Free Radical Concept

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1. Concept Introduction

The Free Radical Concept is best characterized as fully autonomous vehicles capable of driving in both mixed traffic and on dedicated AHS lanes. This concept concentrates the automated driving intelligence on-board the vehicle such that infrastructure-based intelligence and support is used where available, but is not required for AHS operation. By blending vehicle-based intelligence with ITS-based services, the Free Radical Concept ensures that AHS is available on every freeway and to all social classes and user communities. It minimizes physical and electronic infrastructure costs, provides an immediately deployable system, and allows communities to implement traffic management services only where needed for congestion relief. This concept heavily favors affordable private-sector investment, rather than depending heavily on government funding for new roadways and services.

The Free Radical Concept has been developed based on a fundamental understanding of how the system can best be deployed. Two options present themselves: deploy AHS exclusively on dedicated lanes, or evolve the system with existing and developing technologies within the mixed traffic environment. It is recognized that the transition lanes into and out of the dedicated lanes create a mixed traffic environment, leaving new AHS lanes with dedicated on- and off-ramps as the only viable alternative to dealing with mixed traffic. New dedicated lanes with new entrances and exits are attractive, yet have several downfalls. First, they are expensive. Second, they severely limit the market penetration by limiting regions and communities within those regions in which AHS can be deployed. The Free Radical Concept not only accepts operation within mixed traffic as technically achievable, but views this type of evolutionary deployment as favorable for market penetration, social and regional equity, and social acceptability.

Potential Benefits of the Free Radical Concept

The Free Radical Concept envisions four primary benefits from the market-driven deployment scheme:

- ☐ Maximum use of existing infrastructure;
- ☐ In-vehicle technology leading to spin-offs;
- ☐ An appropriate and cost-effective blending with ITS services;
- ☐ Safety and convenience features lead to market-driven system upgrades.

Each of these benefits will be discussed briefly below.

The Free Radical deployment plan envisions using as much existing freeway infrastructure as possible. Where viable and beneficial, new dedicated lanes can be built early on, however this concept prefers to transition existing freeway lanes into dedicated lanes once an appropriate market penetration is achieved. This ensures the maximum use of existing infrastructure and minimizes government expense for building new roadways.

The second benefit is that of spin-off technology, which is a notable side effect of placing most of the automation technology within the vehicle. These technologies can gradually be utilized on non-AHS roadways in a limited fashion. Our nation's freeway system carries 30% of the traffic load; the freeway system is the appropriate place to begin the process of automation, but certainly is not the only place that can benefit from automation capabilities. The spin-off technologies of the Free Radical Concept will not only provide greater safety, but also greater throughput gains on the heavily utilized arterials and rural roads throughout our nation.

Thirdly, the ITS and AHS programs must blend appropriately so as to maximize the use of existing resources. The proposed ITS features, when coupled with automated AHS vehicles will satisfactorily support the throughput and safety gains as well as the convenience features desired by both programs.

Lastly, AHS will be upgradable not only during the deployment cycle, but beyond the "final product" as it is now conceived. The Free Radical Concept begins by promoting enhanced safety and convenience features that are appealing to the new car buyer. Because of the emphasis on user-driven conveniences, the vehicle and electronics industry will continue to upgrade these capabilities to satisfy user demands. Many engineering projects loose usefulness because the technology becomes outdated and the system becomes expensive to upgrade. This can be avoided by developing autonomous vehicles that provide new, user-driven services and capabilities each year.

The market-driven deployment cycle of the Free Radical Concept is presented in Figure 1-1.

2. Concept Reference State Description

The Free Radical Concept supports all vehicle classes, including light, medium, heavy, articulated light, and articulated heavy vehicles. This concept is characterized by fully autonomous vehicles with highly sophisticated on-board sensors and processors. In the Reference State, it will have evolved from being fully integrated with mixed traffic to operating on dedicated freeways. These dedicated freeways are currently existing, manually driven roadways which are transitioned *one lane at a time* from manual to automated. Incrementally greater throughput gains are anticipated at each step in this transition process. It is possible that the rural roadways will never have a fully dedicated lane because two-lane (each direction) roadways will always require the left-hand lane for manual-vehicle passing. This concept thus allows AHS to be deployed in all environments, with throughput and safety enhancements achieved in the urban centers, and convenience and safety enhancements achieved in the rural environments.

AHS-vehicles are harmonized with the roadway via ITS-provided services. These services include (but are not limited to) traffic flow support, travel demand management, incident management, public transport management, route guidance, and en-route driver and transit information. ITS capability *supplements* the autonomous vehicle capability—together, they provide the safety and throughput gains of automated vehicles[1] with the additional throughput gains achievable with infrastructure-based information and planning.

The interaction of AHS and ITS as separate programs is an extremely appealing feature of this concept. The following items are noteworthy aspects of this programmatic separation:

- The vehicle is responsible all control and decision making.
- The infrastructure provides information which can be used in the decision-making process. This implies that the infrastructure takes on no liability for the behavior of the vehicles.
- There is equitable deployment in the urban and rural regions, as the AHS system can function without any ITS being available.
- This concept does not require a huge expenditure of funds for the development and maintenance of an electronic infrastructure that is capable of controlling vehicles.

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[1] It is important to note that the precursor studies identified a major source of congestion to be from non-recurring incidents. Throughput improvements are not only a direct product of autonomous vehicles on dedicated lanes; they are also a *outgrowth* of safety improvements that are immediately realizable in the mixed-traffic environment.

