2.1.5 Comparison of Evaluatory Alternatives

The following Table 2.1.5-I evaluates the five alternatives and the baseline relative to the Objectives and Characteristics. The concept designators relate back to the initial 11 concepts in Section 2.1.3. For example, C4 is discussed in Section 2.1.3.4. Ratings given to each concept are an order relative to other concepts (more than, less than), not a point score (33% greater than). The table is followed by a brief explanation of each of the Objectives/Characteristics listed in the leftmost column, and a discussion of the scores.

The ratings are intended to provide relative ordering, not measure. 6 is high, 0 is low. 2 is higher than 1, but not necessarily twice as much. The Baseline, or current system, is given a rating of 1 or 5 for all System Objectives and Characteristics as a reference.

2.1.5.1. <u>Improve safety</u>

This rating is based on the ability of the concept to reduce number of collisions, the severity of collisions, and the severity of injuries and value of property damage resulting. In general, safety is expected to increase with the increasing sophistication of the system. C2 has a range that goes below the baseline because of the possibility that this concept, which requires driver intervention, will cause drivers to be inattentive so that they do not intervene correctly or in time. C10 has a range which drops below C6 and C8 because the system is seen as being less "robust" - since the vehicles have little autonomous capability, a communications failure could have very serious consequences.

2.1.5.2. <u>Increase throughput</u>

In general, throughput is expected to improve with the increasing technological sophistication of the system. The addition of platooning to concepts which can support it is expected to further increase throughput, moving C6, C8, and C10 toward the upper end of their ranges. C8 and C10 span greater ranges than C6 because it is thought that their centralized control could give them a slight edge over the inter-vehicle coordination required by C6.

2.1.5.3. <u>Enhance mobility</u>

This rating focuses on faster and more predictable trip times, and on the ability of people with reduced capability to use the AHS. All of these concepts will have more predictable trip times than the baseline due to the addition of ITS, with C6, C8 and C10 receiving further benefit from flow control. C4 through C10 will greatly benefit those with disabilities; C2 may not provide all the assistance they need. The concepts are rated on reducing trip times similarly to the Increase Throughput ratings. The Enhance Mobility ratings are seat-of-the-pants average of the three components.

2.1.5.4. <u>More convenient and comfortable highway traveling</u>

This rating focuses on the degree of reduced stress and feeling of security, which is assumed to be higher with increasing control of safety related issues by the AHS, but which may be significantly decreased with platooning until people become accustomed to it. All four of the fully automated concepts have the potential to make users feel secure if they are implemented well. However, this is not just a matter of safety statistics. Many people feel less secure in a commercial airliner than in their family car despite demonstrably better safety statistics.

2.1.5.5. <u>Reduce environmental impact</u>

This rating focuses on reduced emissions through smoother vehicle operations and reduced congestion. C6, C8 and C10 will surpass the other concepts in reducing emissions due to their superior flow control. C8 and C10 may have a slight advantage in smoothness of vehicle operations because maneuvers are centrally choreographed under these concepts.

Table 2.1.5-I. Comparison of Evolutionary Alternatives

	Baseline	Adaptive Cruise Control	Locally Coop-erative	Infra-structure Sup-ported	Infra-structure Managed	Infra-structure Controlled
Concept Designator	C1	C2	C4	C6	C8	C10
Improve Safety	1	0-2	3	3-4	3-4	2-4
Increase Throughput	1	2	3-4	4-5	4-6	4-6
Enhance Mobility	1	2	3	3-4	3-4	3-4
• More Predictable Trip Times	1	2	2	3	3	3
• Assist Those with Disabilities	1	1-2	3	3	3	3
Convenient/Comfortable Highway Traveling	1	2	0-3	0-3	0-3	0-3
Reduce Environmental Impact	1	2	3	4	4-5	4-5
Operate in Inclement Weather	1	1-2	3	4	4	4
Affordable Cost/Economic Feasibil.	5	4	2-3	1-2	1-2	1-2
Benefit Conventional Roadways	1	2	3	3-4	3-4	2-3
• Increase safety on conventional roads	1	2	4	3-4	3	1
Easy to Use	DNA	DNA	DNA	DNA	DNA	DNA
Infrastructure Compatible	5	4	3	2	1-2	1
Facilitate Intermodal/Multimodal Transportation	DNA	DNA	DNA	DNA	DNA	DNA
Ensure Deployability	5	4	3	2	2	1
Provide High Availability	DNA	DNA	DNA	DNA	DNA	DNA
Apply to Rural Highways	5	5	4	3	3	3-4
Disengage the Driver from Driving	1	2	3	3	3	3
Support Travel Demand Management Policies	1	1	2	2	2	2
Support Sustainable Transportation Policies	DNA	DNA	DNA	DNA	DNA	DNA
Provide Flexibility						
• Architectural Flexibility	1	2	3	4	4	3
• Flexibility in Local Traffic Management	1	2	2	3	3	4
Operate in Mixed Traffic with Non-AHS Vehicles	5	5	3	3	3	3-4
Support a Wide Range of Vehicle Classes	5	5	3-4	3-4	4	4
Enhance Operations for Freight Carriers	1	2	3	3-4	3-4	3-4
Support Automated Transit Operations	1	2	3	4	4	4
Provide System Modularity	DNA	5	4	3	2	1

