Cooperative Concept

Tom McKendree
Hughes Aircraft Co.
714-446-2854
714-446-3234 (fax)
tmckendree@msmail3.hac.com

1. Concept Introduction

<<In future insert a table of contents here>>

1.1 Goals and Objectives

Goals and Objectives of the Cooperative Concept -

1) Achieve the Goals and Objectives set forth by NAHSC for any AHS.
2) Define a system which does not require any additional infrastructure intelligence.
3) Concept should be aligned to exploit growth in computing power.
4) Fully use ITS to the extent it is locally available.
5) Define the concept on the interface specifications and vehicle behavior specification--There should be no internal specifications on the vehicles in the National AHS specification.
   a) Note that the interface specifications include the vehicle/roadway interface, and whatever requirements are on the roadway to make more machine readable.
   b) Note also that the vehicle behavior specification will include requirements on globally useful behaviors, rather than just immediately individually useful behaviors, such as allowing other vehicles to make lane changes.

Desirable additional goals and objectives include -

6) Applicable on most or all highways (without significant modification)
7) Provide brain-off driving when mixed with manual traffic at the earliest reasonable date, in order to promote the deployment.

1.2 Concept Philosophy

Part of the conception underlying this concept is the recognition that the need for sensors, communications, and computing power is zero when there is zero traffic, and increases with traffic density. By placing the intelligence on-board the vehicles, wasteful intelligence investments where it is not needed will be avoided, and where intelligent systems are needed, they will be available.

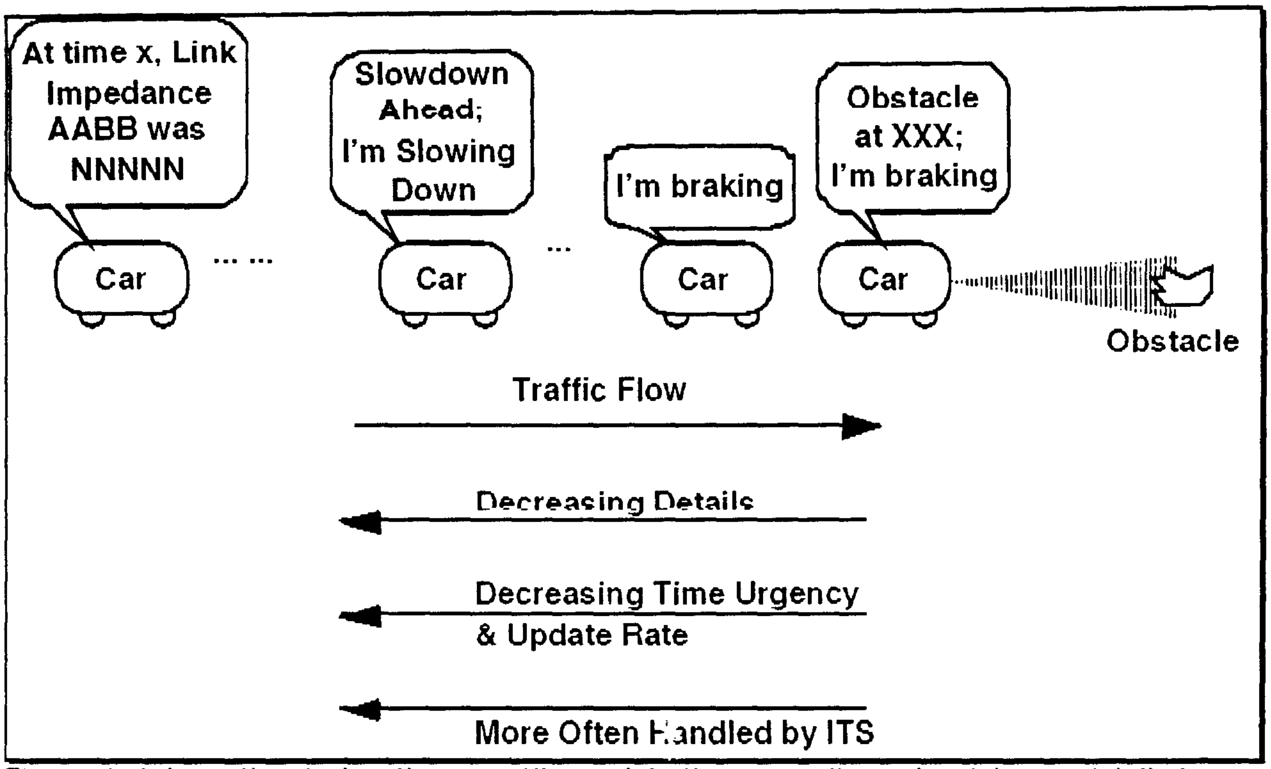

Figure 1. Information is location specific, and further away it need not be as detailed or timely.

Another part of the conception underlying this concept is the relevance of information to the vehicles. Vehicles need very detailed knowledge about their immediate surroundings. Further away fewer details are needed and the information is less time critical. The communications channel will largely be devoted to local information. In comparison it will take little additional bandwidth to pass on traffic and roadway information from further away, and that will be included in this architecture as well.

