with the appropriate vehicles to slow them down and create gaps. The merge control system also receives upstream flow information on merging highways from the AHMC and adjacent stretch control systems.

### Information Flow

The vehicle coordination and regulation control system needs all information necessary to execute speed tracking, inter-vehicle separation tracking and lane change maneuvers. The following table shows additional information flow requirements.

| Description | From System | To System |
|---|---|---|
| Traffic flow on the merging highways | Roadside control systems and AHMC | Merge control system |
| Gap detection on merging lanes | Merge sensing system | Merge control system |
| Gap negotiation on merging lanes | Merge control system | Vehicle coordination system |
| Communication ID of vehicles that need to coordinate their maneuvers | Merge control system | Vehicle coordination systems |
| Gap info on merging lanes | Merge control system | Vehicle planning system |

**Highway Geometry Modifications**: Necessary modifications to help vehicle detection by merge sensing system and lane change/merging lateral control system on the vehicles.

### 2.1.18: Lane to Lane Routing

**General Description:** No explicit lane to lane route is computed in this concept during regular operation. Explicit lane to lane routes may be supplied to emergency vehicles in order to help them reach a particular site quickly. Refer to section 2.1.23 for the description.

### 2.1.19: Highway to Highway Routing

**General Description:** The network routing controller combines average entry and exit rates from the entry and exit controllers with historical data to generate dynamic O-D trip demand estimates.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| incident report, emergency report | Incident & Emergency Detection System | Network Routing Controller |
| average section speed, average section flow | Section Control System | Network Routing Controller |
| average entry rate | Entry Control System | Network Routing Controller |
| average exit rate | Exit Control System | Network Routing Controller |
| dynamic O-D trip demand estimates | ITS Information Service Providers | Network Routing Controller |
| current and predicted AHS link travel time estimates | Network Routing Controller | ITS Information Service Providers |
| current and predicted AHS link travel time estimates, recommended routes | Network Routing Controller | Vehicle Planning & Co-ordination System |

### 2.1.20: AHS Flow Control

**General Description:** AHS flow control is achieved by controlling lane change rates for lane flow balancing, entry metering, speed regulation and inter and intra platoon separation regulation. Lane changes are regulated by broadcasting a lane and destination specific lane change fraction e.g., 60% of the vehicles traveling to exit *d* and in lane *l* should move to the right lane.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| desired speed, desired inter-platoon separation, desired intra-platoon separation, maximum platoon size | Stretch Control System | Vehicle Planning and Co-ordination System |
| desired entry rate | Section Control System | Entry Controller |
| lane and destination specific lane change fraction | Stretch Control System | Vehicle Planning and Co-ordination System |

### 2.1.21: AHS Admission Control

**General Description:** This function consists of the regulation of entry rates. The network routing controller computes desired entry rates over a certain time period and communicates this to the section control system, which then modifies this based on section conditions and communicates a desired entry rate to each entry control system.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| recommended entry rate | Network Routing Controller | Section Control System |
| desired entry rate | Section Control System | Entry Control System |
| vehicle present or not present | Entry Sensing System | Entry Rate Controller |
| command execute entry maneuver | Entry Rate Controller | Vehicle Planning and Co-ordination System |

### 2.1.22: Emergency Detection/Monitoring

**General Description:** Multiple information sources i.e., roadside sensing system, messages from the automated vehicles, and messages from other external agencies can be used for this function. It is assumed that the road image from the roadside sensing systems is transmitted to the AHMC where it can be processed for obstacle and incident detection or viewed by human operators.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| flow, speed, road image | Roadside sensing system | Incident & Emergency Detection System |
| road image | Roadside sensing system | Operator |
| obstacle information, emergency messages | Vehicle Planning and Co-ordination System | Neighboring vehicle coordination system |
| obstacle information, emergency messages | Vehicle Planning and Co-ordination System | Roadside Control System |
| obstacle information, emergency messages | Vehicle Planning and Co-ordination System | Incident & Emergency Detection System |
| emergency information | Law Enforcement Agencies | Incident & Emergency Detection System |
| emergency, incident information | ITS Information Service Providers | Incident & Emergency Detection System |

### 2.1.23: Emergency Response and Incident Clearing

**General Description:** It is expected that for this function Emergency Service Providers will recommend emergency action plans and dispatch emergency vehicles as necessary for emergency medical services or for incident clearing. The section controller will adjust its flow control function by formulating lane change and speed policies to clear a path for emergency vehicles. It may communicate a lane to lane route to the emergency vehicle which is compatible with its flow control actions. The emergency vehicle will be able to communicate with the vehicles on AHS to obtain maneuver coordination. Emergency vehicle maneuvers will be assigned higher priority than the normal mode maneuvers.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| emergency report, incident report | Incident & Emergency Detection System | Network Control System |
| emergency report, incident report | Incident & Emergency Detection System | Emergency Service Providers |
| **Description** | **From System** | **To System** |
| emergency action plan, emergency vehicle dispatch | Emergency Service Providers | Network Control System |
| emergency response recommendation | Network Control System | Section Control System |
| position, destination, assistance request | Emergency Vehicle | Section Control System |
| recommended lane to lane route | Section Control System | Emergency Vehicle |

### 2.1.24: Driver Interrupt Handling

**General Description:** Driver interventions are permitted for vehicle routing, exiting, obstacle recognition, emergency detection and incident detection. In all cases the driver requests are complied with only in a safe manner. If the safety of the driver or other vehicles will be compromised by compliance then the vehicle control systems will override the request.