2.1.5.6. Operate in inclement weather

This rating focuses on automation for sensing, judging speed and stopping distance, braking and steering. C4 benefits from improved sensors for lane-keeping and speed/braking control in poor visibility. If these sensors cannot adjust for increase braking distances on wet pavement this could be a major disadvantage, however. C6 derives further benefits from the capability of the infrastructure to sense roadway obstacles beyond the line-of-sight of the vehicle.

2.1.5.7. Affordable cost/economic feasibility

This rating is one of the more difficult ones to score based on intuition. The assumption was made that cost increases with the degree of automation. The cost trade-off between intelligence in the vehicle and intelligence in the infrastructure is much too complex to be guessed at, and is left to more comprehensive analysis.

2.1.5.8. Benefit conventional roadways

This rating is based on AHS throughput, which will draw vehicles from conventional highways, and on the ability of AHS vehicles to enhance the safety of conventional roadways when they operate on them. The throughput scores are taken from the second Objective/Characteristic. C2 has safety enhancement intended for conventional roads. C4 adds vehicle-based fully automatic control. C6 is similar, but may offer less capability for sensing obstructions and flow control in the absence of the infrastructure. C8 has the position-keeping of local cooperative but few of the other enhancements in the absence of the infrastructure. C10 is highly infra-structure dependent, and probably offers only basic manual control in its absence.

2.1.5.9. Infrastructure compatible

This rating is based on the degree of changes required to the roadway and supporting equipment and facilities. C2 and C4 are vehicle-based systems, and should require few changes, though C4 will probably segregate AHS vehicles, and check them in and out. C6 requires many more infrastructure-based sensors than its predecessors. C8 will probably require more infrastructure than C6, and C10 definitely will, since the infrastructure performs virtually all the detection and processing.

2.1.5.10. Ensure deployability

This rating is based on the technological and economic "distance" between practical stepping-stone AHS configurations which can be used to attain the chosen architecture. C4 can use C2 as a stepping-stone, making it relatively deployable. C6 and C8 require quite a bit of infrastructure to go beyond the capabilities of C2. C10 is the worst, since the system cannot work without a large amount of infrastructure support, and C2 is not usable as a stepping-stone.

2.1.5.11. Apply to rural highways

This rating is based on how well a concept will work if only one lane is available in each direction, AHS and regular vehicles are mixed, and support equipment is more sparsely located than in urban areas. Any concept which relies on platooning will work poorly under these conditions. C2 suffers no disadvantages since it depends only on the vehicle carrying the system. C4 should operate well in a slightly degraded mode - the only imperative is that maneuver coordination recognize vehicles which are not responding and work around them. C6, C8 and C10 require sensor and communications coverage of every foot of roadway to spot obstructions - expensive in rural areas. C10 has a slight advantage in not being a cooperative system and in doing vehicle tracking - it can treat non-AHS vehicles like moving obstacles, and work around them.

2.1.5.12. Disengage the driver from driving

This rating is based on the extent to which the vehicle is automatically controlled. C2 provides semi-automatic control of the vehicle; C4 through C10 provide automatic control.

