takes control of the vehicle, the on-board computer can be switched off.

13.5.1.4. Malfunction management

Malfunctions are classified into two major classes:

- Vehicle malfunction, and
- Infrastructure malfunction

13.5.1.4.1. Vehicle malfunction

Before entering the AHS lane, the vehicle on-board computer goes through a self check. In case of a fault it prevents the driver from merging into the AHS lane by sounding an alarm. Also, if the driver still tries to merge into the AHS lane, the roadside controllers deny the request. The on-board computer never enters the quasi-automatic state, thereby preventing the driver from entering the AHS lane.

There is a possibility that a vehicle on-board system might malfunction while the car is moving in the AHS lane. The worst case scenario is computer malfunction. Since the on-board computer is the heart of the system, its failure (even though rare) causes tremendous problems to the driver. In such a case, the roadside controller detects this problem and relays this information to the regional traffic management center. The regional traffic management center treats this car as a non AHS vehicle. Handling of non AHS vehicles was discussed in section 5.1.2.3. The steering locks for few moments and an alarm sounds to inform the driver to take control of the vehicle. Also, the speed gradually decreases in order to break the platoon. The driver exits from the AHS lane by using the next gap available. The rest of the vehicles resume their journey after the departure of the malfunctioned vehicle from the AHS lane.

One hundred percent redundancy is provided by having a backup computer to take over in case the main on-board computer fails. Another way of solving this problem is to have a small computer that is programmed to take the vehicle out of the AHS lane only in case of such an emergency and that disengages after giving control to the driver.

13.5.1.4.2. Infrastructure malfunction

In this design, an infrastructure malfunction is not very critical as every stage has a backup to take control. In case of a roadside controller failure, the regional traffic management center detects it either by signal loss or data corruption. The regional traffic center shifts all the necessary parameters to adjacent roadside controllers to take control.

This backup management is on temporary basis and a maintenance crew is dispatched to replace/repair the defective controller component(s).

13.5.1.5. Emergency handling

In case of emergencies, the regional traffic management center relays global commands to all the AHS vehicles in that region to go to high safety mode. High safety mode is defined as shutting down the AHS functions by breaking the platoons slowly, reducing the speed, informing the drivers to change out of the AHS lane, etc. (i.e., the graceful degradation of the AHS system).

13.5.1.6. Flow control

Flow control is managed by roadside controllers in conjunction with regional traffic management centers. Roadside controllers inform the regional traffic management center about traffic conditions on the AHS lane (total number of cars passed in a certain time, average number of cars per platoon etc.). The regional traffic management center allows or disallows more AHS vehicles on the AHS lane. Regional traffic management centers have global traffic knowledge for an entire region. Regional traffic management centers share data with each other for better traffic flow control. Also, these centers are aware of any obstruction on an AHS lane, and so can redirect AHS traffic to non AHS lanes in advance.

13.6 IMPLEMENTATIONS

The implementation of this system depends on providing an array of electronic devices on-board the vehicle and enhancing the existing highway infrastructure. The success of this AHS concept relies on the speed and accuracy of on-board computers and instruments in conjunction with support provided by ground-based systems.

13.6.1 On-Board Vehicle Systems

The on-board vehicle systems consists of a(n):

- On-board computer,
- Headway detection system,
- Lateral sensing system,
- Side-looking proximity sensors,
- Lateral and longitudinal control subsystems,
- Communication module,
- Antenna array, and
- Backup power system.

Refer to diagram 2 for an overview of on-board vehicle systems and signal flows.

13.6.1.1. On-Board Computer

The on-board computer incorporates all necessary hardware, i.e., temporary and permanent storage devices, backlit LCD screen, keypad, and an adequate number of ports to communicate with all the on-board systems.

13.6.1.2. Headway detection system

The headway detection system consists of all essential hardware to provide range information to the on-board computer. The hardware includes a dedicated processor to relieve the on-board computer for other critical decisions.

13.6.1.3. Lateral sensing system

The lateral sensing system provides lateral guidance to the on-board computer. The lateral guidance employs a dedicated CPU to relieve the on-board computer for other critical decisions.