Free Radical passenger vehicles, buses, and trucks are capable of operating either individually or within small convoys with reduced headways. These convoys are made possible due to the on-board sensors and processors that ensure quick reaction times to events on the roadway. Vehicle-to-vehicle communication allows AHS vehicles to identify one another; because the behavior of AHS vehicles is far more predictable than that of manually driven vehicles, two automated vehicles may close the gap using the communication loop for emergency braking only. For the transit and trucking industry, it will be possible to have drone follow-on vehicles that can be deposited and picked up at strategically important locations. This virtual coupling of trucks and buses will allow for the use of smaller vehicles which can be optimally linked as a function of the time of day, location, and cargo/passenger loading.

Vehicle flow optimization is being developed for ITS that optimizes flow given the number of vehicles within each link of a network. This optimization is done without knowing origin/destination pairs for each vehicle within the system. The Free Radical Concept recognizes that additional gains in throughput are achievable with additional central control. This concept will support supplementary AHS-provided optimization, however issues of personal privacy and benefit-to-cost ratio are major considerations in this decision.

The Free Radical Concept will accommodate and support both full driver disengagement as well as driver engagement.

A representational diagram of a potential system architecture is shown in Figure 2.1, below. Table 2.1 presents the details of this physical architecture in the Reference State.

Pre-AHS → **Early Automation** → **Enhanced Automation** → **Full AHS**

Pre-AHS

Independent Vehicle-Based Technologies

- Adaptive Cruise Control
- Lane Departure Warning
- Lane Keeping
- Obstacle Detection
- Onboard Road Condition Sensors
- Vehicle-to-Vehicle and Roadside-to-Vehicle Communication Options

Early Automation

Integrated Vehicle-Based Technologies

- System Capable of Maneuver Decisions and Executions
- Obstacle Avoidance
- Truck and Transit Convoys
- Communication with ITS—information integrated into decision making.

System Features

- Driver Disengaged
- Mixed Traffic
- Use of Existing Roadways
- Increased Safety and Convenience
- Moderate Throughput Gains

Enhanced Automation

Fully Integrated AHS/ITS

- ITS Traffic Support Fully Available

System Features

- Passenger Vehicle Convoys
- Driver Disengaged
- Mixed Traffic
- Use of Existing Roadways
- Increased Safety and Convenience
- Moderate Throughput Gains

Full AHS

Fully Integrated AHS/ITS on Dedicated Lanes

Rural

- On four-lane rural highways, a lane may never be dedicated to AHS-only. This is due to the need for manual vehicles to pass using the left-most lane.

Urban

- Lanes are transitioned, one at a time, from manual to automated control. Virtual barriers are used.
- New, dedicated lanes are possible in environments where rights of way are available.

System Features

- Greatly Enhanced Throughput

The Deployment for the Rural and Urban Cases is the Same

except for

- **The Time Frame in which Steps Occur**
- **The Criteria which are used for Transitioning a Lane and/or Freeway to AHS use**