**Information Flow**

| Description | From System | To System |
|---|---|---|
| take next exit, take particular exit, take exit for a particular highway, follow particular route, stop request, obstacle of particular type and shape in particular location, emergency of particular type in particular location, ready to hand-off | Driver | Vehicle Planning and Co-ordination System |
| will exit shortly message, take control of vehicle request, emergency alert message, downstream congestion info | Vehicle Planning and Co-ordination System | Driver |

## (3) Deployment Stage Variations

There exist a number of different possible deployment scenarios. This section summarizes a market-driven AHS deployment scenario.

A Market Driven Scenario:

This scenario consists of six main stages. See Figure 3.1.1 for chronological order.

Stage 1 ⟶ Stage 2 ⟶
| ⟶ Stage 4 ⟶ Stage 5 ⟶ Stage 6
Stage 3 ⟶

Figure 3.1: A Market-Driven AHS Deployment Scenario

This scenario can be partitioned into three major different components of stages. Stages 1 and 2 are pre-AHS stages, which are designed to build up public demand for automation technology. Stage 3 constitutes an AHS but is designed to serve as a technological testbed for a fully automated AHS and to showcase user and societal benefits. In other words, it builds up the supply. Note that Stages 1 and 2 can be deployed in parallel with Stage 3. After the deployment of Stages 1, 2 and/or 3, Stages 4, 5 and 6 can then be deployed.

Stages 4, 5 and 6 all constitute an AHS, but with different operational functionality. Stages 5 and 6 can be combined to provide congestion relief faster, if the technological difference between them turns out to be insignificant and the public is eager to adopt Stage 6.

(3.1) Stage 1: Delegation of Driving Chores

This stage has the following features:

- vision-based lane-line tracking for lane-keeping
- radar-based adaptive cruise control
- full driver supervision while delegating driving chores
- driver alertness and attentiveness monitoring
- usefulness on all roadways, including freeways and city-streets
- no infrastructure modification needed
- applicability to all vehicle classes
- trucking industry as a potential first customer

Geographical Scope: all roadways with lane lines

- rural highways
- city streets
- freeways

Vehicle Classes Supported: all vehicle classes, including trucks
Vehicle Type: partial automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.1.1) Functional Descriptions

Functions with a "+" indicate those being added at this stage. Those without that mark are to be provided at later stages.

+ 2.1.1 Speed tracking
+ 2.1.2 Inter-vehicle separation tracking
+ 2.1.3 Lane keeping
  2.1.4 Lane changing
+ 2.1.5 Road geometry recognition: only lines for current lane
  2.1.6 Obstacle recognition
  2.1.7 Obstacle avoidance
  2.1.8 Speed decision
  2.1.9 Inter-vehicle separation decision
  2.1.10 Lane change decision
  2.1.11 Lane change co-ordination
  2.1.12 Platoon formation and dissipation
  2.1.13 Vehicle operational status monitoring
+ 2.1.14 Driver status monitoring
  2.1.15 Vehicle entry
  2.1.16 Vehicle exit
  2.1.17 Automated highway merging
  2.1.18 Lane to lane routing within a single highway
  2.1.19 Highway to highway routing
  2.1.20 AHS flow control
  2.1.21 AHS admission control
  2.1.22 Emergency detection/monitoring
  2.1.23 Emergency Response and Incident clearing
  2.1.24 Driver Interrupt Handling

(3.1.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | manufacturing, servicing | potentially large market |
| Vehicle Electronics | manufacturing, servicing | potentially large market |
| Highway Design & Construction | none | none |
| Trucking | use | comfort, safety & productivity |
| Transit | use | comfort, safety & productivity |
| Environmental Interests | neutral (AHS automating driving) | none |
| Transportation Users | use | comfort, safety & productivity |
| Government Agencies | none | none |
| Insurance | underwriting & collecting data | potentially large market |

(3.2) Stage 2: Delegation to More Automation, Under More Conditions

This stage features the following:

- Stage 1 + more automation capabilities
  => higher degree of automation
  => useful under more driving conditions
- still full driver supervision while delegating more driving chores
- driver alertness and attentiveness monitoring continued
- useful on all roadways
- infrastructure modification begins
  - lane markers
  - infrastructure-to-vehicles-broadcast communication

Geographical Scope: all roadways
Vehicle Classes Supported: all classes
Vehicle Type: partial automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.2.1) Functional Descriptions

Functions with a "+" indicate those being added at this stage. Those with a "v" mark have been implemented in the previous stage(s). Those without that mark are to be provided at later stages.

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
+ 2.1.4 Lane changing: (turn-signaling included)
v 2.1.5 Road geometry recognition: neighboring lanes
+ 2.1.6 Obstacle recognition: limited, supervised by driver
+ 2.1.7 Obstacle avoidance: limited, supervised by driver
+ 2.1.8 Speed decision

+ 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision: limited, subject to driver approval
  2.1.11 Lane change co-ordination
  2.1.12 Platoon formation and dissipation
+ 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
  2.1.15 Vehicle entry
  2.1.16 Vehicle exit
  2.1.17 Automated highway merging
  2.1.18 Lane to lane routing within a single highway
  2.1.19 Highway to highway routing
  2.1.20 AHS flow control
  2.1.21 AHS admission control
  2.1.22 Emergency detection/monitoring
  2.1.23 Emergency Response and Incident clearing
  2.1.24 Driver Interrupt Handling