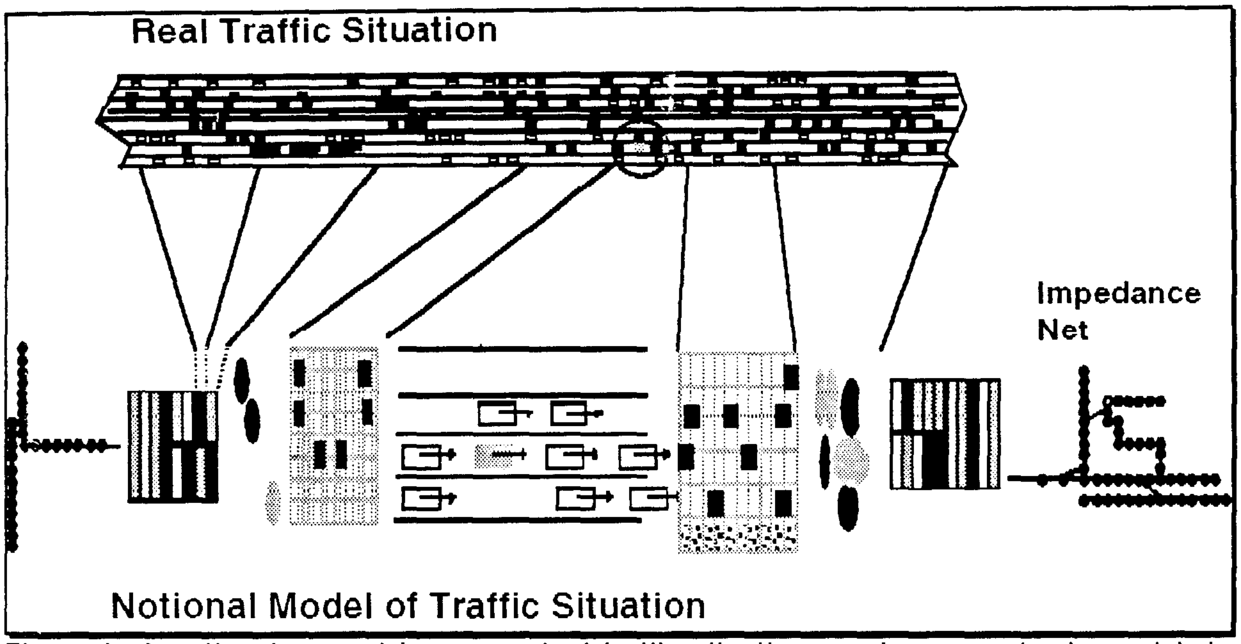

Figure 2. A notional map of how an actual traffic situation can be more simply modeled with decreasing detail at greater range.

A third part of the conception underlying this concept is how to handle communications. It is believed that the driving case for communications will be when traffic is at its densest at velocity, and then something unexpected goes very wrong (e.g., a tire blows and a vehicle is sent on an uncontrolled vector across multiple lanes, forcing everyone else to evade an incident in real time). A communications channel properly sized for this incident will have a great deal of available capacity during ordinary operations.

1.3 Communications Bandwidth Requirements

A preliminary analysis of the communications bandwidth requirements for this concept was conducted. That analysis found that the required bandwidth should fall well within the reasonable bandwidth availability for such a system. The messages considered in that analysis are listed below.

- "Lookout!"
- Sudden Obstacle Detection
- Ongoing Vehicular Mishap
- Changes to baseline vector
- Intended major changes to baseline vector
- Observed, unreported changes in other vehicles vectors
- Vector on moving obstacles
- Proposal or ratification for Contingency plan (e.g., 2 rounds proposal, 1 round vote, 1 round awk back)
- Parameter values for upcoming merge (e.g., traffic in other lane and req'd spacing density in this lane (implicit))
- Upcoming gross (e.g., logical) roadway geometry (including:)
  - Logical starting and ending of lanes
  - Block upgrade level of a stretch of roadway
  - Other gross roadway geometry information
- Summary Vehicle Characteristics
- Vehicle Characteristics
- Additional Vehicle Characteristics (broadcast at a very low rate; when vehicles quickly pass, they may not all get this message)

- Emergency command of other vehicles [when commandership is prenegotiated]
- Possibly suspicious vehicle
- "I am an Emergency Vehicle!"
  - Pull Over
- Desire for regular maneuver
- Vehicle baseline vector [and orientation difference]
- Confirmation (agreement) for regular maneuver
- Confirmation on known, fixed obstacles
- Detailed upcoming roadway geometry
- Traffic Status next few exits
- Preset Merge protocol for upcoming merge point
- Top-level description of extant platoons (size, location, speed, makeup)
- Regional Link Impedances (or equivalent info content)
- Preplan contingency plans
  - Generalized plans (o order estimate: 1 plan = 1 byte for each of up to 50 vehicles = up to ~400+ bits/plan)
- Immediate response to "Lookout!" (more if negotiated)
- Clock synchronization
- Long range map database changes
- Sensor Cross Calibration
- Alert Ordinary Gross Maneuver (e.g., Lane Change)
- Hazard Warning to Proposed Ordinary Gross Maneuver
- Ordinary Gross Maneuver Ok Acknowledge

2. Concept Reference State Description

Physical Architecture

The physical architecture description is deliberately sparse. It is an objective of this concept to not require a detailed specification on the physical architecture. In the discussion of the functions, however, some examples of physical systems which could perform some of the described functions are suggested.

Location	System Type	System Description	
Vehicle	Sensor	Name	Sensor Suite
		Function	Gather external information and monitor internal vehicle status
		Candidate Technologies	Vision system, Radar, Speedometer, tachometer, accelerometers, gyroscope, compass, etc. Multiple sensors will be used. Different vehicles may use different sensors.
	Control System	Name	On-Board Computers
		Function	Process information on-board. Includes all automated decision making.
		Candidate Technologies	Functionally dedicated CPUs, a monolithic fault-tolerant computer, neural nets for part, etc.
	Communication System	Name	Vehicle to Vehicle Communications

		Function	Non-line of sight, short range, shared mobile data channel, of TBD capacity (1/4 - 10 Mbps), with the ability to communicate across longer hops at lower data rates
		Candidate Technologies	different radio technologies
	Actuators	Name	Actuators
		Function	Translate signals from on-board computers to physical actions
		Candidate Technologies	Electric motors
	Human Interface	Name	User Interface Layer
		Function	Provide and manage the interface between the AHS and vehicle passengers, including the driver
		Candidate Technologies	Computer, user interface devices such as voice synthesis and recognition, heads up display, control buttons, etc.

Location	System Type	System Description	
Roadside	Communication System	Name	Road markings
		Function	Facilitate performance of vehicle sensors in sensing vehicle environment (particularly roadway)
		Candidate Technologies	Paint, reflective speed bumps, radar reflective strips, etc.
	Communication System	Name	Vehicle to Vehicle Communications Roadside beacon
		Function	Support passing of information between the traffic stream and the infrastructure (optional)
		Candidate Technologies	Fixed devices which include a Vehicle to Vehicle Radio, official vehicles in AHS traffic stream, with a data channel (e.g., radio or cellular) to the infrastructure
	Sensor	Name	Roadside Sensor
		Function	Monitor a section of roadway (e.g., around a curve or in a tunnel where the vehicle will not be able to see an obstacle in time)
		Candidate Technologies	Various staring and scanning sensors
	Communication System	Name	ITS

		Function	Provide ITS services beyond AHS (primarily information gathering, and passing)
		Candidate Technologies	See National ITS Architecture

Location	System Type	System Description	
Centrally Located—Not Roadside	ITS	Name	ITS Control
		Function	Non roadside ITS functions in support of ITS services
		Candidate Technologies	See National ITS Architecture
	TBD	Name	TBD (May be multiple systems)
		Function	TBD (will not be required for an effective AHS)
		Candidate Technologies	TBD

2.1. AHS Functional Descriptions

2.1.1 Speed Tracking

This function is performed by the vehicle. The on board computers receive information on position, speed and acceleration from multiple sources, and command the actuators in a manner that embodies the desired speed.