Figure 1-1: Deployment Steps for Free Radical Vehicle Concept

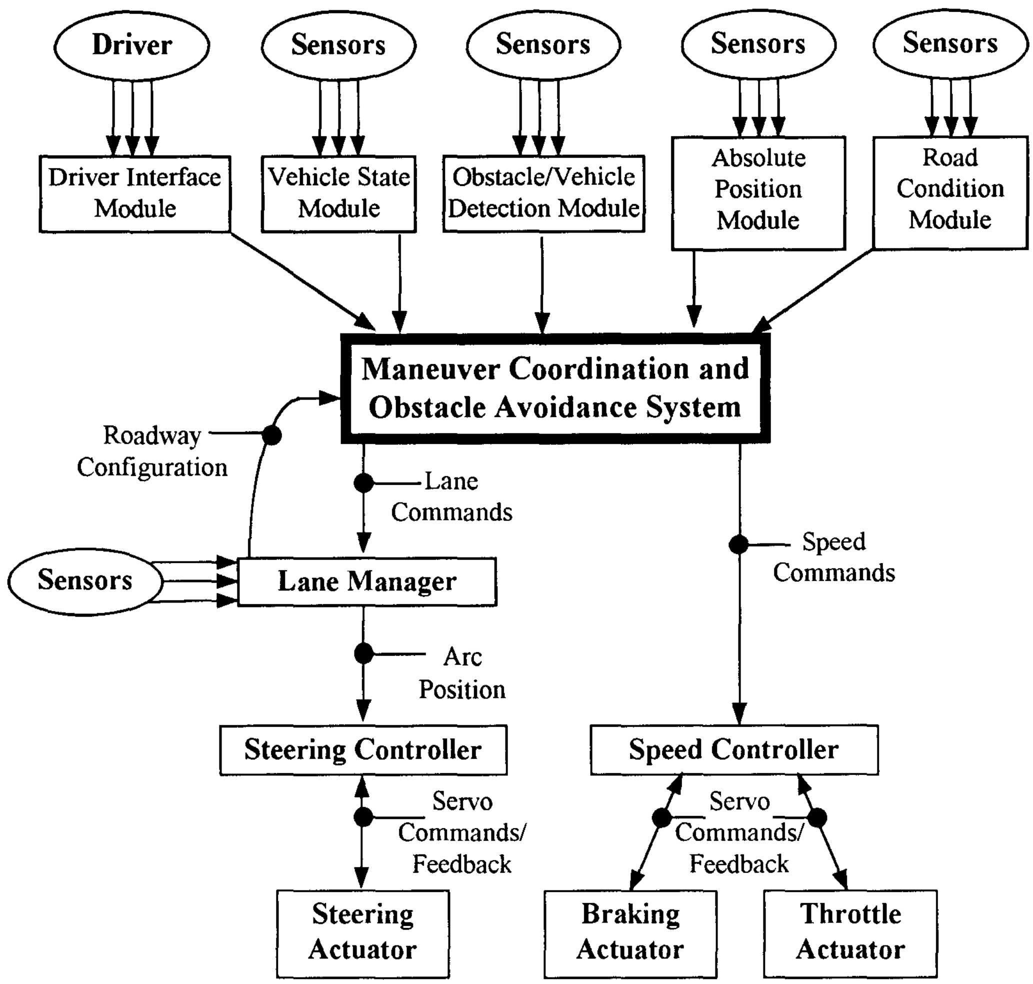

Figure 2-1: In-Vehicle System Architecture

Table 2.1: Potential Physical Architecture

Location	System Type	System Description	
Vehicle	Control System	Name	Maneuver Coordination and Obstacle Avoidance System (MCOAS)
		Function	Coordinate the motion of the vehicle, including acceleration/deceleration/speed maintenance, turning, and braking.
		Subsystems	Lane Manager Speed Controller □ Braking Controller □ Throttle Controller
Vehicle	Control System	Name	Lane Manager
		Function	Generate the steering commands for the vehicle
		Sub-Systems	Steering Controller
Vehicle	Control System	Name	Speed Controller
		Function	Generate the speed-related servo commands
		Subsystems	Braking Controller Throttle Controller
Vehicle	Control System	Name	Steering Controller
		Function	Generate servo commands for steering actuator
Vehicle	Control System	Name	Braking Controller
		Function	Generate servo commands for braking actuator
Vehicle	Control System	Name	Throttle Controller
		Function	Generate servo commands for throttle actuator
Vehicle	Sensor	Name	Lateral Position Sensors
		Function	Identify lane(s)/lane position
		Potential Technologies	Vision System Magnetometer System GPS/Mapping System Radar Reflective Stripe System
Vehicle	Sensor	Name	Absolute Position Sensors
		Function	Determine true vehicle position
		Potential Technologies	GPS/Mapping Compass
Vehicle	Sensor	Name	Vehicle and Obstacle Detection Sensors
		Function	Identify vehicle/obstacle location
		Potential Technologies	Radar Doppler Radar Capaciflector Vision
Vehicle	Sensor	Name	Vehicle State Sensors
		Function	Sense vehicle speed, pitch, yaw, and roll Determine acceleration/deceleration Detect skidding/slippage
		Potential Technologies	Speedometer Wheel Encoder GPS/Mapping Optical Correlator Inertial Navigation System □ Accelerometers □ Gyroscope

Table 2-1: Potential Physical Architecture (Continued)

Location	System Type	System Description	
Vehicle	Sensor	Name	Vehicle State Sensors
		Functions	Determine vehicle state
		Potential Technologies	Sensors for detecting vibration, shock, and acoustic patterns
Vehicle	Sensor	Name	Road Condition Sensors
		Functions	Determine road condition
		Potential Technologies	Barometer Thermometer Inertial Navigation System (detect icing) Vision System
Vehicle and Roadside	Comm Device	Name	Wireless Transmitter/Receiver
		Function	Transmit and receive messages from between roadside and vehicle and between neighboring vehicles.
		Technology	Wireless Technology
Vehicle	Actuators	Name	Steering Actuator
		Function	Execute steering command
		Technology	Electric motor
Vehicle	Actuators	Name	Throttle Actuator
		Function	Execute throttle command
		Technology	Electric motor
Vehicle	Actuators	Name	Brake Actuator
		Function	Execute Braking Command
		Technology	Electric motor
Vehicle	Driver	Name	Driver Interface
		Function	To provide an interface for the driver to be involved in the decision making process. This concept will support driver engagement until this issue is resolved within the Consortium.

2.1. AHS Function Descriptions

2.1.1. Speed tracking

The speed tracking sensing data will be provided to the Speed Controller and the Maneuver Coordination and Obstacle Avoidance System

Table 2.1.1.1 Information Flow Table

Description	From System	To System
Speed of Vehicle	Vehicle State Sensors	Speed Controller
Speed of Vehicle	Vehicle State Sensors	MCOAS

2.1.2. Inter-vehicle separation tracking

Inter-vehicle separation tracking is accomplished by sensing the surrounding environment and relaying the appropriate information to the MCOAS.

Table 2.1.2.1 Information Flow Table

Description	From System	To System
Distance to vehicle in front	Vehicle & Obstacle Detection Sensors	MCOAS
Distance to vehicle in front	Vehicle & Obstacle Detection Sensors	Speed Controller

2.1.3. Lane keeping

Lane keeping is a function that may have redundant systems so as to ensure high system availability.

Table 2.1.3.1 Information Flow Table

Description	From System	To System
Lanes relative to vehicle position	Lateral Position Sensors	Lane Manager
Lanes relative to vehicle position	Lateral Position Sensors	MCOAS

2.1.4. Lane changing

This function is the path planning and path tracking required for vehicle lane change. All of the maneuver planning functions are performed in the MCOAS.