(3.2.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | adding features | potentially large market |
| Vehicle Electronics | adding features | potentially large market |
| Highway Design & Construction | adding markers & comm | profit |
| Trucking | use | more comfort, safety & prod. |
| Transit | use | more comfort, safety & prod. |
| Environmental Interests | neutral | none |
| Transportation Users | use | more comfort |
| Government Agencies | infra. investment | safety and traffic control |
| Insurance | insuring and coll. data | potentially large market |

(3.3) Stage 3: Testbed and Showcase of Full Automation

The features of this stage are:

- full bus automation: hands-off and feet-off on dedicated lane(s)
- closed system:
  - physically segregated bus and HOV lane
  - vehicles centrally maintained and inspected
- supervised by professional drivers
- technology testbed
- system benefits showcase

Geographical Scope: closed systems, e.g. Lincoln Tunnel, etc.
Vehicle Classes Supported: bus
Vehicle Type: full automation
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.3.1) AHS Function Descriptions

+ 2.1.1 Speed tracking
+ 2.1.2 Inter-vehicle separation tracking
+ 2.1.3 Lane keeping
+ 2.1.4 Lane changing
+ 2.1.5 Road geometry recognition
+ 2.1.6 Obstacle recognition
+ 2.1.7 Obstacle avoidance
+ 2.1.8 Speed decision
+ 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision
+ 2.1.11 Lane change co-ordination
+ 2.1.12 Platoon formation and dissipation

+ 2.1.13 Vehicle operational status monitoring
+ 2.1.14 Driver status monitoring
+ 2.1.15 Vehicle entry: check-in can be done at garages
+ 2.1.16 Vehicle exit
+ 2.1.17 Automated highway merging
+ 2.1.18 Lane to lane routing within a single highway
+ 2.1.19 Highway to highway routing
+ 2.1.20 AHS flow control
+ 2.1.21 AHS admission control
+ 2.1.22 Emergency detection/monitoring
+ 2.1.23 Emergency Response and Incident clearing
+ 2.1.24 Driver Interrupt Handling

(3.3.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | technology testbed | technology verification |
| Vehicle Electronics | technology testbed | technology verification |
| Highway Design & Construction | infrastructure mod. | little but high potential |
| Trucking | none | none |
| Transit | use | comfort, safety & prod. |
| Environmental Interests | support | people throughput |
| Transportation Users | transit users use | trip time reduction, comfort, safety |
| Government Agencies | investment | people throughput, cong. red. |
| Insurance | collecting data | potential large market |

(3.4) Stage 4: Segregated and Infrastructure-Assisted "Free-Agents" with Infra-V. comm but without V-V Comm.

This stage features:

- full automation on a single dedicated lane (no mixing with manual v.); no lane changing is required while merging of two streams of traffic into one is required
- infrastructure -> v. comm. required
- merging at on-ramps assisted by infra. via broadcasting of vehicle-specific instructions based on (i) vehicle id obtained at the entrances and (ii) vehicle position tracking on the mainline; (iii) speed and spacing regulation on the mainline
- "pricing out" vehicles with lower automation capabilities, e.g. those with no V<->V and infra.<->V comm.

Geographical Scope: adding or converting a dedicated lane
Vehicle Classes Supported: all + electrical and other 0-emission classes
Vehicle Type: mixing vehicles with different auto. capability
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.4.1) AHS Functional Descriptions

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
v 2.1.4 Lane changing
v 2.1.5 Road geometry recognition
v 2.1.6 Obstacle recognition
v 2.1.7 Obstacle avoidance
v 2.1.8 Speed decision
v 2.1.9 Inter-vehicle separation decision
2.1.10 Lane change decision
2.1.11 Lane change co-ordination
2.1.12 Platoon formation and dissipation
v 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
+ 2.1.15 Vehicle entry
+ 2.1.16 Vehicle exit
+ 2.1.17 Automated highway merging
2.1.18 Lane to lane routing within a single highway
+ 2.1.19 Highway to highway routing
+ 2.1.20 AHS flow control
+ 2.1.21 AHS admission control
+ 2.1.22 Emergency detection/monitoring
+ 2.1.23 Emergency Response and Incident clearing
+ 2.1.24 Driver Interrupt Handling

(3.4.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | manufacturing and servicing | potential large market |
| Vehicle Electronics | manufacturing and servicing | potential large market |
| Highway Design & Construction | infra. intel. & construction | potential large market |
| Trucking | use | prod., comfort & safety |
| Transit | use | safety, comfort & prod. |
| Environmental Interests | neutral (0-emission vehicles) | none |
| Transportation Users | use | trip time reduction |
| Government Agencies | funding | system throughput and safety |
| Insurance | underwriting & coll. data | potential large market |

(3.5) Stage 5: Segregated and Infrastructure-Assisted "Free-Agents" with Infra-V. and V-V Comm.