Description	From System	To System
Control signals which embody desired speed	On-Board Computers	Vehicle Actuators
Internal measurements of current speed & acceleration	Sensor Suite	On-Board Computers
Direct measurements of position (and possibly speed) relative to the roadway	Sensor Suite	On-Board Computers
Reports on apparent position, speed (and possibly acceleration)	Other vehicles	Vehicle to Vehicle Communications
Reports on apparent position, speed (and possibly acceleration)	Vehicle to Vehicle Communications	On-Board Computers
Reports on vehicle speed	On-Board Computers	Other Vehicles (via Vehicle to Vehicle Communications)

2.1.2 Inter-Vehicle Separation Tracking

This function is performed by the vehicles operating in concert, and implemented by the set of individual vehicle maneuvers.

Description	From System	To System
Control signals which embody maneuvers which maintain inter-vehicle separation	On-Board Computers	Vehicle Actuators
Measured separation, (and possibly rate of change)	Sensor Suite	On-Board Computers
Reports on apparent relative positions and velocities speed (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Reports on apparent third party positions and velocities speed (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Negotiations of policy regarding proper inter-vehicle separation (may be implicit in some cases, and includes special cases, such as making room for merges)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

2.1.3 Lane Keeping

This function is performed by the individual vehicle. Inputs from the lane-keeping sensors are compared with road curvature and any requested bias in the lane. If the vehicle is not positioned properly, a steering correction which takes speed into account is computed.

Description	From System	To System
Control signals which embody maneuvers which maintain vehicles in their proper lane	On-Board Computers	Vehicle Actuators
Measured position, velocity (and possibly acceleration) with respect to the roadway and lane markings	Sensor Suite	On-Board Computers
Joint definition of the lane geometry and position relative to the traffic	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Negotiations of policy regarding proper lane keeping (may be implicit) for special cases (such as lane changes and contingency handling)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

2.1.4 Lane Changing

The function is performed by individual vehicles.

Description	From System	To System
Control signals which embody the proper lane change maneuver	On-Board Computers	Vehicle Actuators
Measured position, velocity (and possibly acceleration) with respect to the roadway, traffic, and lane markings	Sensor Suite	On-Board Computers
Receive reports on apparent relative positions and velocities speed (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Report on other vehicle's apparent relative positions and velocities speed (and possibly accelerations) during their lane change	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.5 Road Geometry Recognition

This function is performed both by the vehicle, and by the cooperative set of vehicles. The Road Geometry Recognition function forms part of the foundation for all maneuvers. Road geometry information for upcoming roadway is transmitted (with decreasing precision for roadway further away) downstream using the vehicle to vehicle communications protocol.

As a notional hardware unit, the on-board computers could include a shared memory module with a map of the outside world, maintained and updated by the vehicle. Such a map need not encode data format that presupposes ongoing full correctness, nor do the vehicle algorithms need to be predicated on the assumption that the map is a completely accurate representation of reality.

Description	From System	To System
Relative physical position, orientation, and possibly velocity of roadway	Roadway markers	(via direct sensing) Sensor Suite
Measured physical position, orientation, and possibly velocity of roadway and roadway markers	Sensor Suite	On-Board Computers
Map of physical roadway to some level of detail	External database entry (e.g., CD ROM)	On-Board Computers
Description of roadway at different ranges, with less detail at greater range	Further vehicles	Closer vehicles
Description of roadway at different ranges, with less detail at greater range	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

Measured own position, velocity (and possibly acceleration), directly sense the roadway, traffic, lane markings, and the obstacle	Sensor Suite	On-Board Computers
Receive reports on apparent vehicle and obstacle positions and velocities (and possibly acceleration)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Report on other vehicles and the obstacles apparent relative and velocities speed (and possibly accelerations) in an intelligent (non-channel redundant) manner	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Other Protocol Signals (in accordance with invoked contingency plan)	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)
Jointly establish and follow steady-state conditions once the incident has settled down	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)

2.1.8 Speed Decision

This function is performed by the vehicle with input from other vehicles.

Description	From System	To System
Sensed external state	Sensor Suite	On-Board Computers
Informed external state	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Speed Decision (may be implicit)	On-Board Computers	On-Board Computers
Speed Intentions (may be buried within larger intentions message. May be implicit)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.9 Inter-Vehicle Separation Decision

This function is performed by the vehicle with input from other vehicles.

Description	From System	To System
Sensed external state	Sensor Suite	On-Board Computers

Description of roadway at different ranges, with less detail at greater range	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.6 Obstacle Recognition

This function is performed primarily by the vehicle. The onboard sensors detect possible obstacles, and on-board processing makes a determination. Suspected obstacles may be revisited. Multiple vehicles may examine the same suspected obstacle with their own sensors (In many situations, if there is not multiple vehicles with line of sight to the suspected obstacle, then the vehicle can change lanes on suspicion only).

The proposed physical architecture does not prohibit the addition of fixed roadside sensors, looking for obstacles, and reporting them to vehicles using the vehicle to vehicle communications protocol. To an AHS vehicle this would be indistinguishable from just another AHS vehicle that happened to be out of the traffic flow and happened to see the obstacle around the bend.

Description	From System	To System
Measured signals from outside environment	Sensor Suite	On -Board Computers
Position, velocity, and general characteristics of nearby obstacles known by other vehicles	Other vehicles (via Vehicle to Vehicle Communications)	On -Board Computers
Position and general characteristics of nearby suspected obstacles, identified by other vehicles	Other vehicles (via Vehicle to Vehicle Communications)	On -Board Computers

2.1.7 Obstacle Avoidance

This function is performed by the vehicle, in cooperation with other vehicles. There are two manners in which this function might be performed. (Note, this function was defined in the outline presupposing a separate obstacle recognition function.)