Table 2.1.4.1 Information Flow Table

Description	From System	To System
Roadway Configuration	Lane Manager	MCOAS
Lateral Position Data	Lateral Position Sensors	MCOAS
Absolute Position Data	Absolute Position Sensors	MCOAS
Vehicle/Obstacle Location Data	Vehicle/Obstacle Sensors	MCOAS
Vehicle State	Vehicle State Sensors	MCOAS
Roadway Conditions	Road Condition Sensors	MCOAS
Lane Change Command	MCOAS	Lane Manager
Speed Command	MCOAS	Speed Controller

2.1.5. Road geometry recognition

This function is for the determination of the roadway geometry. The roadway geometry will be determined via the integration of sensor data and possibly coordination with a GPS/Mapping System.

Table 2.1.1.1 Information Flow Table

Description	From System	To System
Sensed Roadway Geometry Data	On-board sensors	Lane Manager
Absolute Position	Absolute Position Sensor	Lane Manager
Roadway Geometry Information	Lane Manager	MCOAS

2.1.6. Obstacle recognition

Obstacle recognition is a critical function for the Free Radical Concept. The obstacle recognition function will occur with the input of a variety of sensors and correlated with known obstacles and obstacle behavior.

Table 2.1.6.1 Information Flow Table

Description	From System	To System
Vehicle & Obstacle Detection Information	Vehicle & Obstacle Detection Sensors	MCOAS

2.1.7. Obstacle avoidance

Once obstacles (including vehicles) are detected, the MCOAS will determine the most appropriate and effective way to flow with, maneuver around, or stop for them.

Table 2.1.6.1 Information Flow Table

Description	From System	To System
Lane Commands	MCOAS	Lane Manager
Desired Speed	MCOAS	Speed Controller

2.1.8. Speed decision

The vehicle will determine speed based on a variety of input, including the traffic flow speed, the speed limit and preferential speed as set by the infrastructure, and the current roadway conditions. If the vehicle determines that the preferential speed as set by the infrastructure is too fast for the given roadway conditions, it will adjust its speed accordingly and relay a preferential speed to the infrastructure.

ITS will provide preferential speeds given traffic flow conditions and known accident data. The vehicle is, at all times, responsible for maintaining control, and is thus capable of reducing any speed decision made by the infrastructure if the road conditions cannot support it.

Table 2.1.8.1 Information Flow Table

Description	From System	To System
Speed Limit/Preferential Speed	Infrastructure	MCOAS
Vehicle & Obstacle Data	Vehicle & Obstacle Detection Sensors	MCOAS
Road Condition Data	Road Condition Sensors	MCOAS
Roadway Configuration Data	Lane Manager	MCOAS
Speed of Vehicle	MCOAS	Speed Controller

2.1.9. Inter-vehicle separation decision

In the controlled environment of a dedicated lane and/or freeway, the distance between vehicles will be a function of several parameters. In that an AHS-vehicle is following another AHS-vehicle, the separation distance can be reduced to a level that is appropriate for being able to sense and react to the lead vehicle. The follow-on vehicle will integrate roadway configuration and condition information to ensure that the separation distance is appropriate for the conditions du jour.

It is believed at this time that communications will be used to verify that the lead vehicle is AHS-equipped or not. If it is, braking data may be sent to follow-on vehicles for the purpose of redundancy and smoother control. This braking data will not be required at any time, however, such that the system will always be able to maintain control, even with a communications failure. Vehicle-to-vehicle communications will be used for emergency braking. It is expected that the communication-system be less redundant than for other concepts, reducing the hardware and processing expense. In the Free Radical Concept, the communication system is considered beneficial, but non-essential, for AHS operation.

The separation distance that is anticipated for free-radical vehicles will be sufficient to support vehicle entry without infrastructure control. This will allow vehicles to enter the system, even if the inter-vehicle gap distance is maximized. After the entry maneuver has been executed, all vehicles will adjust their gap distances accordingly.

Variation for Mixed-Mode Traffic: In the mixed AHS/non-AHS traffic scenario, the AHS vehicle will first determine if the vehicle ahead of it is manually driven. If so, the separation distance will be appropriate for the traffic conditions and will be the same as if all traffic were manual. This spacing is for the comfort of the manual driver in the lead vehicle rather than due to a limitation of the automated *vehicle. If the AHS-vehicle is following another AHS-vehicle, the separation distance can be reduced to a level that is appropriate for being able to sense and react to the lead vehicle.*

Table 2.1.9.1 Information Flow Table

Description	From System	To System
Vehicle capability information	MCOAS of one vehicle (if existing)	MCOAS of another
Roadway Configuration	Lane Manager	MCOAS
Roadway Conditions	Roadway Condition Sensors	MCOAS
Lane commands	MCOAS	Lane Manager
Speed Commands	MCOAS	Speed Controller

2.1.10. Lane change decision

The AHS-equipped vehicle will need to determine when and if to change lanes. This determination is made by the vehicle given the roadway conditions, roadway configuration, actual versus desired speed, average speed of lead vehicle, and average speed of traffic in adjacent lanes.

This decision becomes important for the Free Radical Concept because there is a mix of vehicle classes on all AHS freeways. It is anticipated that many trucks will be unable to handle the desired speed as determined by the infrastructure. AHS-vehicles will need to determine what the status of vehicle flow in adjacent lanes is and if it is worth making a lane change.