13.6.1.4. Side looking proximity sensors

Each vehicle is equipped with two side looking proximity sensors, one mounted on each side. These proximity sensors are the capacitive or inductive type and provide information about their presence to the on-board computer. Another option is to use a laser range finder as a proximity sensor. This way the on-board computer not only detects the presence of an object but also obtains range information. This option helps the on-board computer to make better decisions. These proximity sensors also help the on-board computer to avoid collisions through advanced warning when an object is too close.

13.6.1.5. Lateral and longitudinal control subsystems

The longitudinal control subsystem consists of throttling and braking control whereas the lateral control subsystem consists of steering control. The on-board computer generates the commands to control both subsystems. These subsystems have no intelligence of their own.

13.6.1.6. Communication module

The communication module contains radio modems and transceivers for the allocated frequencies. The communication module handles bi-directional, short range vehicle-to-roadside controller communications.

13.6.1.7. Antenna array

The antenna for short range communication between the vehicle and the roadside controller is a wide beam, low-gain unidirectional antenna.

13.6.1.8. Backup power system

A separate rechargeable battery is used to power the vehicle on-board systems and is charged by the vehicle battery charging system. A power flow monitor ensures that power only flows from the vehicle battery charging system to the separate rechargeable battery. A power monitor checks the battery and informs the on-board computer about its condition.

13.6.2 Infrastructure Modifications

In order for this system to work properly, infrastructure modifications are essential. This concept dictates regular maintenance and continuous vigilance over the dedicated lane condition.

Low-level modifications require that lane striping is maintained on a regular basis. Measurements are necessary to keep the AHS lane separated from non AHS lane. Gaps are provided at suitable intervals for the AHS traffic to merge and separate from the AHS lane.

Mid-level modifications are the roadside controllers and regional traffic management centers. The number of roadside controllers depends upon the number of obstacles (high rise buildings, trees, high tension lines etc.) as well as other radio frequency generating devices such as radio stations, cellular phone stations, and airports that are present in a particular area. Each regional traffic management center only handles a certain number of roadside controllers due to bandwidth constraints.

Roadside controllers are equipped with radio modem and transceivers to communicate with vehicles, local computers, surveillance equipment, weather sensing gear, and requisite hardware required to talk to regional traffic management centers such as fiber/copper link or radio modem and transceiver. Optional items are a camera with tilt and pan outfit. The camera has all the necessary hardware to communicate with the local computer.

The regional traffic management center is equipped with computers, high resolution monitors, and communication equipment such as a fiber/copper link or a radio modem and transceiver.

13.6.2.1. Rural highway implementation

Roadside controllers need power to run. Two possible providers exist. Power is provided by the local power company if they have an underground or overhead power line in the near vicinity. Alternatively, power is provided to roadside controllers by the highway department, who can lay an underground power line alongside the freeway. Laying an underground power line requires transformer stations at certain distances to maintain the original voltage level.

A separate conduit alongside the underground power line serves as a carrier for the fiber/copper link. This eliminates the use of expensive radio modem/transceiver combinations. Such a link between roadside controllers and regional traffic management centers is more reliable.

There is not much radio frequency interference in a rural area, so roadside controllers can have high power transceivers to communicate with vehicles. This eliminates the need to have roadside controllers close-by and permits design freedom in the installation of roadside controllers at larger distances.

13.6.2.2 Urban region implementation

Urban region implementation is totally opposite to rural region implementation. Urban regions have access to power at almost all locations. The available power is generally of good quality and is very reliable.

Radio frequency interference is much greater in urban areas and the chance of having obstacles such as high rise buildings, trees, and high tension power lines is much greater. This requires more roadside controllers, which in turn require low power transceivers so there is no interference with each other or with other nearby radio equipment.

Urban areas have access to phone lines and dedicated lines leased from local phone companies. Leasing a dedicated line eliminates the need to have a radio modem/ transceiver combination in each roadside controller to communicate with the regional traffic management center. This greatly reduces the cost per roadside controller.