2.1.7.1 Routine Obstacle Avoidance

The first manner might be thought of as obstacle avoidances for easy situations. In this case, the obstacle (or suspected obstacle) is sensed. This may be traffic that comes upon the obstacle, or it may be a stationary obstacle, with established traffic lanes by-passing the obstacle. If the latter, then vehicles merely travel ordinarily, and happen to bypass the obstacle.

If the former, then the lead vehicle[s] identify the suspected obstacle as they approach it. The geometry is such that they easily change lanes, and avoid the obstacle, informing upstream traffic of the situation (if they cannot easily do this, then the obstacle is avoided using contingency operations as discussed below).

Description	From System	To System
Control signals which embody maneuvers wherein vehicles avoid [suspected] obstacle	On-Board Computers	Vehicle Actuators

Measured position, velocity (and possibly acceleration) with respect to the roadway and lane markings	Sensor Suite	On-Board Computers
Joint definition of the ad hoc lane geometry and position relative to the traffic	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Negotiations of policy regarding maneuvers	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Negotiations of policy regarding maneuvers	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.7.2 Obstacle Avoidance During Contingency Operations

This is an example of the more general function, Contingency Operations. These are exception operations, designed to handle suddenly difficult situations. Often, contingency operations will include passing information upstream so that following traffic will slow down, and if necessary come to a stop, before the incident, giving the vehicles immediately on the scene the time and space to deal with the problem.

The vehicles recognize the obstacle, and recognize the need to invoke contingency operations. A plan in response to the obstacle is selected through rapid messages between vehicles in the immediate area, and that plan is executed. At the end of the plan, steady state traffic flow around the obstacle is established. It's maintenance is described in 2.1.7.1.

Description	From System	To System
Propose Baseline Contingency Plan (ordinary function before contingency handling is invoked)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Proposed Baseline Contingency Plans (ordinary function before contingency handling is invoked)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Declare "Lookout!" and Invoke Contingency Plan Selection	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Receive "Lookout!"	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Contingency Plan Selection Process (e.g., 2 rounds of preference expression, 1 round of selection, and 1 round acknowledgment)	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers and Other vehicles (via Vehicle to Vehicle Communications)
Control signals which embody maneuvers which enact contingency plan maneuvers, avoiding obstacle	On-Board Computers	Vehicle Actuators

Informed external state (includes apparent roadway conditions, and braking capabilities of nearby vehicles, and requested maneuvers such as lane changes)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Inter-Vehicle Separation Decision (may be implicit)	On-Board Computers	On-Board Computers
Inter-Vehicle Separation Intentions (may be buried within larger intentions message. May be implicit)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.10 Lane Change Decision

There are three different lane change decision functions, depending on the purpose of the lane change.

2.1.10.1 Self Directed Lane Change For Navigation Decision

This function is the purely on-board decision to make a lane change. The classic example of a self-directed lane change is in preparation for making an exit, or not being in a lane which requires an undesired exit. It would also be a self-directed lane-change to move the next-to leftmost lane, in preparation for joining an approaching platoon.

Description	From System	To System
Sensed external state	Sensor Suite	On-Board Computers
Informed external state (includes apparent roadway conditions, and braking capabilities of nearby vehicles)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change Decision (may be implicit)	On-Board Computers	On-Board Computers
Lane Change Intentions (may be buried within larger intentions message. May be implicit)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.10.2 Lane Change Decision For Load Balancing

This function is the decision to make a lane change to more evenly balance the load between lanes for smoother traffic flow. Two approaches are suggested. The first is performed by individual vehicles with input from other vehicles. The second is performed by vehicles as a group, described from the perspective of a vehicle initiating the action.

Description	From System	To System
Digest of roadway conditions for next stretch of road	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

Lane Change Decision (based on implicit coordination rules)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Message to other vehicles, describing intended lane change maneuver	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Lane Change hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change ok acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

Description	From System	To System
Digest of roadway conditions for next stretch of road	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Request for a volunteer to change lanes to balance flow	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Response to request for volunteers (including declared range goal on the stretch)	All other vehicles in immediate area (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change Decision (based on coordination rules; implicit in responses to request for volunteers)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Lane Change Decision (based on coordination rules)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Message to other vehicles, describing intended lane change maneuver	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Lane Change hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change ok acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

2.1.10.3 Lane Change Decision As Part of Contingency Operations

This function is the decision to make a lane change in accordance with a contingency plan. It is performed by the vehicle with input from other vehicles (particularly, the selection of the contingency plan). In some contingency plans the lane change is explicitly called for in the contingency plan, making the decision trivial. In other contingency plans, the vehicle is responsible for determining that the contingency plan implies that it is to make the lane change (for example, a plan where the vehicles in a particular lane logically count off into groups of three, with one group swerving left and braking, one group swerving right and braking, and one group staying in the lane and braking).

It is expected that in contingency operations, vehicles will not request other vehicles to make space for them in support of a lane change—the necessary maneuvers will already have been embedded into the contingency plan. On the other hand, as contingency operations are further defined some contingency plans may be identified wherein it will be the explicit duty of vehicles (or at least some vehicles) to engage in that sort of communications.

[Data flow table not included]

2.1.11 Lane Change Coordination

This is also three different functions, depending on the purpose of the lane change.

2.1.11.1 Coordination of Lane Changes for Navigation

The vehicle wishing a lane change sends both a general intention, and proposes a specific lane change. (This specific lane change could be a one-vehicle maneuver, i.e., moving into a gap, or a multi-vehicle maneuver, i.e., create gap, and then move in.) All vehicles directly involved with the maneuver must acknowledge back ok before the maneuver starts. A vehicle that senses or infers a possible hazard with a proposed maneuver can alert others of the problem.

The data flow below is from the point of view of a vehicle wishing to change lanes. (The vehicle must be able to generate and send the symmetric messages when other vehicles change lanes.)

Description	From System	To System
Message to other vehicles, alerting of desire to change lanes	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Message to other vehicles, describing intended lane change maneuver	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Lane Change hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change ok acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

2.1.11.2 Coordination of Lane Changes for Load Balancing

In lane changes for load balancing, the lane change decision will have been publicly made among the vehicles in the immediate area, and the lane change will have been coordinated within that decision process.