Table 2.1.10.1 Information Flow Table

Description	From System	To System
Vehicle capability information	MCOAS of one vehicle	MCOAS of another
Lane commands	MCOAS	Lane Manager
Speed Commands	MCOAS	Speed Controller

2.1.11. Lane change co-ordination

Lane change coordination is accomplished by the autonomous vehicle sensing the location of vehicles in adjacent lanes. Once the vehicle has determined that a lane change is in its best interest, it "looks" for an opening in adjacent traffic, determines that it is safe to move, and executes the maneuver.

Table 2.1.11.1 Information Flow Table

Description	From System	To System
Vehicle capability information	MCOAS of one vehicle	MCOAS of another
Roadway Configuration	Lane Manager	MCOAS
Roadway Conditions	Roadway Condition Sensors	MCOAS
Lane commands	MCOAS	Lane Manager
Speed Commands	MCOAS	Speed Controller

2.1.12. Platoon formation and dissipation

Not applicable.

2.1.13. Vehicle operational status monitoring

The vehicle will be able to determine a sensor has ceased to function and/or if that sensor has been sending erratic, contradictory information. It will be able to inform the driver of the problem and to not incorporate the information from that sensor until a more thorough evaluation can be made.

It is intended that the vehicle will have enough redundancy coming from a variety of sensor-types. This will allow for high availability of the system, even if not all sensors are fully operational.

2.1.14. Driver status monitoring

At this time, it is believed that the driver will be capable of contributing information to the vehicle, but will not be required to do so. This is subject to review given the outcome of studies done by the Consortium on the driver involvement issue.

The vehicle will not monitor the driver for alertness during the automated portion of the trip. The vehicle will be able to determine if the driver is not retaking control as the vehicle prepares to exit the highway. If the driver is not responding appropriately (or not responding at all), the vehicle will regain control of the vehicle and pull it to the side of the road.

Table 2.1.14.1 Information Flow Table

Description	From System	To System
Roadway Configuration Info	Lane Manager	MCOAS
Road Condition Information	Road Condition Sensors	MCOAS
Vehicle & Obstacle Information	Vehicle/Obstacle Detection Sensors	MCOAS
Lateral Position	Lateral Position Sensors	MCOAS

2.1.15. Vehicle entry

Vehicle entry is greatly simplified in this concept. Once the left-most lane on a freeway is dedicated, the adjacent lane becomes a mixed-flow lane from which the automated vehicle will transition into the automated lane. This function will be handled by the vehicle, using the systems described above.

Table 2.1.15.1 Information Flow Table

Description	From System	To System
Roadway Configuration	Lane Manager	MCOAS
Lateral Position Data	Lateral Position Sensors	MCOAS
Absolute Position Data	Absolute Position Sensors	MCOAS
Vehicle/Obstacle Location Data	Vehicle/Obstacle Sensors	MCOAS
Vehicle State	Vehicle State Sensors	MCOAS
Roadway Conditions	Road Condition Sensors	MCOAS
Lane Change Command	MCOAS	Lane Manager
Speed Command	MCOAS	Speed Controller

2.1.16. Vehicle exit

Again, vehicle exit is greatly simplified in this concept. The vehicle continues autonomously until it reaches its exit. Several kilometers prior to the exit, the vehicle signals the driver that he will be regaining control in a short amount of time. The vehicle will move the vehicle out of the dedicated lane into the adjacent lane and transitions control to the driver once standard, manual conditions are reached. If the vehicle determines that the driver is not responding or is not responding appropriately, the vehicle will regain control and drive the vehicle to a safe location at the side of the road.

Table 2.1.16.1 Information Flow Table

Description	From System	To System
Roadway Configuration	Lane Manager	MCOAS
Lateral Position Data	Lateral Position Sensors	MCOAS
Absolute Position Data	Absolute Position Sensors	MCOAS
Vehicle/Obstacle Location Data	Vehicle/Obstacle Sensors	MCOAS
Vehicle State	Vehicle State Sensors	MCOAS
Roadway Conditions	Road Condition Sensors	MCOAS
Lane Change Command	MCOAS	Lane Manager
Speed Command	MCOAS	Speed Controller

2.1.17. Automated highway merging

If a vehicle is merging from one automated highway to another, the vehicle simply follows the appropriate path and speeds for this merge. The vehicle changes lanes to the exit lane, follows the appropriate ramp speed, and merges into the new highway flow of traffic.

Table 2.1.17.1 Information Flow Table

Description	From System	To System
Roadway Configuration	Lane Manager	MCOAS
Lateral Position Data	Lateral Position Sensors	MCOAS
Absolute Position Data	Absolute Position Sensors	MCOAS
Vehicle/Obstacle Location Data	Vehicle/Obstacle Sensors	MCOAS
Vehicle State	Vehicle State Sensors	MCOAS
Roadway Conditions	Road Condition Sensors	MCOAS
Lane Change Command	MCOAS	Lane Manager
Speed Command	MCOAS	Speed Controller

2.1.18. Lane to lane routing within a single highway

This is the same as is described in Section 2.1.10 Lane Change Decision and in Section 2.1.11 Lane Change Coordination.