The main features of this stage are

- full automation on multiple dedicated lanes
- v-v and infrastructure <-> v. comm. required
- merging at on-ramps done more efficiently through the assistance by infra. via infra. <-> v. communication and v-v communication
- spontaneous platooning
- lane-changing coordinated through v-v comm.
- "pricing out" vehicles with lower automation capabilities, e.g. those that cannot platoon

Geographical Scope: more dedicated AHS lanes
Vehicle Classes Supported: all, including 0-emission ones
Vehicle Type: mixing of vehicles with different auto. capabilities,
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.5.1) AHS Functional Descriptions

v 2.1.1 Speed tracking
v 2.1.2 Inter-vehicle separation tracking
v 2.1.3 Lane keeping
v 2.1.4 Lane changing
v 2.1.5 Road geometry recognition
v 2.1.6 Obstacle recognition
v 2.1.7 Obstacle avoidance
v 2.1.8 Speed decision
v 2.1.9 Inter-vehicle separation decision
+ 2.1.10 Lane change decision
+ 2.1.11 Lane change co-ordination
+ 2.1.12 Platoon formation and dissipation
v 2.1.13 Vehicle operational status monitoring
v 2.1.14 Driver status monitoring
v 2.1.15 Vehicle entry
v 2.1.16 Vehicle exit
v 2.1.17 Automated highway merging
+ 2.1.18 Lane to lane routing within a single highway
v 2.1.19 Highway to highway routing
v 2.1.20 AHS flow control
v 2.1.21 AHS admission control
v 2.1.22 Emergency detection/monitoring
v 2.1.23 Emergency Response and Incident clearing
v 2.1.24 Driver Interrupt Handling

(3.5.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | manufacturing and servicing | potential large market |
| Vehicle Electronics | manufacturing and servicing | potential large market |
| Highway Design & Construction | intel. enhancement | potential large market |
| Trucking | use | prod., comfort & safety |
| Transit | use | safety, comfort & prod. |
| Environmental Interests | neutral (0-emission included) | none |
| Transportation Users | use | more comfort (flow stability), more trip time reduction, more safety |
| Government Agencies | funding | more throughput, safety |
| Insurance | underwriting & coll. data | potential large market |

(3.6) Stage 6: Segregated and Infrastructure-Assisted Platooning with Infra-V. and V-V Comm.

The main additional features of this stage include:

- platooning, during peak hours and perhaps on designated lanes only
- vehicles without v-v and infra-v comm. disallowed

Note: Stages 5 and 6 can be combined to provide large capacity gain faster

Geographical Scope: designating platooning lanes
Vehicle Classes Supported: all vehicle classes
Vehicle Type: mixing vehicles with different capabilities, e.g. "free-agent" vs. "platooning"
Absent AHS Functions: (See Functional Descriptions below.)
Identical AHS Functions: (See Functional Descriptions below.)

(3.6.1) AHS Function Descriptions: ALL, with platoon maneuvers, e.g., platoon lane-changing.

(3.6.2) Stakeholders' Participation

| Stakeholder | Role | Benefits |
|---|---|---|
| Vehicle Industry | manufacturing & servicing | potential large market |
| Vehicle Electronics | manufacturing & servicing | potential large market |
| Highway Design & Construction | intel. enhancements | potential large market |
| Trucking | use | prod., comfort & safety |
| Transit | use | more trip time reduction |
| Environmental Interests | neutral | none |
| Transportation Users | use | more trip time reduction |
| Government Agencies | funding | more throughput |
| Insurance | underwriting | potential large market |

## Section 4: Local Tailorability

The Infrastructure assisted concept offers the following architectural options in its stage 6 deployment. A valid combination is one choice from each of the five pairs, i.e., there are 32 local options. All are compatible with the concept.

1. platooning or free agent
2. single or multiple lanes
3. dedicated or transition lane entry and exit
4. long lane entry and long lane exit with infrastructure support in entry and exit zones only or short lane entry and short lane exit with infrastructure assistance in entry and exit zones only
5. global infrastructure supported flow control or static signage flow control

All 32 combinations are expected to be equally safe. In general, the different combinations will differ in the maximum throughput levels they can support and the sophistication of flow control they offer. Enhanced flow control capability can be used to facilitate inter-jurisdicational co-operation, corridor control, inter-modal interaction and flexible pricing. It can also be used to improve service reliability. Just as the different combinations differ in the benefits they offer, they will also differ in their investment requirements. Thus local communities may construct architectures by choosing options based on their needs. Possible dimensions defining need may be

- average area travel demand
- time of day travel demand
- travel demand by vehicle automation level
- manual vehicle travel demand
- highway real estate availability and cost
- desired benefit levels
- public investment priorities

We highlight salient features of the architectural options by discussing two examples.

Example 1: A typical rural area, after analyzing some of the given dimensions, may choose to support free agent operation, single dedicated lane, transition lane entry and exit, long lane entry and exit with infrastructure support and static signage flow control. This combination is expected to have the lowest control and communication infrastructure cost, though its real estate costs may be higher than other combinations. It also supports the largest class of automated vehicles since it has the minimal set of vehicle system requirements, i.e., systems for long vehicle following, lane keeping, gap alignment, lane-shift and signage reception. More sophisticated vehicles remain compatible.

Example 2: An urban area with high volume traffic may choose to support platooned operation, multiple lanes, dedicated entry and exit, short lane entry and exit with infrastructure assistance in entry and exit zones and global infrastructure supported flow control. This combination is expected to have the highest control and communication infrastructure costs, though also the lowest real estate requirements if new automated highways are to be built. It also has the maximal set of vehicle system requirements, though it is expected to deliver the highest level of benefit. The global infrastructure supported flow control can be used for fast and reliable incident identification and clearing, thus reducing trip time variance. It can be used for vehicle lane assignment to achieve transit priority, people priority (HOV), commercial vehicle lanes. The twin benefits of trip time reliability and priority lane assignment can support flexible pricing schemes to manage congestion and yield higher returns on investment. The tighter flow control capabilities can be used for the dynamic re-allocation of freeway capacity to balance congestion in different freeway/arterial corridors. This allows inter-jurisdicational co-ordination in the form of co-ordinated control of multiple transportation networks. Increased freeway trip time reliability and priority lane assignment to transit or other commercial traffic facilitates inter-modal planning and interfacing. The global dynamic flow control capability can be used to support time of day variations such as platooning during peak period congestion and free agent operation during lean congestion periods. It can be used to broadcast vehicle class specific separation policies for, e.g., special isolation of HAZMAT vehicles, creation of mixed class platoons or single class platoons.