[Data flow table not included]

2.1.11.3 Coordination of Lane Changes for Contingency Operations

A selected contingency plan will (implicitly) include the coordination of lane changes called for in that plan.

[Data flow table not included]

2.1.12 Platoon Formation and Dispersal

Platooning remains a crosscutting issue. This concept will support platooning if desired.

That vehicles desire to platoon, and information on extant platoons, are propagated long distances in the traffic flow. Interested vehicles maneuver together and form up platoons where possible. Platoon dispersal is handled within the platoon.

Note, in this cooperative concept, high throughput formations analogous but not identical to platoons may be possible.

The data flow below is from the point of view of a vehicle wishing to platoon. (Non-platooning vehicles must still support message passing up and down-stream.)

Description	From System	To System
Desire to platoon and desired platoon characteristics	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Description of extant platoon	Other vehicle, within the platoon (via Vehicle to Vehicle Communications)	On-Board Computers
Digest of extant platoons and platooning desires up/down stream	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
New Platoon initiation	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Platoon Maintenance Parameters	Other vehicle in platoon (determined by Platooning protocol)	On-Board Computers (via Vehicle to Vehicle Communications)
Platoon Maintenance Parameters	On-Board Computers	Other vehicles in platoon (via Vehicle to Vehicle Communications)
Platoon Join Request	On Board Computers	Other vehicles, in platoon (via Vehicle to Vehicle Communications)
Platoon Join Acknowledgment	Other vehicle in platoon (determined by platooning protocol)	On-Board Computers (via Vehicle to Vehicle Communications)
Message to other vehicles, alerting of desire to exit platoon	On-Board Computers	Other vehicles (particularly in platoon) (via Vehicle to Vehicle Communications)
Message to other vehicles, describing intended platoon exit maneuver	On-Board Computers	Other vehicles (including nearby vehicles not in the platoon) (via Vehicle to Vehicle Communications)
Platoon exit hazard warning	Other vehicles (including nearby vehicles not in the platoon) (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change ok acknowledge	Other vehicles (possibly including nearby vehicles not in the platoon) (via Vehicle to Vehicle Communications)	On-Board Computers

2.1.13 Vehicle Operational Status Monitoring

The AHS vehicle will perform a complete operational status check before entering automated mode, and ongoing checks during automated operation. These tests will occur in every element of the physical architecture, including the On-Board Computers. The AHS vehicle will not enter automated mode if the operational status check is not passed.

(Note: A vehicle which is traveling in automated mode when it detects a failure will follow pre-programmed logic which will depend on the severity of the failure and the vehicle's understanding of the roadway state at that time. The action dictated by the logic may for example be to get off at the next exit, move to the shoulder and stop, hand over control to the driver (depending on the results of this cross-cutting study), or stop in the lane.)

Description	From System	To System
Operational Status Check	On-Board Computers	Vehicle to Vehicle Communications
Operational Status Check	On-Board Computers	Sensor Suite
Operational Status Check	On-Board Computers	Actuators
Operational Status Check	On-Board Computers	User Interface Layer
Failure or Ok message	Vehicle to Vehicle Communications	On-Board Computers
Failure or Ok message	Sensor Suite	On-Board Computers
Failure or Ok message	Actuators	On-Board Computers
Failure or Ok message	User Interface Layer	On-Board Computers
User Notices and Alerts of Automated Failures	On-Board Computers	User Interface Layer
Notices and Alerts of Automated Failures	On-Board Computers	Other Vehicles (via Vehicle to Vehicle Communications)

2.1.14 Driver Status Monitoring

The AHS vehicle will be able to perform a driver responsiveness check when appropriate. This function would be performed by the driver interface layer. Details deferred pending completion of the appropriate cross-cutting study.

[Data flow table not included]

2.1.15 Vehicle Entry

In order to minimize malfunctioning AHS vehicles and harmonize entering vehicles with the traffic and communications flow, AHS vehicles will be checked in by other AHS vehicles on the roadway.

The proposed physical architecture does not prohibit the as a local option the addition of check-in beacons controlling physically barriers, preventing rogue manual vehicles and malfunctioning AHS vehicles from entering the roadway.

2.1.15.1 Solo Normal Entry

On an uncontrolled AHS roadway, when there are no other vehicles around, and AHS vehicle determines that fact, and merely drives onto the roadway. The vehicle maintains an active communication system that will alert other vehicles on approach.

Description	From System	To System
Lack of communications	Vehicle to Vehicle Communications	On-Board Computers
Sensing roadway, with no traffic seen	Sensor Suite	On-Board Computers
"Hello, I'm here" message	On-Board Computers (through the Vehicle to Vehicle Communications)	Nearby Airspace (and thence to any other vehicles which enter range)
Control signals which embody the proper entry maneuver	On-Board Computers	Vehicle Actuators

2.1.15.2 Normal Entry Into Traffic

The vehicle announces its approach to the roadway, and establishes a communications link with the other vehicles. Those vehicles inform the approaching vehicle of roadway conditions (including detailed traffic information), and perform a remote check in test on the vehicle. If passed, the vehicle then enters the traffic flow as an ordinary logical maneuver (similar to a lane change).

The table below is constructed from the perspective of a vehicle trying to enter the roadway, but all vehicles must be capable of generating the symmetric messages.

Description	From System	To System
"Hello, I'm here" message	On-Board Computers	Other Vehicles (via Vehicle to Vehicle Communications)
Roadway and traffic status messages	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Check in Test Message	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Check in Test Response	On Board Computers	Other Vehicles (via Vehicle to Vehicle Communications)
Check in Pass Acknowledgment	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Check in Failure Notification	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Message to other vehicles, alerting of desire to enter traffic	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Message to other vehicles, describing intended entry maneuver	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Entry hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Entry OK acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Control signals which embody the proper entry maneuver	On-Board Computers	Vehicle Actuators
Measured position, velocity (and possibly acceleration) with respect to the roadway, traffic, and lane markings	Sensor Suite	On-Board Computers

Receive reports on apparent relative positions and velocities (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Report on other vehicle's apparent relative positions and velocities (and possibly accelerations) during their entry	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.16 Vehicle Exit

As the vehicle approaches the exit, the user interface layer alerts the driver to take control. The driver takes control, and the On-Board computers monitor the driver's performance. If the driver does not satisfactorily take and execute control, then the on-board computer continue or take back control of the vehicle. If the driver cannot take back control to make an exit, the vehicle should have the option of going to the next emergency exit location, where the vehicle will pull off of the highway and stop, and the driver may take over manually while parked. Assuming the driver does provide adequate control, then the driver manually drives off the freeway at the exit and continues. During the whole period until after the vehicle has left the highway, it stays within vehicle to vehicle communications, announcing its location, and monitoring the traffic. Note that "under manual control," and "exiting the AHS system" are logical characteristics of the vehicle that will be broadcast.