2.1.5.13. Support travel demand management policies

This rating is based on the concept's ability to support congestion pricing. The sole differentiator here was whether the infrastructure could support billing as a function of time, i.e., whether it checks vehicles in and out of AHS. C2 does not; the other concepts are expected to do so.

2.1.5.14. Provide flexibility

The description of this rating is ambiguous. It may refer to architectural flexibility, which is whether the concept can be modified easily by adding options (e.g., platooning), or by moving responsibility for a function from the vehicle to the infrastructure or vice versa. C4 through C10 can accept platooning, and C6 and C8 have several functions which could be either vehicle or infrastructure-based. It may also refer to flexibility in local traffic management, which is the ability of a system to be used by local authorities to support their particular traffic management strategy. C2 and C4 give minimal capability here through ITS. C6 and C8 allow traffic management through their flow control function, and C10 gives authorities as much control as the law and the driver will allow.

2.1.5.15. Operate in mixed traffic with non-AHS vehicles

This rating is based on throughput and safety in an environment where there are a substantial number of non-AHS vehicles. C2 suffers no disadvantages since it depends only on the vehicle carrying the system. C4, C6 and C8 should operate well in a slightly degraded mode - the only imperative is that maneuver coordination and flow control functions recognize vehicles which are not responding and work around them. C10, while subject to the same constrains, has a slight advantage in doing vehicle tracking — it can treat non-AHS vehicles like moving obstacles, and work around them.

2.1.5.16. Support a wide range of vehicle classes

This rating is based on the concept's ability to support passenger cars, trucks, and transit vehicles, among others. C2 can be implemented without difficulty on all vehicle classes, as long as the on-board computer knows the characteristics of the vehicle. C8 and C10 can handle multiple vehicle classes; all that is required is for the vehicle to communicate its class, and for the system to look up the appropriate characteristics in a table. This is also possible for C4 and C6, which require inter-vehicle coordination, but may be more difficult given limited on-board data storage and processing capacity.

2.1.5.17. Enhance operations for freight carriers

This rating is based on the concepts ability to reduce trip time, reduce trip time variation, disengage the driver, and guide freight vehicles through weighing and inspection stations. The first three are expected to dominate, and therefore this rating is a seat-of-the-pants average of Disengage the Driver and Enhance Mobility.

2.1.5.18. Support automated transit operations

This rating is based on the concept's ability to reduce trip time, reduce trip time variation, and facilitate transfers to other modes. ITS can provide schedule and location information on other modes of transportation under all concepts. However, the automated systems (C4 through C10) could choose a transit mode and line, and deliver the traveler to the appropriate parking. C6 through C10 rate slightly higher on the basis of reduced trip time and increased predictability.

2.1.5.19. Provide system modularity

This rating is based on a concept's ability to have one or more subsystems modified or upgraded with a minimum of impact to the remaining subsystems. C2 has two subsystems which have no infrastructure dependencies, and are potentially independent of each other. C4 has potentially four subsystems of which the same can be said, except that they dependent on equipment installed in other vehicles. C6, C8 and C10 have an increasing degree of interdependency between vehicle-based subsystems and the infrastructure.

2.2 COMMUNICATIONS

2.2.1 Characteristic Description

The communications requirements of the AHS system are interdependent with several related functions. AHS functions such as position control, navigation/route guidance, maneuver coordination, and traffic operations may be implemented with one or more types of communications links to provide data transfer. AHS operations may be enhanced through integration of communications capabilities including vehicle-to-vehicle, vehicle-to-infrastructure/infrastructure-to-vehicle, and infrastructure-to-infrastructure data links. The AHS functions are discussed in terms of the expected data link requirements. Communications systems which can be used for vehicle-to-vehicle, vehicle-to-infrastructure – infrastructure-to-vehicle, and infrastructure-to-infrastructure data links are also described.

2.2.1.1. Data link requirements to support AHS functions

Various communications technologies may be used to support four general AHS functions: periodic update of vehicle control loop data, vehicle maneuver coordination, transfer of origin/destination and navigation data, and dissemination of zone or region traffic management information. The operating requirements of a specific communications system are based on several factors, including message latency, access protocol, and data rate. The communications capabilities expected to support each function are described in the following paragraphs.