2.1.19. Highway to highway routing

The AHS vehicle will determine the most appropriate route given the real-time information that it receives from the infrastructure-based ITS services. These ITS services are centralized and give the vehicle a broad view of the system as a whole. All decision-making and safety critical processing resides on-board the vehicles.

If dedicated infrastructure has been implemented for highway-to-highway merging for the dedicated lane, the vehicle will continue seamlessly within the dedicated lane. If special ramps have not been implemented, the vehicle will be capable of exiting the dedicated lane, flowing within the manual traffic onto the desired highway, and reentering the dedicated lane on the second highway.

Table 2.1.19.1 Information Flow Table

Description	From System	To System
Traffic Flow Information Travel Demand Information Incident Management Information Route Guidance En-route Information	ITS System	MCOAS
GPS/Mapping	Vehicle Sensors	MCOAS

2.1.20. AHS flow control

Flow control continually improves as more and more vehicles become AHS-equipped. As distances between vehicles become constant due to the AHS-vehicle capability, less accordion effects will be noticeable in mixed traffic. These improvements are most noticeable in the AHS-only lanes, and are, of course, optimized on the AHS-freeways.

2.1.21. AHS admission control

Admission control is achieved through ramp metering that is provided by the ITS services. It is also anticipated that some level of admission control and enforcement will be used for the AHS-only freeway systems. This can be achieved very simply through a law-enforcement presence and will not require elaborate entry-rejection systems. In the event that a rogue vehicles does manage to enter the freeway, its presence can be easily handled by the autonomous vehicles, which are fully capable of operating in mixed traffic.

2.1.22. Emergency detection/monitoring

Any emergency that has been observed by the driver can be immediately be transmitted to the infrastructure. Follow-on vehicles can provide updated information to the infrastructure. The infrastructure will also be capable of monitoring the situation through basic ITS services.

Table 2.1.22.1 Information Flow Table

Description	From System	To System
Emergency location & severity information	MCOAS	Infrastructure (ITS)

2.1.23. Emergency Response and Incident clearing

Emergency situations are dealt two ways. First, the infrastructure can transmit information about where emergency situations are so that vehicles can appropriately be rerouted. Secondly, emergency vehicles will have the ability to transmit a distress signal to AHS-vehicles so that the vehicles automatically "make way" for the emergency vehicles.

Table 2.1.23.1 Information Flow Table

Description	From System	To System
Emergency location information	ITS System	MCOAS
Distress "make way" signal	Emergency Vehicle	MCOAS

2.2. Urban Variation

Absent AHS Functions: None
Identical AHS Functions: All

Although this is not the "norm," it will be possible to build new, dedicated lanes in the specific locations if it is deemed necessary for throughput gains.

2.3. Inter-Urban Variation

Absent AHS Functions: None
Identical AHS Functions: All

Although this is not the "norm," it will be possible to build new, dedicated lanes in the specific locations if it is deemed necessary for throughput gains.

2.4. Rural Variation

Absent AHS Functions: In the rural case, an entire freeway may never be completely requisitioned. In this case, the vehicles will always be operating in mixed-traffic. It may also be that the same level of ITS

services are not available in the rural areas that are available in the urban areas. This should have little impact on throughput and little or no impact on safety.
Identical AHS Functions: All

3. Deployment Stage Variation

The Free Radical Concept is a market-driven deployment scheme. Understanding the deployment scenarios is critical to understanding the depth and breath of the entire concept. Please refer to Figure 1.1 as an overview of the deployment stages.

The deployment path for the urban, inter-urban, and rural cases involve the same set of sequential steps, however the time frame in which these steps will occur will likely be different for the different scenarios. Also worth noting is that the criteria for transitioning a lane and requisitioning a freeway will likely be different for the rural and urban cases.

In that this concept heavily interfaces with the ITS system, variations in the system benefits may be seen from the urban to the rural environment. These differences are solely a function of the local objectives, e.g. throughput gains will be achievable earlier in the urban environment because of two predictable factors: ITS services will be first available there, and the criteria for transitioning a lane is lower. Additionally, it may be cost effective in *some* urban corridors to build new, dedicated lanes, although this is the exception to the general principle of utilizing existing infrastructure.

In all cases, automated vehicles will be capable of operating without any interface with ITS services if need be.

3.1. Initial Deployment (Pre-AHS)

Geographical Scope: Urban, Inter-Urban, and Rural
Vehicle Classes Supported: Light, Medium, Heavy, Articulated Light and Articulated Heavy Vehicles
Vehicle Types Supported: Manual and Automatic
Absent AHS Functions: Vehicles are not automated. They only have convenience and safety-enhancement features. The driver is fully engaged and responsible for the vehicle motion. The vehicle will not be capable of using lane keeping and adaptive cruise control at the same time, less the driver get the false impression that the vehicle can function as an integrated and fully automated unit.
Identical AHS Functions: None.

3.1.1. AHS Function Description

The first stage of Free Radical deployment scheme is best characterized as "Pre-AHS." The following market-driven features are expected to be on the market prior to the NAHSC's contract completion: adaptive cruise control, lane keeping, lane departure warning, obstacle detection and warning, on-board road condition sensors, and vehicle-to-roadside communication. These features will not be coordinated with one another until the next phase of the deployment cycle.