This description is predicated on the assumptions that automated driving mixed with manual traffic will prove feasible (at least in this limited case), and that process described is appropriate given human factors concerns. Either may not prove correct, which would alter the exit function from what is described here.

Description	From System	To System
Alert driver of approaching exit	On Board Computers	User Interface Layer
Driver prepared to take control	User Interface Layer	On-Board Computers
Driver control commands to vehicle (on resumption of control)	User Interface Layer (From Driver)	On-Board Computers, or non-AHS portion of vehicle
Measured signals from vehicle and outside environment	Sensor Suite	On -Board Computers
Exterior reported information	Other vehicles (via Vehicle to Vehicle Communications)	On -Board Computers
Control signals which embody the driver's commands (optional approach)	On-Board Computers	Vehicle Actuators
Receive reports on apparent relative positions and velocities speed (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers

Report on other vehicle's apparent relative positions and velocities speed (and possibly accelerations) during their lane change	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.17 Automated Highway Merging

Merging of the traffic streams from two AHS roadways will involve preparation of the traffic upstream, and be performed jointly by the vehicles. Well upstream, each traffic stream will have logical traffic data, including traffic densities, of both traffic streams. This will create a slightly more than sufficient density of gaps in the merging lanes for efficient merging. As the traffic streams approach, specific vehicles and gaps will be aligned, and the traffic will merge.

The data flow table below assumes the approach for pre-merge traffic spacing will be one candidate approach for load-balancing lane changes. This may be revisited, and additional approaches are expected.

Description	From System	To System
Logical traffic information (including traffic densities and merge protocol)	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Pass on logical traffic information	On-Board Computers	Other Vehicles (via Vehicle to Vehicle Communications)
Message to other vehicles, describing intended lane change maneuver (out of future merge lane, to create space)	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Lane Change hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Lane Change ok acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Control signals which embody the proper lane change maneuver	On-Board Computers	Vehicle Actuators
Measured position, velocity (and possibly acceleration) with respect to the roadway, traffic, and lane markings	Sensor Suite	On-Board Computers
Receive reports on apparent relative positions and velocities (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Report on other vehicle's apparent relative positions and velocities (and possibly accelerations) during their lane change	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)
Logical assignment (vehicle to gap) before merge	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

Pass logical assignment (vehicle to gap) before merge upstream	Vehicle to Vehicle Communications	Other Vehicles
Merge hazard warning	Other vehicles (via Vehicle to Vehicle Communications)	On Board Computers
Merge ok acknowledge	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Control signals which embody the proper merge maneuver	On-Board Computers	Vehicle Actuators
Measured position, velocity (and possibly acceleration) with respect to the roadway, traffic, and lane markings	Sensor Suite	On-Board Computers
Receive reports on apparent relative positions and velocities (and possibly accelerations)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Report on other vehicle's apparent relative positions and velocities (and possibly accelerations) during their lane change	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

2.1.18 Lane-to-Lane Routing Within a Single Highway

Lane selection on an AHS highway is done by the vehicles, based on the on board map of the roadway stretch, the vehicle's navigation objectives (e.g., does it need to make a particular exit coming up), and lane-specific information on traffic along the stretch of roadway. The vehicle's choice will include lane selection for the purposes of flow optimization and traffic control around an obstruction.

[Data flow table not included]

2.1.19 Highway-to-Highway Routing

The choice of highways to get the vehicle from its AHS entry point to its AHS exit is made by the vehicle using the vehicles navigation objective (e.g., "I am trying to reach location X"), and information from its on-board region map, which will include received information on the near real-time status of the roadway. For segments a long distance away, the roadway status may be as simple as link impedances. Much of this information may be provided by ITS, where available. The navigation objective will have come from the user, via the user interface, and may include such items as fastest route, scenic route, or specific requested waypoints.

[Data flow table not included]

2.1.20 AHS Flow Control

Flow control is performed by the network of vehicles, using the shared knowledge about the traffic situation, and coordination rules for flow control.

[Data flow table not included]

2.1.21 AHS Admission Control

Admission control is performed by the vehicles based on the distributed traffic picture of the region. When traffic patterns are dense, vehicles may be delayed on their entry during the check in procedure, but only in accordance with rules defining how traffic patterns justify what vehicle entry delays. Default rules for this will be included in the AHS specification (interface and behavior specifications).

AHS Admission control policy could be set on particular roadways by local transportation authorities, which must provide some data link (Vehicle to Vehicle Communications beacon or ITS) to inform vehicles of the local policy. infrastructure based on current average speed and throughput for the highway segments under control of the TOC, knowledge of usual daily, weekly and annual traffic patterns, and on reports from adjacent TOC's. The commands to implement the desired flow patterns are communicated to the vehicles through a roadside beacon at the entry ramp.

The proposed physical architecture does not prohibit roadside devices using the Vehicle to Vehicle Communications protocol and physically controlling an entry. Such infrastructure could be used for firm AHS Admission Control, if desired.

[Data flow table not included]

2.1.22 Emergency Detection/Monitoring

Emergency detection is performed *in situ* by the vehicles. As part of the basic traffic information, the fact of the emergency is propagated up and down stream. At some point it may be detected by ITS services, most likely be listening in on the AHS communications traffic stream. ITS may then send the information to emergency response vehicles, and more broadly in the region.

[Data flow table not included]

2.1.23 Emergency Response and Incident Clearing

Immediate emergency responses are handled by vehicles on the scene through contingency operations. Knowledge of the incident is quickly propagated through the traffic streams, and emergency vehicles can quickly respond to the incident.

Description	From System	To System
Roadway and traffic status messages (Including incident information, knowledge of approaching emergency vehicles, and digest of prohibited roadway)	Other Vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
"I am an emergency vehicles, clear the way!"	Other [Emergency] Vehicle	On Board Computers (via Vehicle to Vehicle Communications)
Description of prohibited roadway (due to roadwork, such as clearing an accident)	Other [Emergency] Vehicle	On-Board Computers (via Vehicle to Vehicle Communications)

2.1.24 Driver Interrupt Handling

Details deferred pending completion of the appropriate cross-cutting study.