Position control

The headway control loop algorithm may require exchange of velocity and acceleration information for each vehicle within an assigned coordination unit to support close-following modes. Key technical requirements include strict timing and contention-free bandwidth access. Vehicle control loop data transfers may require short, deterministic latencies as small as 10 msec. Vehicles in close-following configurations will require a dedicated transmit opportunity every 20 msec to 50 msec. The ability to override the normal velocity and acceleration message update rate may be necessary to optimize emergency braking capabilities. The quantity of information contained in each data transfer is expected to be less than 100 bits. The safety-critical nature of the control loop data will also require highly reliable communications channels to increase the probability of error-free data transfer. A significant percentage of the message bandwidth may be consumed by error detection and/or correction protocols. The selected communications technology will be subject to requirements set by the control loop function to a large extent.

Direct communication of velocity and acceleration data between vehicles is one approach to headway control. Velocity and acceleration information may also be obtained by using radar detection. A following vehicle equipped with Doppler radar can sense range to a leading vehicle. Velocity and acceleration can be obtained through processing of successive radar return signals.

Maneuver coordination

Functions including merge, separation, lane change, enter, and exit maneuvers will be automated in a mature AHS. Both steady-state and emergency (collision avoidance) conditions must be supported; the requirements differ since emergency maneuvers are safety-critical, increasing time restrictions on data transfers. Communications will be required to provide time-critical data transfers necessary for emergency maneuvers such as lane changes to avoid obstacles. The steady-state message channel may be compatible with a contention access protocol, as long as the maximum access time meets the required limits. Emergency maneuvers may require access times in the range of 20 msec to 50 msec. Bandwidth access methods must be capable of assigning priority to emergency messages if necessary to meet safety-critical latency requirements. Packets are expected to be on the order of 50 to 100 bits. The relatively low update rate of steady-state maneuvers may be compatible with message protocols which incorporate repeat transmissions to meet data error rate requirements. This type of communication link may be satisfied by either vehicle-to-vehicle or two-way vehicle-to-infrastructure systems.

Route guidance

The navigation aspect of this function is expected to be available as a subset of ITS capabilities in the time frame projected for AHS implementation. The most significant issues in the area of navigation are the resolution, accuracy, interface, and update rate of available technologies. AHS should expect to influence navigation technology to permit straightforward integration of functionality. The ability to communicate origin/destination information may also be required to support real-time trip modification. Message size and latencies are yet to be determined. This task is compatible with two-way infrastructure-to-vehicle link capabilities. Contention access as well as non-deterministic latency can be tolerated. Packet sizes may vary, and standard packet protocols may be used. Both point-to-point and broadcast modes must be supported. Point-to-point links will allow the vehicle to transfer origin or destination requests to the infrastructure, for example. A broadcast message may be used to transfer traveler information from the infrastructure to a group of vehicles in a coordination unit simultaneously.

Traffic operations

The traffic operations function will include traffic flow management within a network of automated lanes. Communications may be required to support transfer of incident or environment information from roadside sensors to the TMC and the dissemination of route availability data along the infrastructure to roadside processors. Existing protocol and packet switching standards are expected to be compatible with traffic operations information exchange requirements. Message size and latencies are yet to be determined. The tasks will be supported by one-way infrastructure-to-vehicle and infrastructure-to-infrastructure communication links.

2.2.1.2. AHS communications links

Data transfers which support various AHS functions may be communicated via one or more paths. The individual communications systems may be capable of point-to-point, point-to-multipoint, or broadcast data transfers. The capabilities of each type of communications link are outlined in the following paragraphs.

Vehicle-to-vehicle

Vehicle-to-vehicle control loop data transfers are expected to include velocity and acceleration information. The data link can be accomplished using one-way point-to-point transfers from a leading vehicle to the vehicle immediately following. It is also possible to implement this function using one-way point-to-multipoint transfers from the lead vehicle to all vehicles within its assigned coordination unit. Minimum vehicle headway and elimination of low-differential-velocity collisions in ultra-close vehicle following may be possible by providing two-way point-to-point communications between a leading vehicle and the vehicle immediately following. A feedback loop which provides following vehicle deceleration information to the lead vehicle in emergency braking maneuvers may allow stopping distance to be minimized while preventing collisions. This concept was introduced in the PSA as coordinated braking.