# Section 5: Degraded Modes of Operation

Distributed intelligence allows robust fault tolerant operation and graceful degradation of performance (not safety) in case of failures or adverse environmental disturbances. A closer examination of the functionality of each system reveals the following information.

- The infrastructure control system is not safety critical for the operation of automated vehicles on the AHS. Therefore loss of infrastructure functionality (either due to infrastructure system failure or infrastructure to vehicle communication failure) does not compromise vehicle safety, though it may compromise throughput. The failure of the entire infrastructure control will be a rare occurrence due to its distributed design. Each link of the roadway is divided into several stretch control systems which are independent but communicate with each other and with the AHMC over a wireline network (high reliability). Therefore the probability of all the stretch control systems failing simultaneously is small. A single stretch control system may prevent optimal throughput. However, traffiic can continue to flow at a non-optimal level. Similarly a failure in the wireline network may result in some of the stretch control systems not receiving global traffic information. This may imply some reduction in throughput.
- The infrastructure controllers at the merge/entry/exit are however designed to achieve tight coordination between vehicles. This prevents capacity bottlenecks at critical network nodes. Again, because of the distributed design, the probability that all the entry or exit or merge control system will fail simultaneously is very low. The physical infrastructure could be designed so that in the event of infrastructure failure, entry/exit/merging can be executed as a regular lane change at reduced speed by vehicles in co-operative free agent mode.
- The automated vehicle with its sensors, actuators, communication devices and controllers can operate safely, by selecting between normal and degraded vehicle modes, without infrastructure assistance. There are three modes of operation for any vehicle; as a platoon leader, platoon follower or free agent. There may be different sensors and communication devices for short range and long range operation. The functionalities of these different sets of sensors and communication devices can be fused for fault tolerant operation.
- The inter-vehicle communication capability allows notification of failures to neighboring vehicles and can be used to execute emergency maneuvers so that the faulty vehicle can safely exit, or stop on the shoulder/lane. Thus, the communication (vehicle-vehicle, vehicle-infrastructure) can be effectively used to localize the extent of a fault so that the performance within a small neighborhood of the faulty vehicle is temporarily affected and the rest of the highway operation continues undisturbed.
- In case of an on-board vehicle failure, the infrastructure control system can inform the neighboring vehicles and secure their assistance in taking the faulty vehicle to the shoulder or exit.
- Special maneuver protocols and control laws are designed for emergencies and degraded modes of operation so as to ensure the safety of the faulty vehicle. These maneuvers are assigned higher priority than the normal mode maneuvers (join, split, lane change, entry, exit), thereby ensuring that the neighboring vehicles will immediately assist the faulty vehicle to execute the emergency maneuver. The faults can be classified according to their effect on the capability of the automated vehicle, and then degraded mode strategies can be designed for faulty vehicles. The purpose of the emergency maneuvers is to localize the fault and assist the faulty vehicle to stop (in the lane or on the shoulder) or take the next exit.
- In case of an incident (such as a collision, stopped vehicle, etc.), the infrastructure control

system can actively participate in dissipating the congestion and providing access to emergency vehicles.

In summary, the distribution of intelligence allows fault localization and rapid response to clear an incidents, and help the faulty vehicle to continue, or take the next exit, or stop. The platooning organization provides multiple modes of operation thereby allowing the failed vehicle to be assisted in several ways. Even vehicles with brake failures can be stopped safely with assisted braking from the preceding vehicle in the platoon. In terms of layered functionality, if the roadside control system fails or loses contact with the vehicles, the vehicles will operate in cooperative mode. If the vehicle cannot communicate with other vehicles, it will function as a free agent autonomous vehicle with highly reduced functionality until it reaches the nearest exit. If the AHMC or the communication between AHMC & sectional controller fails, the sectional controllers will operate using local information. Thus, the concept allows a gradual degradation of performance matched with failures of increasing severity, while maintaining safety.

We look at specific failures of some of the systems and the corresponding degraded modes of operation:

1. Stretch Control System: The stretch control system supplies the information to improve throughput, such as desired speeds, lane change proportions, averages delays downstream, etc. Even if this information is unavailable to the vehicle (because of the infrastructure controller being down), the vehicles can still operate as cooperative vehicles and follow the posted speed limits. There abcense of dynamic updates on downstream traffic conditions and incidents mayreduce throughput. If the infrastructure ability to detect obstacles and relay this information is lost, then the vehicles will rely solely on the on-board obstacle detection system. At this point, vehicles may reduce speed and increase the spacing so as to maintain safety. Therefore, this is not a safety critical system.
2. Entry, Exit, Merge Controller: The infrastructure based entry, exit and merge control systems are actively involved in execution of these critical maneuvers for increasing throughput. If a particular entry (exit) control system develops a failure, that particular entrance (exit) can be shut down temporarily. On the other hand, if the entry (exit) lanes are long enough, then automated entry/exit can still be carried out as a normal lane change using sensing and vehicle-vehicle communication although at a reduced speed or reduced entry rate and using free agent mode of operation. This requires a backup beacon/message sign system that informs the vehicles in the automated lane to slow down and not to engage in any maneuver. In this mode, the entrance ramp also invokes a backup entry metering system that allows entry at a slow rate. In case of merge controller failure, one of the merging highways is blocked until the controller is repaired. If the problem persists, then platooning mode is turned off and desired speed reduced near affected area to allow sufficient time for vehicles to complete their maneuvers in the space provided. Again, the performance of the system reduces due to missed exits, slow entry rate, etc. but the safety of the vehicles is not affected.
3. Inter-Vehicle Communication (Regulation): If vehicle-vehicle communication used for intra-platoon information exchange fails, then the faulty vehicle will de-platoon, and coninue as a free agent. This will have minimal effect on safety or global throughput.
4. Neighborhood Sensing System: If any of the sensors in the neighborhood sensing system fail, then the redundant sensors (or sensor readings from other sensors with data processing, e.g., acceleration information can be extracted by differentiating the speedometer output) are used. The vehicle immediately breaks up from its platoon and operates as a free agent. It will take the next exit using degraded mode maneuvers and get the problem repaired at a service station.
5. If the ability to be a free agent or a leader goes down, (e.g., multiple sensor failure, inter-

vehicle communication failure, etc.) then the vehicle can stop, either in the middle of the lane or on the shoulder if the adjacent lanes are lightly loaded and the capability to change lane using sensors still exists. On the other hand, the vehicle may still be able to function as a follower in a platoon. In this case, it can be electronically towed out (to the shoulder or the exit) by another normal operating vehicle, acting as a lead vehicle, using degraded mode maneuvers.

6. Inter-Vehicle Communication (Maneuver Coordination): If the inter-vehicle communication fails, the faulty vehicle can still operate as a free agent, but all the maneuver executions must be entirely sensor based. Thus in a dense traffic scenario, the vehicle will not be able to change lanes. If its ITS or vehicle to infrastructure communication system is working, the vehicle can notify the infrastructure which in turn may increase the inter-platoon spacing so that the faulty vehicle can change lane and exit the highway.
7. Actuation System: If the throttle or the steering actuators fail, the vehicles applies emergency braking to come to a halt. If the brake actuator goes down & if the vehicle is operating as a follower, the vehicle ahead can help this faulty vehicle to come to a halt. The faulty vehicle can be allowed to collide with preceding vehicle at a very low velocity without affecting the safety of vehicles or the passengers. The assisting vehicle can then bring both the vehicles to a stop.
8. Robust controllers are designed for some of the critical failures such as tire burst, range, range rate sensor failures, accelerometer failures, and actuator failures so that the vehicle can still function at a reduced speed and functionality.
9. The normal mode and degraded mode control laws are designed such that in inclement weather condition, the parameters of the controller (such as required gap for lane change, speed, inter-vehicle separation, etc.) can be tuned so as to maintain safety. The performance (throughput) of the system will be reduced due to inclement weather conditions. The information about the environmental disturbances is obtained via multiple sources, including broadcast from infrastructure, on-board sensors and estimation algorithms in the regulation layer controllers that identify vehicle parameters such as tire cornering stiffness, rolling resistance, road surface condition, etc.

The highly distributed and layered configuration of the system, implies that only extremely rare combinations of multiple system failures could produce catastrophic conditions.

**Degraded AHS Function Description Table**

| Degraded AHS Function | Cause of Degradation | Degraded Mode of Operation |
|---|---|---|
| Throughput Optimization | Stretch control system failure | Vehicles perform their own routing based on static info. |
| Efficient entry/exit/merging | Entry/Exit/Merging system failure | 1. Shut down affected entry/exit/merge point, or 2. Low speed free agent operation entry/exit/merging |
| Throughput | Environmental disturbances (inclement weather) | (Depending on the disturbance) Increase spacing, Decrease speed, Update maneuver control law parameters, etc. |
| A vehicle can not operate in a platoon | Inter-vehicle communication fail (necessary for follower operation) or short range sensing failure | Vehicle operates as a free agent |
| Vehicle actuation & steering | Throttle, steering failure | Vehicle stops on the highway |
| Vehicle braking | Brake failure | 1. Front vehicle in the platoon can assist to stop 2. Vehicle slowly stops by itself |
| Maneuver coordination | Inter-vehicle comm. Failure | Vehicle stops either on the road or on shoulder |
| Any | Multiple on-board systems failure | Vehicle stops |
| Sensing of surrounding vehicles or self state | Self state or neighborhood sensor failure | Vehicle uses info obtained from other sensors and communication to safely change lanes and exit or stop on shoulder. |

## Section 6: Societal and Institutional Factors

What we are looking for are societal and institutional factors, both potential advantages and disadvantages, relative to this concept that may be used as a concept discriminator to assist in the concept evaluation process. Societal and institutional factors are discussed and are felt to be concept discriminators, however, the discrimination across the two infrastructure-based concepts, supported and assisted, has thus far not been made. The differences between these two concepts with respect to these factors does need to be made.

- Being part of the MPO/State DOT planning and decision-making process

The deployment of automated highway systems (AHS) will require flexibility so that it can be shaped to fit the planning and decision-making processes at the MPO and State DOT levels. The AHS alternative will have to compete with other transportation options to address problems such as congestion and air quality. Infrastructure plays a substantial role in this concept via providing guidance to vehicles, and commands for vehicular maneuvers in specific zones. The question to ask in order to discriminate among the five concept families is the following: With what degree of ease or difficulty does this concept fit into the planning and decision-making processes at the regional and state levels? AHS having both vehicle and infrastructure systems could make satisfying this factor more complex than for other concepts.