[Data flow table not included]

2.1.25 Select Preferred Contingency Plan

When contingency operations are invoked, it becomes necessary for each vehicle to rapidly express its preference on the contingency plan to be jointly enacted. This creates the need for a very fast acting function "select preferred contingency plan."

One candidate physical implementation might be using a neural net. With a possible pallet of ~1000 plans, this would call for ~1000 neurons (with fully cross-inhibited links) for selecting the plans, and a lot more for processing and reducing information. A SWAG is that this requires ~16k neurons able to converge in less than half a millisecond, and a larger neuron set would implement a better algorithm.

Description	From System	To System
Sensed external state	Sensor Suite	On-Board Computers
Informed external state (includes apparent roadway conditions, and braking capabilities of nearby vehicles)	Other vehicles (via Vehicle to Vehicle Communications)	On-Board Computers
Select preferred contingency plan	On-Board Computers	On-Board Computers
Announce preferred contingency plan	On-Board Computers	Other vehicles (via Vehicle to Vehicle Communications)

3. Deployment Stage Variation

The Cooperative Concept is an open standard Market driven concept. The deployment path follows two main lines, the "Official AHS" line, and the "Beyond AHS Activities" line. Only the official AHS line is within the influence of NAHSC. Five stages are summarized, although, the fifth stage is really multiple stages.

Stage	1	2	3	4	5
Name	***Pre-AHS***	***Prototype and Early Automation***	***Operational Test and Enhanced Operations***	***Full AHS***	***Follow-On AHS***
Milestone To Begin Phase	NAHSC initiated	Prototype Evolved AHS Standard (block 0.8) Released	F[illegible]t Operational Test Opens	Release of Full Deployment AHS Specification (If mixed with manual then feasible); or first Full Deployment	Official release of Major Block Upgrade to AHS Specification

Official AHS Activities	Workshops, '97 Demo, Develop & refine concept, Develop Draft Specification, Specification with Prototype	Continued research to refine AHS specification, Development of baseline for Operational Tests, Selection, design & construction of operational tests, Release AHS Specification block 0.9	Complete rollout of operational tests, evaluate operational tests, continue research on full AHS (particularly feasibility of mixed with manual, if appearing promising), Develop AHS specification for full deployment, Release AHS Specification block 1.0	Roll-out full AHS, certify vehicles as "AHS Compliant," Monitor rollout, collect information on difficulties, collect new message types,	Continue to certify "AHS Compliant" vehicles (now by Block level), monitor and evaluate ongoing AHS use, collect additional messages types (if any), Release further follow on's to AHS Specification
Capabilities of Official AHS	Demo, improving definition and simulation of concept, prototype test	Test-track workable AHS, Extensive test to refine concept in preparation for operational test	Deployable AHS with constraints	Full AHS capability (including high throughput on dedicated lanes) (Hopefully mixed with manual possible)	Greater processing power, more accurate sensors, more accurate and faster responding actuators
Beyond AHS Activities	ITS Development, Non-consortium research on AHS,	Attempted development of automated vehicles for ordinary highways, Deployment automated vehicles for ordinary highways if feasible, Deployment of foreign precursor AHS systems, Deployment of ITS, possible deployment of truck convoys, wider deployment of obstacle alert, drive by wire increasingly fielded	Growth and "rooting" of ITS, Development of Automated vehicles for ordinary highways if feasible, Deployment of AHS for ordinary highways if feasible (hopefully choosing to embed the AHS comm spec.)	Other stakeholders add "extensions" to AHS Communications protocol, Growth and "rooting" of ITS (particularly if mixed w/ manual possible), development of automated surface street capabilities (& perhaps eventual deployment)	Continued development and deployment non-highway automated driving, Eventually, development of AHS capabilities on non dedicated roadways, and eventually full trip automation

Beyond AHS Capabilities	Adaptive Cruise Control, Lane Departure Warning, Lane Keeping (not with ACC), Obstacle Detection, Vehicle Detection, Onboard Road Condition Sensors, Roadside-to-Vehicle Communications, Drive by wire feasible	Some obstacle avoidance capability	Possibly mixed with manual,	Mixed with manual more probably,	Probably, a number of capabilities which will then be very significant, but which are not predictable

It is expected that in the operational tests, various forms of "cheating" will be allowed to make the test more feasible. Nonetheless, that "cheating" should be in a form that is as nearly compatible to the final AHS as possible. For example, even if the full roll out system is capable of fully automated driving mixed with manual traffic, the operational tests may be on dedicated lanes, with only AHS vehicles allowed. One possible operational test would be to deploy a full system, but with a large subsidy (~$10k) per vehicle to make the system affordable for the operational test. Another possible operational test would be to deploy more limited vehicles, able to use all the messages in the communications protocol, but not able to generate many of the messages (e.g., road and traffic digest information) in real time. Deployed along with these vehicles would be a heavy infrastructure support system along the AHS roadway, generating and sending the remaining messages. A third possibility would be to add more extensive machine readable features to the operational test roadway than are intended for the full deployment.

A concern is that during stages 2 or 3 a competing standard would emerge from the "Beyond AHS" track. The two candidates for competing standards are Foreign government standards and de facto evolutionary standards from industry. Technical challenges may minimize this threat. It is also hoped that the early promulgation of draft AHS standards (0.8 and 0.9) will avoid the worst problems by inducing any competing AHS standard to include "hooks" so that it could interoperate with NAHS standard vehicles.