13.6.3 Deployment

A minimal deployable system consists of vehicle mounted lateral and longitudinal control and minimal infrastructure support. Infrastructure support is limited to lane maintenance only. A vehicle equipped with such a system assists the driver in keeping the car under better control by maintaining the distance between the vehicle in front and by keeping the car in the middle of the lane. This is a quasi-automatic system, giving the driver the option to override anything the driver does not like. The driver must still stay alert, but this is less stressful than having full control over the car.

With full system in operation, the driver not only drives in a stress free environment, but has time to do other work while traveling in an AHS vehicle.

14. CONCEPT 12A: INFRASTRUCTURE MANAGED MIXED FREE AGENTS

14.1 OVERVIEW

This chapter describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Mixed Free Agents".

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

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

Concept #12b allows mixing of vehicle classes in AHS lanes, at least for transitional, highway interchange and entry/exit purposes. It opens up the possibility that conventional highway structures can be modified slightly to prepare them for the AHS system. At the same time, it calls for free agents instead of platoons as the primary units of longitudinal and lateral control.

This concept represents the possibility that the most cost-effective way of achieving maximum throughput is by allowing the vehicle classes to mix in transition areas, thereby eliminating the need for special exits and interchanges, and by taking the middle path in both vehicle-based intelligent control and infrastructure based control. The infrastructure is expected to be an intelligent agent that monitors every vehicle but does not control any unless requested under normal circumstances; this keeps the cost low. The vehicle is expected to be intelligent enough to keep its lane and sense its immediate surroundings, but is not expected to accomplish lane changes or manage initial placement without infrastructure help.

The distinguishing feature of this concept is the maximum achievable throughput without using platooning and medium cost infrastructure. Complete vehicle automation and global traffic flow management are going to be the important factors in achieving that goal. Infrastructure setup investment is mainly in the setting up traffic management centers and communication networks.

14.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

	Concept Characteristic	Dimension Alternative
1	Distribution of Intelligence	Infrastructure managed
2	Separation Policy	Free Agent
3	Mixing of AHS and non-AHS Vehicles in the Same Lane	Dedicated lanes with physical barriers
4	Mixing of Vehicle Classes in a Lane	Mixed
5	Entry/Exit	Dedicated
6	Obstacle Avoidance	Automatic sensing and automatic maneuver if possible

1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, transfers full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and possibly for lateral control. The main mode of

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

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

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

4. Each AHS lane can, in principle, be used by vehicles of all classes. The AHS system is geared to handle mixed traffic in all lanes. However, the characteristic is highly tailorable according to local requirements. In a more typical scenario, the local officials may bar the heavy vehicles from the lane of lighter vehicles, but let the light vehicles use the lane reserved for heavier vehicles, especially for transition purposes at entry/exit points and highway-to-highway interchanges. Though mixing of vehicle classes is permitted, each lane may still be denoted for main use by certain classes of vehicles. A more detailed protocol of lane usage is left for the local authorities. As compared to the no-mixing option, the mixing option is much easier to implement as far as the physical highway structure is concerned. Conventional highways can be upgraded gradually to function as AHS highways. However, maximum throughput in the mixing option is significantly less, though still greater than with conventional highways.

5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes, i.e., at no time does AHS traffic mix with non-AHS traffic. Since mixing of vehicle classes is permitted in a lane, one lane per entry/exit suffices. Local officials may opt for more lanes per entry/exit, each possibly catering to a different AHS lane and a different set of vehicle classes.

6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both on-board the vehicle and the ones in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle would be made, if considered possible. Possible

maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking. The response considers obstacle size and type. The safety of the vehicle in question and the others around it is the supreme concern. At no stage is human involvement expected, except possibly in the sensing of the obstacle. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporary or permanent non-AHS vehicle on the highway is considered an obstacle.

14.3 OPERATIONAL CONCEPT

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

Before these point of views are presented, it is illustrative to consider the four modes of operation a vehicle can have based on who is in charge. The intelligent agent in charge makes high level decisions that are executed by agents lower in the control hierarchy.