- Public and private roles in AHS construction, operation, and maintenance

The construction, operation, and maintenance of an AHS, in particular, the funding of each of these factors, the extent of institutional involvement, and institutional inter-relationships are important factors to consider as concept discriminators. The AHS having both vehicle and infrastructure components could make this factor more complex than for other concepts.

- Liability implications and other legal issues

The identification of such legal issues is significant and will serve as concept discriminators. Such issues were explored during the PSA studies and it was concluded there that most of these are not unique to AHS and/or that they are being addressed through earlier ITS technology deployments, e.g. privacy. These issues must be monitored throughout the NAHSC process for their implications on design and deployment. The one issue that is believed to have implications unique to AHS is liability. Examples of potentially relevant legal requirements and principles include those pertaining to:

- liability for traffic accidents resulting from the transfer of control from the driver to the vehicle and/or the roadway including allocation of responsibility among the driver, vehicle manufacturer, vendors of other components, and the AHS highway authority.
- liability for accidents from catastrophic system failure

Examples of issues that could arise from application of such principles to AHS include:

- whether highway authorities or vehicle manufacturers will be subject to unacceptable liability risk for accidents caused by an AHS malfunction
- whether vehicle manufacturers will demand a high degree of standardization in AHS approaches to reduce liability risk
- whether drivers' privacy rights or the public's right to information could subject highway authorities to unacceptable liability risks

The AHS having both vehicle and infrastructure systems with an option of driving in platoons could make this factor more complex than for other concepts.

- Human in the system issues

Ensuring a very high degree of safety and driver confidence will be critical for AHS to be successful. Such assurance is complex to achieve in aviation, where operators, i.e. pilots, must have hours of training and pass certification and licensing tests. It will be more difficult in a highway environment, as vehicle operators, i.e. drivers, are likely to include anyone with a valid driver's license. Human-in-the-system factors that arise and that will differ across the concepts include the following:

- psychology of human responses to automation (willingness and comfort level associated with giving up control of driving)
- driver performance under circumstances of automated control
- acceptability of hands off vehicle movement at high speed
- ease with which driver resumes control upon transfer from automated to manual operation
- driving under conditions of lane width reduction or close proximity to physical barriers
- adaptability to driving in a platoon formation

- Integrating AHS with transit operations from an S&I perspective

Transit has the potential to have significant benefits in such roadway transportation problem areas as congestion, safety, air quality, and fuel consumption, and in addressing social equity, land use, and other environmental issues of AHS. Transit provides the opportunity for AHS to serve the needs of people and markets other than automobile owners and drivers. Transit applications, particularly in early deployments, also offer the opportunity to demonstrate AHS technologies with a group of trained drivers and users. In addition to the technical issues associated with fully integrating transit vehicles into an AHS concept, there are numerous non-technical issues as well that should be considered upon examination of the five concepts. The transit industry is an important stakeholder and it could have concerns about the extent of the technological changes associated with a particular AHS concept and the degree they may be accepted within the industry. Other concerns include the potential changing role of the driver with the potential for changes in driver training, salaries, work rules, insurance, liability, and management/labor relationships.

- Social equity considerations for AHS

An often heard concern from some AHS critics that needs investigation is their perception that AHS will not be accessible to all people and it has a responsibility to develop a system that is maximally accessible as possible at least partly since the NAHSC is a publicly funded program. AHS is viewed by some critics as "another toy for the rich". This issue of accessibility is related to cost, ability and willingness to pay, and breadth of vehicle types that are amenable to automation. For example, the successful integration of AHS with transit operations that ultimately improves transit safety, level of service, and even potentially, increases ridership could go a substantial way toward moderating the criticism of AHS as elitist. At least qualitatively, this factor is a concept discriminator.

- Transportation/land use interactions and linkages with emissions and fuel consumption

There are travel-related factors stemming from concerns over the consequences of AHS implementation and operation on how much more travel is made, by what means and its impacts on vehicle emissions and fuel usage.

The current transportation paradigm or model of "how things are done" or "the way the urban transportation system works" may be described succinctly as people driving alone in their cars on vast networks of urban freeways that over time has led to urban sprawl. The issue is that AHS, as currently envisioned by some critics, would only encourage the continuation of this same type of "business as usual" behavior, i.e. more driving, more single-occupancy-vehicle (SOV) driving, and more urban sprawl. AHS would emphasize the further development of highways and make only SOV driving more attractive by increasing its convenience and comfort at the expense of other modes of travel, such as public transit and high-occupancy-vehicle (HOV) driving.

The encouragement of more SOV driving could then mean an increase in trips, trip length, and volume of drivers, even above what such increases might be over time without automated highway systems. These effects could be the result unless there were in place strong measures to counteract them, such as (1) transportation demand management, (2) congestion pricing, (3) parking pricing, and (4) land use planning and management. The AHS program has not been viewed as having mitigating measures such as these or others at a central and important place in its research and development effort.

The concern that automated highway systems would encourage and eventually lead to an increase in driving is also referred to as the induced or latent demand effect. Recall that induced demand may be moderated by the advent of the measures such as transportation demand management or land use planning and management. Associated with induced demand is a concern for the potential increase in vehicle emissions. Several variables, however, play a role in the determination of the actual net impact on emissions.