3.1 Stakeholder Benefits

Expected Stakeholder Role/Benefits Vs Deployment Phase

Phase	*Pre-AHS*	*Prototype and Early Automation*	*Operational Test and Enhanced Operations*	*Full AHS*	*Follow-On AHS*
Vehicle Electronics	Help shape a major candidate electronics business, define a slice of bandwidth?	Shake down technology and improve confidence in major future market	Sell substantial vehicle electronics with Federal subsidy, build market share for major future market,	Huge market for vehicle electronics, (possibly increased market for roadside electronics) for orig. equip. and for retrofit	Continued huge market for vehicle electronics, spur to upgrade sales, less "commodidization" of market

Highway Design and Construction	Concurrent engineering input to avoid major future headaches	Improved confidence in estimates of future highway construction needs (including high throughput entry/exit)	Probably, heavy highway construction/ modification in 1-3 areas, possibly including significant roadway preparation and accommodation to roadside infrastructure	widespread high-way modification to entry/exit points for increased throughput	Support various specialized AHS physical needs. Details hard to foresee
Trucking	Concurrent engineering input to avoid major future headaches; better chance AHS will serve real trucking needs	Possibly spin-off truck convoys, greater upward compatibility with future AHS	Greater speed, trip time reliability and throughput on OTs, Likely spin-off truck convoys, upgradeable to future AHS	Greater speed, trip time reliability and throughput across highway system (reduced costs), greatly reduced driver error hazard from other traffic	Continued high speed, trip time reliability and throughput across highway system, improved safety and system performance
Transit	Concurrent engineering input to avoid major future headaches, better chance AHS will serve real transit needs	Possible spin-off transit features, improved safety and situational awareness	Greater speed, trip time reliability and throughput in OTs, Federal money for Operational Test, transit investments are upgradeable to future AHS	Cost savings, more reliable service to compete for more market share	Continued high service quality, additional details hard to foresee
Environ-mental Interests	Concurrent engineering input to minimize future environmental problems with AHS	Research may indirectly help spur the development of low and zero emissions vehicles	In OT areas reduction in emissions per vehicle mile due to smoother driving and much less "highway stall," potential for very detailed highway behavior/pollution research	reduction in emissions per vehicle mile; possibly narrower lanes in urban & intercity rts.	Continued benefits, new benefits reasonably likely with block upgrade, but details hard to foresee
NAHSC Core	Continued research funding, sense of centrality, chance to shape the destiny of highway travel				Continued research to upgrade and expand the protocol

Phase	***Pre-AHS***	***Prototype and Early Automation***	***Operational Test and Enhanced Operations***	***Full AHS***	***Follow-On AHS***
Trans-portation Users	Excitement about future driving possibilities,	ITS and possible spin-off AHS features improve safety and situational awareness,	In OT regions, greater speed and throughput, Driver fully disengaged: Shorter, more reliable trip times, less chance of secondary accident Spin-off vehicle sensors increase safety and decrease stress for non-OT vehicles	Greater speed and throughput, Driver fully disengaged: Shorter, more reliable trip times, less chance of secondary accident: hopefully, immediate AHS applicability across entire highway system	Continued high speed, trip time reliability and throughput across highway system, improved safety and system performance, possibly full trip automation, additional details hard to foresee
Government Agencies	Recognition for being forward looking, function which can claim to require government, ongoing small budget	Set preliminary AHS standards, ongoing noticeable budget	Opportunity to conduct large OTs (with significant budget), Set AHS standards; gain public confidence in and acceptance of automated vehicles	Avoid expensive and hard to fund maintenance costs, vast increase in data on incidents from "black boxes," Help maintain and enforce AHS standards, direct association with a major public priority (personal transportation), good will from public for success	Continued need to upgrade and improve protocol, ongoing research budget
Insurance Industry	Concurrent engineering input to minimize future insurance risk (and address other insurance concerns)	Provide advice in development plans to assure novel liabilities are well defined and tightly controlled	Reduced highway losses in the OT areas. Reduced losses of automated highways from vehicle sensor warnings. Very detailed collision information (from black boxes) help detailed safety improvement plans and detailed actuarial analysis, chance to shakedown actuarial models in preparation for national AHS rollout	Reduced losses nationwide, Heavy suppression of fraud and reduced litigation uncertainty from detailed incident data (black boxes), able to fold detailed data into national actuarial analysis,	Continued high safety, evolved security capabilities, additional details hard to foresee

4. Local Tailorability

Formal local tailorability in this concept is primarily limited to ordinary freedoms in roadway design. This concept does not impose special constraints on the physical structure of the highway (although it may induce indirect changes, such as requiring the ability to handle a much higher vehicle rate on entry and exit). The principle AHS-specific option for local tailorability is the ability to designate specific stretches of highway as certain "block upgrade" levels, prohibiting lower level vehicles from traveling on those stretches. The other principle AHS-specific option for local tailorability is to allow localities to specify stretches of roadway as restricted to AHS only traffic. (Depending on how well platooning performs, vehicles may platoon on AHS-only roads.)

The proposed architecture does not prohibit as a local option that localities could accomplish all the functions of infrastructure support and infrastructure management through the use of roadside beacons which communicate to the vehicles via the Vehicle to Vehicle communications protocol.

5. Degraded Modes/Robustness of Reference State Concept

In this concept, there is no central infrastructure to fail, and thus no degraded performance from this quarter. Vehicles may fail, and the other vehicles operate around the failed vehicles (in the worst case, this will create an incident that will need to be cleared). All vehicles are capable of running manually of AHS, a degraded mode that could be invoked in an emergency. If the vehicles can operate automated mixed with manual, then they will be able to operate autonomously if the vehicle to vehicle communications channel is lost.

6. Societal and Institutional Issues

Among the societal and institutional issues:

A. AHS enforcement vehicles (e.g., CHP) must be able to identify specific nearby vehicles as the source of particular messages. Failure to follow the vehicle behavior specification is a publicly evident infraction, and should be grounds for the equivalent of at least a "fix it" ticket.

B. Part of the enforcement mechanism is the placing of virtual tags on vehicles. If a vehicle acts inappropriately, that error can be identified by ordinary vehicles, and henceforth vehicles can inform each other "that vehicle broke rule X," along with a fast moving message up and down the traffic stream "Rule [X] broken at location ABC, violator being watched." From a legal standpoint, this is likely analogous to "hearsay," insufficient for conviction, but probable cause for pulling a vehicle over for warning and investigation.

C. Vehicles may be required to carry a "black box" that records the recent history of the vehicle and its environment. This could be very useful in reconstructing incidents, both for safety improvements and legal reasons.

7. Other Issues and Concluding Remarks

7.1 Technology Needs and Interests

A very preliminary list of technical needs and interests inspired by this concept includes:

- Estimate capabilities of low cost, short range (side looking) sensors
- Is a radar-reflective paint feasible that could also be used as a standard paint in highway markings?
- How feasible would be highway reflectors (or Bots dots) that are also radar reflective?