- The vehicle is in charge through the use of an array of intelligent control systems.
- The vehicle (and in exceptional circumstances the driver) authorizes the infrastructure to take charge, for example during the lane changes, entry/exit, and emergencies.
- The infrastructure wrests control from the vehicle.
- The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle is no longer in control, it is unable to get it back on its own; the infrastructure has to reinstate control. Whenever a transfer of control takes place from the infrastructure to the vehicle, the vehicle has to actively take over control and convince the infrastructure it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains control. Similarly, once the driver transfers control to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate control; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains control.

14.3.1 Driver Point of View

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

The only operation a driver can possibly perform is the change of exit.

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

14.3.2 Vehicle Point of View

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

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

1. Lane Following: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are located on-board, control the vehicle longitudinally.
2. Request Lane Change: The vehicle decides to change lane and registers a

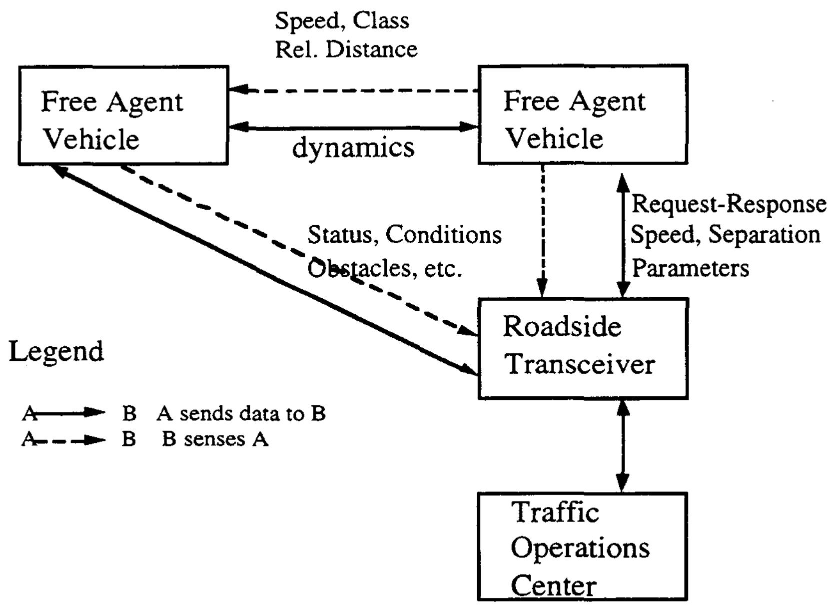

Figure H.14.3-1. System Diagram

request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agents aboard the vehicle. The request cannot normally be denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and taken out of the control loop until the lane has been automatically changed. Control passes to the vehicle from the infrastructure when the vehicle is stably located in the new lane.

3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit. In any case, a request is registered with the infrastructure. The request is granted under normal circumstances, unless the requested exit is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur, and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of the infrastructure. Automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking.

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

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

14.4 SYSTEM DIAGRAM

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

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

The infrastructure-to-vehicle data communication consists mainly of responses to vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc. While the exact content of the communicated messages has not yet been defined, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are given below.

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

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control be localized. Each roadside transceiver only communicates with a finite and limited number of vehicles. The optimal numbers need to be computed after a careful analysis. At this time, only a rough estimate is possible. It is also a good idea to make it possible for two adjacent roadside transceivers to receive vehicle-to-infrastructure communications for purposes of redundancy and reliability, which requires doubling the range of communication from the vehicle-to-roadside as opposed to the other way around. The roadside-to-vehicle communications are made reliable by on-vehicle redundancies. However, it would be desirable for one, and only one, roadside transceiver to attempt to communicate with each vehicle. The hand-over of the vehicle from one roadside transceiver to the next can be handled by the Traffic Operations Center.