3.2. Deployment Stage 2: Minimal Automation

Geographical Scope: Urban, Inter-Urban, and Rural
Vehicle Classes Supported: Light, Medium, Heavy, Articulated Light and Articulated Heavy Vehicles
Vehicle Types Supported: Automatic only, carbon-based fuels as well as electric vehicles
Absent AHS functions: Passenger Vehicle Convoys, passenger vehicle-to-vehicle communications.
Identical AHS Functions: Electronically linked trucks and buses.

3.2.1. AHS Function Description

In the Minimal Automation State, all independent in-vehicle technology will be integrated to create a fully autonomous vehicle. Vehicle-to-vehicle communications will be limited to the trucking and transit industry, who have a vested interest in early convoy capability. This stage will provide a real-life testbed for the use of convoy technology in the mixed environment prior to releasing this capability to passenger vehicles. Convoys will be limited in numbers and lengths to ensure that all other traffic can adequately maneuver around them. .

The automated vehicles are fully integrated with manual vehicles on manual roadways. Moderate throughput gains are achieved as a direct result of the safety enhancements in the automated vehicles—these benefits continue to grow as greater numbers of vehicles become AHS equipped. At the point where adequate market penetration warrants, lanes may be requisitioned for dedicated AHS-use only.

Automated vehicles enjoy the benefits not only of automated vehicles, but also of linking into ITS services. This link provides information on roadway and traffic conditions as well as routing preferences given the driver's destination. Over time, these features will be further expanded to provide a global view of the local traffic situation, including the congestion on arterials and heavily-trafficked side-streets.

3.3. Deployment Stage 3: Enhanced Automation

Geographical Scope: Urban, Inter-Urban, and Rural
Vehicle Classes Supported: Light, Medium, Heavy, Articulated Light and Articulated Heavy Vehicles
Vehicle Types Supported: Automatic only, carbon-based fuels as well as electric vehicles
Absent AHS functions: None, however automated vehicles are still integrated with mixed traffic.
Identical AHS Functions: All.

3.3.1. AHS Function Description

In the Enhanced Automation State, vehicle-to-vehicle communications is added to the passenger vehicle capability to allow AHS vehicles to reduce headways not only in dedicated lanes, but also in mixed traffic.. When in mixed traffic, these reduced-spacing vehicle convoys will be limited in number and length to ensure that all other traffic can adequately maneuver around them.

It is anticipated that, at this point in the process, ITS will have developed in the urban environment to include a global view of the local traffic situation. This will allow AHS-vehicles to become aware of congestion on arterials and heavily-trafficked side-streets and to make appropriate routing decisions. Two possibilities exist for the handling of this information. First, the information can be relayed to the driver, and the driver can make routing decisions. Secondly, the driver can allow the vehicle to take that information and make a choice for him, such that he is never bothered on his trip. It is expected that the ITS information will not just be "5 minute delay on route x," but rather "current delays are x, and are anticipated to be y given the current incoming traffic load." Thus, ITS is not just relaying basic state information, but predicting state information given the information relayed to it by the AHS vehicles and by common loading patterns that also account for non-AHS vehicles in the flow.

3.4. Deployment Stage 4: Full AHS

As mentioned in section 2, "Full AHS" will be achievable when enough vehicles become AHS equipped to permit a lane to be transitioned and/or a freeway to be requisitioned. Given the average vehicle lifetime, it is expected that 10 years will pass from the preliminary deployment of integrated technologies to the point where the system can be declared "Full AHS." The availability of ITS services will be dependent on the location, time frame, and funding available.

It is a bit myopic to consider this stage "Full AHS," because this system is designed to be continuously upgradable, even beyond the "final product" as it is now conceived. The Free Radical Concept is intent on developing autonomous vehicles that each year provide new, market-driven capabilities and features. These autonomous vehicles will interface with upgradable, infrastructure-based ITS services—the integration of AHS vehicles and with ITS traffic management services provide much enhanced safety and badly needed throughput gains that are not only affordable, but achievable.

3.5. Stakeholder Benefits: Deployment and Reference State Matrix

The expected role and benefits for each stage in the deployment of the Free Radical Concept are outlined in Table 3.5-1.

4. Local Tailorability

The uniqueness of this concept is that it is highly tailorable to local needs and conditions. In environments where dedicated lanes and ITS services provide no benefit, AHS will still be implemented. In locations where enhanced ITS services are worth the expense to the taxpayer, they can easily be integrated and utilized by the AHS system. Local governments can make decisions regarding the construction of new, dedicated lanes given local political sensitivities and needs, and can also dictate when lanes are requisitioned for AHS-dedication. I

5. Degraded and Upgraded Modes/Robustness of Reference State Concept

One of the great advantages of this concept is that infrastructure down-time will not, in any way, prevent vehicles from operating on the AHS system. Although throughput and emergency handling may be affected due to a lack of communication with the infrastructure, all vehicles will continue to operate at appropriate speeds under automated control.

The second great advantage of this system is that, if enough in-vehicle systems fail so that the AHS-vehicle cannot continue under automated control, control can be transferred to manual. This will cause no serious interruption in AHS flow, as all AHS-vehicles are capable of operating in mixed traffic.

Table 5.1 Degraded AHS Function Description Table

Degraded AHS Function	Cause of Degradation	Degraded Mode of Operation
Throughput not optimized	Infrastructure failure (communications, processing, etc.)	Autonomous vehicles operating without benefit of ITS services
Throughput not optimized	Foul weather	Spacing increased to accommodate roadway conditions
Any	Sensor failure on vehicle	Vehicle uses redundant systems
Any	Multiple sensor failures	Vehicle cannot operate in auto-mode.