Emissions may be affected through changes in the (1) operation of the vehicle, (2) number of drivers, (3) volume of trips, and (4) trip length. The most prevalent environmental concerns expressed about automated highway systems concerned the potential for leading to increases in volume of drivers, trips, and trip length, which on an aggregate basis in terms of total emissions' tonnage, would mean an emissions' increase. Moreover, certain pollutants, such as, oxides of nitrogen, tend to increase with increases in speed. Thus, with more freely flowing traffic and greater speeds associated with AHS, amounts of such pollutants could increase. Also, if vehicles accessing or egressing the AHS develop into lengthy queues, additional emissions' build-ups could result at the on- and off-ramps.

AHS research and development, however, will proceed along with other technological advances in areas such as emission control technologies, clean fuels, electric vehicles and other areas that could have the effect of reducing emissions on a per mile basis. Moreover, AHS associated with these two infrastructure concepts could smooth out the flow of traffic, remove or at least reduce stop-and-go, idling, and sharp acceleration and deceleration driving modes which contribute to vehicle emissions. Moreover, in the context of automated vehicles traveling with much smaller headways than presently possible, i.e., in platoons, preliminary research has indicated there are emission reductions for all vehicles, including the lead vehicle. The true net effect on vehicle emissions is unknown at the present time.

Also associated with induced demand is a concern for the potential increase in <u>vehicle fuel usage</u>. As in the case for vehicle emissions, several variables play a role in the determination of the actual net impact on fuel usage. AHS may have the impact of leading to an increase in driving, which on an aggregate basis of total fuel consumed would mean a fuel usage increase. Moreover, fuel economy is a function of speed, and increases in speed associated with AHS could lead to increases in fuel consumption. Also, if vehicles accessing or egressing the AHS develop into lengthy queues, vehicle fuel consumption would be affected.

Again, AHS R&D will proceed along with other technological advances in areas such as vehicle fuel economy in addition to possible increases in the national corporate average fuel economy (CAFE) standards that would have the effect of reducing fuel consumption on a per mile basis. In addition, AHS associated with these two infrastructure-related concepts could smooth out the flow of traffic as previously described which could reduce vehicle fuel usage. As in the case for vehicle emissions, in the context of automated vehicles traveling with much smaller headways than presently possible early research has indicated there are fuel efficiency increases for all vehicles. The net effect on fuel usage is unknown at the present time.

The infrastructure assisted concept differs from the concept of infrastructure supported AHS in that the latter functions without any infrastructure-to-individual-vehicle communication. Infrastructure supported AHS does include infrastructure-to-vehicles-broadcast communication over some given area. Overall, the two infrastructure-related concepts will likely cost more for the infrastructure but less for the vehicle, and have the potential to provide a substantially greater degree of benefits. A cost-benefit tradeoff is necessary to help understand the differences among the concepts.

## (7) Other Issues

Section 6 addresses societal and institutional issues. In this section, we address technological and other issues. We first discuss some important technological requirements for implementing this concept. We then discuss, in the context of this particular concept, the possible requirement differences between supporting platooning and supporting the free-agent vehicle following rule.

Vehicle-to-vehicle communication requires that the communicating vehicles be identified and dedicated channels can be set up. Technology must be developed to reliably perform these tasks for maneuvers like lane-changing, platoon joining, merging etc. Further concept development can benefit from the expertise of the Consortium's Technology Team.

A vehicle, in performing maneuvers, can fuse information obtained from several different sources, namely on-board sensors, on-board maps, information communicated from the infrastructure and information communicated from the neighboring vehicles. This fusion task may be complicated. Particularly, fusing microscopic information about the roadway geometry and traffic condition from the on-board sensors and from the infrastructure may require merging of relative-distance-based description of the moving vehicle's surroundings with the absolute-position-based description (actually relative to the location of the infrastructure sensors). This may in turn require accurate vehicle positioning system, perhaps to the accuracy of several meters. Whether such fusion will be required for lateral positioning remains to be seen. If it is indeed required, then the accuracy requirement is likely to be much higher. These may pose some technological challenges.

Some people have observed that much of the design task for a complex system with high safety requirements is devoted to detailed failure event analysis and to achieving fail-safety or fail-softness after failures. Such detailed analysis work is yet to be performed for this concept and may eventually result in significant changes to the concept described in this document.

In the rest of this section, we point out the major differences between supporting platooning and supporting the free-agent vehicle following rule in this concept.

We first address normal operations. The large majority of the hardware and software needed to make platooned AHS work are also needed for fully automated but non-platoon AHS. The features that would be peculiar to a platoon AHS are:

- vehicle-to-vehicle communication system capable of transferring reasonably high bandwidth control information (in the range of kilobytes per second);

- ranging sensors with accuracy of several centimeters within the range of a few meters;

- software logic for joining and splitting platoons.

Platooned operations also impose more severe performance requirements than the free-agent separation policy in the following areas.

- safety-verified cooperative maneuvering protocol;

- very fast and precise throttle and brake control actuators.

Finally, we address failure and emergency events. Since free-agent operation is a special case of platooning, the set of all possible failure and emergency events for free-agent operation is a proper subset of its platooning counterpart. In other words, platooning will incur more failure and emergency events than free-agent operation. On the other hand there are also more strategies for fault handling. Safe handling of these events may impose stringent technological requirements on system design (and perhaps requirements on driver training), which may increase the system complexity and cost.