To summarize the requisite communication:

- Vehicle in front to Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, and estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.
- Vehicle in front to Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back permits this vehicle to detect relative position and relative speed.
- Vehicle in back to Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 960 bps channel, 25% duty cycle, 1/4 mile maximum range.
- Infrastructure to Vehicle: Message Content: Command and control requests,

speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 960 bps channel, 25% duty cycle, 1 mile maximum range.

- Vehicle to Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 960 bps channel, 5% duty cycle, 2 mile maximum range.
- Infrastructure to ANY vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range.

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

14.5 FUNCTIONAL ALLOCATION

14.5.1 Baseline Functions

14.5.1.1. Check-in

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

14.5.1.2. Transition from manual to automatic control

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

14.5.1.3. Automated Sensing of roadway, vehicles and obstacles

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

14.5.1.4. Longitudinal sensing

Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle.

14.5.1.5. Lateral sensing

Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle.

14.5.1.6. Obstacle sensing

Vehicle sensors are able to sense at least some kinds of obstructions other than vehicles.

14.5.1.7. Vehicle longitudinal position sensing

Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy).

14.5.1.8. Vehicle lateral position sensing

Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

14.5.1.9. Automated Sensing of vehicles and obstacles

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

14.5.1.10. Collision avoidance

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

14.5.1.11. Automated headway keeping

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

14.5.1.12. Automated Lateral Controller. (Lane Keeping)

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

14.5.1.13. Detection of hazards

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

14.5.1.14. Normal Maneuver planning

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

14.5.1.15. Emergency Maneuver planning

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

14.5.1.16. Normal Maneuver execution

Allocated to the vehicle and is executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

14.5.1.17. Emergency Maneuver execution

Allocated to the Vehicle and is executed by the on-board controller, though in some cases, the driver may be called in to take control. An exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver may have the option to intervene, but his intervention power may be limited or his intervention power may depend on the situation. That is, certain scenarios may allow more driver input than others. This appears to be a very problematic issue with respect to the eventual deployment of AHS.

14.5.1.18. Transition from automatic to manual control

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

14.5.1.19. Check out

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

14.5.1.20. Flow control

Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. The sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS. A central controller at the Traffic Operations Center decides on optimal velocity, spacing and traffic routing to control and optimize traffic flow.

14.5.1.21. Malfunction management

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

14.5.1.22. Handling of emergencies

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

14.6 IMPLEMENTATION

In this section, one possible implementation concept is described. This is not the only possible implementation or even the most recommended one. It is only a representative example of an implementation that permits visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between system components.

14.6.1 Vehicle

The vehicle requires the following functions and subsystems:

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

1. Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.
2. Accurate longitudinal position sensing. The longitudinal position of the vehicle is known in absolute terms and in terms of relative position to other vehicles. The absolute position is for navigation and trip destination control purposes and the relative position for velocity and headway maintenance and control, as well as for collision avoidance.
3. Accurate lateral position sensing and lane position identification. The lateral position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for lane keeping, lane changing and navigation purposes and the relative position is mostly for collision avoidance especially during lane changing.
4. Collision avoidance based on obstacle sensing in combination with vehicle-to-vehicle and vehicle-to-infrastructure communications. Vehicle sensors are not adequate and do not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore, the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.
5. Maneuver coordination between vehicles. Every aspect of the motion of the vehicle, especially lane changes, is orchestrated and coordinated by a control authority at a higher level than each vehicle itself. This control authority is distributed collectively among vehicles or it is assigned to the infrastructure. Most likely, a local decision affects the assignment of this control authority. In urban regions, the authority is exclusive to the infrastructure. In rural regions, the authority is distributed among vehicles and in every case it is dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.
6. Automatic route guidance based on navigation computers and interaction with the infrastructure.
7. Supervisory controller which monitors everything and alerts the driver of any single point failure. Malfunction management is one of the more complicated issues facing AHS system designers. It is desirable, if not essential, that every part of the automation be covered by multiple redundancies so that no single point failure affects the operation of the system. At the same time, any failure must be immediately detectable and the driver must become aware of it as soon as possible to assume partial or full control of the vehicle if necessary.