Table 5.2 Upgraded AHS Function Description Table

Upgraded AHS Function	Cause of Upgradation	Upgraded Mode of Operation
Emergency Braking	Any	Autonomous vehicles transmit emergency braking data to surrounding cars to maximize response time in emergency situations.
AHS-provided vehicle flow optimization beyond ITS services	Particularly difficult congestion that requires o/d pair information for full optimization	Far more vehicle-to-roadway integration, less personal privacy, greater throughput.

6. Societal and Institutional Factors

There are many societal and institutional factors associated with the Free Radical Concept. The following benefits and issues are now raised.

1. Autonomous vehicles will require more vigorous and frequent inspection than is currently standard.
   - States with no inspection practices will have a harder time transitioning into AHS.
   - The incremental deployment of this Concept will help with general public acceptance of more frequent and rigorous inspection cycles.

2. Market acceptance is probably higher with this concept because of the "American Love Affair" with their vehicle and their personal autonomy. Thus it is believed that this concept will have greater market penetration.
3. The incremental deployment scheme allows gradual acceptance of automation to occur. This occurs with general education and perception changes that alleviate people's fear of placing their lives in the hands of a machine on a daily basis.
4. By making this system convenient and readily available to all, there are few if any fairness issues raised in terms of both geographical and social equity.
5. Emissions and energy saving benefits can be accrued early in the deployment process due to more uniform driving cycles.
6. Because of the nature of this concept, emergency vehicle access issues disappear.
7. There are few issues associated with land use and environmental impact of building new roads in this concept.
8. Funding issues need to be addressed, as this concept is heavily biased towards individual and private sector investment.
9. Users will experience benefits early in the deployment process and the gradual introduction of automation is likely to lead to wider market acceptance and eventually adoption.
10. While some of the specific benefits on a dedicated AHS facility are likely to be lower that other concepts, the free radical concept is likely to broader benefits for agencies and transportation users in a region or in a particular corridor. For example, the safety and communications benefits will be realized both on and off the AHS facility. Similarly, the links to ITS can be enhanced in the early stages of deployment and additional benefits will be accrued.

7. Other Issues and Concluding Remarks

The following items are seen as positive and negative aspects of the concept.

Positive Aspects:

1. Immediate Deployment
2. Low Infrastructure Costs
    - Use of existing freeways
    - No new infrastructure (except in special cases)
3. Optimal balancing of ITS and AHS program resources
4. High spin-off potentials
5. Excellent value added for the rural environment
6. Control and communications systems are more simplistic for autonomous vehicles than for platoon-capable vehicles (tolerances can be greater)
7. The entry/exit problem is far easier for autonomous vehicles
8. Safety and throughput enhancements.
9. Convenience and comfort enhancements.

Negative Aspects of the Concept:

1. Vehicle cost may be higher than for other concepts, although the less-stringent communications and control systems may make the opposite true.
2. During the deployment phase, safety may not be as great as when autonomous vehicles are operating on a dedicated, barriered lane.
3. Fuel consumption reductions are lower because of high convenience and equitable access.

Table 3.5-1: Stakeholder Benefits: Deployment and Reference State Matrix

	Pre-AHS	Minimal Automation	Enhanced Automation	AHS
Vehicle Industry	Role: Develop independent, in-vehicle technologies Benefits: Profit, enhanced image	Role: Lead in the integration of independent technologies Benefits: As before	Role: Continue to develop/evolve in-vehicle technology Benefits: As before	Role: Continue to develop in-vehicle technology Benefits: As before
Vehicle Electronics	Role: Develop independent, in-vehicle technologies Benefits: Profit, enhanced image	Role: Play lead role in the integration of independent technologies Benefits: As before	Role: Continue to develop/evolve in-vehicle technology Benefits: As before	Role: Continue to develop in-vehicle technology Benefits: As before
Highway Design and Construction	Role: Lead coordination with ITS program. Develop and build new electronic infrastructure nation-wide. Build new physical infrastructure in few places required. Benefits: Profit, enhanced image, spin-off technology	Role: Play lead role in the integration of infrastructure-to-vehicle capabilities. Develop and build new electronic infrastructure nation-wide Benefits: As before	Role: Evolve infrastructure capability and services Benefits: Profit, enhanced image, spin-off technology. Diversification from large-scale construction to integrated electronics.	Role: Continue to develop infrastructure capability and services Benefits: As before.
Trucking	Roles: Involvement in early convoy capabilities Benefits: Improved safety, comfort, convenience, trip time reliability, and throughput (system-wide), and reduced operating costs.	Role: Heavily involved in the development and deployment of convoy capability. Benefits: As before	Role: Further involvement with trucking-industry-based enhancements, including longer convoys, smaller vehicles. Benefits: As before	Role: Continued evolution of AHS-related benefits to the trucking industry. Benefits: As before
Transit	Roles: Involvement in early convoy capabilities Benefits: Improved safety, comfort, convenience, trip time reliability, and throughput (system-wide), and reduced operating costs.	Role: Heavily involved in the development and deployment of convoy capability. Benefits: As before. Additionally, enhanced image may increase ridership	Role: Further involvement with transit-industry-based enhancements, including longer convoys, smaller vehicles. Benefits: As before	Role: Continued evolution of AHS-related benefits to the trucking industry. Benefits: As before