14.6.1.1. Required vehicle components

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

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

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

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

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

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

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

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

14.6.1.2. Vehicle implementation issues and considerations

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

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

14.6.2 Infrastructure

Required infrastructure components:

1. Low-level infrastructure components:

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

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

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

2. Intermediate-level infrastructure components

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

3. High-level infrastructure components

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

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

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

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

14.6.2.1. <u>Rural Highway</u>

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

14.6.2.2. <u>Urban Highway</u>

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

14.6.3 Deployment

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

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

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

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

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

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

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

14.7 GENERAL ISSUES AND CONSIDERATIONS

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

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

Sensory Failures
Vehicle cannot sense its own position:

Vehicle cannot sense the presence of other vehicles ahead,

Vehicle cannot sense the presence of obstacles ahead,

Vehicle cannot sense the presence of other vehicles aside,

Vehicle cannot sense the presence of obstacles aside, and

Vehicle cannot sense the weather conditions around.

Longitudinal Control
Vehicle cannot maintain velocity,

Vehicle cannot maintain the desired headway Lateral Control Failures, and

Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles,

Vehicle cannot receive communication from other infrastructure,

Vehicle cannot transmit to other vehicles, and

Vehicle cannot transmit to the infrastructure.

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

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

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy is required for most automation subsystems to guarantee fail-safe operation. Triple redundancy is required on the most critical subsystems. If designed properly, degradation of the

system, in case of failure, occurs in a fashion so that if the infrastructure is unable to control a particular vehicle, it should pass control to the vehicle. In case the vehicle is unable to control itself, it is able to pass control to the driver. Each has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

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

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

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

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

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

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

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

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

What speed(s) would typical users travel at? How tailorable is this?
These are conflicting requirements. A low typical velocity hurts efficiency and performance. A high typical velocity hurts fuel economy and generates potentially dangerous conditions in case of malfunctions. The risks increase

exponentially with speed. The exact figures must be analyzed. An estimate is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed needs to be tailorable to local conditions, but the maximum speed probably does not.

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

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

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. Their attention to actual driving operations will be of a very high-level, infrequent type. On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept, though mixing of vehicle classes in a lane makes it a uphill task. The infrastructure has to constantly monitor the vehicle (the on-board agents still perform the micro-control), so the additional cost can be justifiably passed on to the freight carrier.

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

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

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

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

What features of this concept will most contribute to increasing safety over the present system?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features function as designed all the time. Reliability, which is often the most important one to evaluate safety, is not considered at this time.

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

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

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

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

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

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

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

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

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

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

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

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

Multitude of Electronic Control Mechanisms
Each control mechanism alone is designed to operate at levels that are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of system reliability.

Heavy redundancy and multiple backup systems can improve the reliability of the system. extent and at what cost remains to be studied.

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

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

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

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

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

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

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

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

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

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user)?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities

will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view?

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

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

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

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

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

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

15. CONCEPT 12B: CONCEPT #12B: INFRASTRUCTURE MANAGED UNMIXED FREE AGENTS

15.1 OVERVIEW

This chapter describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Unmixed Free Agents".

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

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

Concept #12b is one of the two tiered concepts. It differs from the other one in the regard that it calls for free agents instead of platoons as primary units of longitudinal and lateral control.

This concept represents the possibility that the most cost-effective way of achieving maximum throughput is by separating each vehicle class in its own lane and by taking the middle path in both vehicle-based intelligent control and infrastructure based control. The infrastructure is expected to be an intelligent agent which monitors every vehicle but does not control any unless requested under normal circumstances, keeping the cost low. The vehicle is expected to be intelligent enough to keep its lane and sense its immediate surroundings, but not expected to accomplish lane changes, or manage the initial placement without the infrastructure's help.

The distinguishing feature of this concept is the maximum achievable throughput without using platooning. Complete vehicle automation, global traffic flow management and no mixing of vehicle classes are going to be the important factors in achieving that goal. However, infrastructure setup investment is the single most important cost. Because of the tiered nature of AHS, complex and expensive interchanges and exits are required to implement this concept.

15.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

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