Vehicle-to-vehicle data transfer can be supported by RF radio or infrared signal technologies. The mobile RF communication channel is subject to multipath fading, interference due to high numbers of users, and rapidly varying coordination unit location. Radio communication protocols can support the full range of one- or two-way links, point-to-point or -multipoint, and broadcast communications. Addressing may be included in the message overhead to allow selective transfer of vehicle-specific data. Infrared signals are not susceptible to interference, but are subject to degradation under conditions of decreased visibility such as fog, rain, or dust. Infrared links are limited to one-way point-to-point communication, introducing propagation delays in transferring information from the lead vehicle to all vehicles within a coordination unit.

Vehicle-to-infrastructure

The vehicle-to-infrastructure link may be used to transfer real-time trip planning information in support of entry and exit requests. Vehicle instrumentation must allow user input of origin and/or destination information and implement transfer of this data from the user interface via a communications device to the roadside. Two-way point-to-point links are expected to be well suited to this application, allowing the vehicle to transmit requests and receive entry or exit commands from the roadside. One candidate technology is Vehicle-Roadside Communications (VRC) using a tag in the vehicle and a beacon at the roadside. VRC is coming into use for automated toll collection and commercial vehicle operations, and incorporates a vehicle tag which is capable of serial interface to a data bus and active data transfers to roadside beacons. Many vehicle-vehicle RF communication links are also capable of supporting the two-way link with the infrastructure.

Infrastructure-to-vehicle

The infrastructure-to-vehicle link may be used to transfer coordination information in support of join or split maneuvers. One-way, broadcast communications links from the infrastructure to vehicles within a localized area may be used to disseminate traffic flow information such as route or lane closures. This feature is expected to become available as an ITS technology prior to deployment of full AHS functionality.

Infrastructure-to-infrastructure

Infrastructure-to-infrastructure communications will link roadside devices with one another and with the Traffic Operations Center (TOC). Leased telephone lines or fiber optic cable can provide connectivity for this link in areas where infrastructure exists or is installed at the time the roadway is constructed. RF communication technologies such as microwave or unlicensed spread spectrum can be used in areas where land lines are prohibitive or short links are needed to connect existing infrastructure instrumentation.

The applicability of specific technologies depends on the type of data required for the AHS specific function, such as position location, route guidance, or control loop information. The accuracy and resolution required will determine one aspect of the link requirements. The rate at which information must be updated is another important parameter. The ability to uniquely identify individual vehicles with methods such as time slot assignments or unique codes may be another factor. Susceptibility to interference and the ability of a particular technology to operate in inclement weather will affect the data error rate and must be considered. The security of the communications system may be important to prevent transmission of corrupted data, and may be addressed using methods such as data encryption.

2.2.2 Possible Solutions

The teams will describe and contrast each reasonable solution for this characteristic. The teams will describe the significant aspects of each solution. For a technology characteristic, this involves a description of the hardware and software components needed to support the solution and a description of the relative strengths and weaknesses (pros and cons) of each component. For an architecture characteristic, this involves a description of the strengths and weaknesses of each architectural option and of the implications of the design components. For an operating requirement characteristic, this involves describing the strengths and weaknesses of the performance of each solution as well as describing the design and architecture implications of each solution.)

Five baseline solutions are presented, including:

1) ITS Technology: an approach in which AHS does not add communications capability beyond the technologies brought to market by related ITS developments.

2) Commercial Technology: existing and emerging commercially available communications infrastructure is exploited to support AHS communications requirements.

3) Existing Technology: communications products which have been developed for related ITS services are assigned to support specific AHS functionality.

4) Advanced Technology: communications products under development or deployment are assigned to support specific AHS functionality.

5) Dedicated Technology: dedicate specific frequency bands to AHS use for operation of spread spectrum communications based on existing unlicensed operations technology.

2.2.2.1. ITS technology

The first approach proposes a solution in which vehicle position control, route guidance, and maneuver coordination are performed within the individual vehicle. No vehicle-to-vehicle, vehicle-to-infrastructure, or infrastructure-to-infrastructure communications are used to link vehicles within a coordination unit or with the TOC. The vehicle operates as an autonomous unit using emerging ITS technologies to implement AHS capabilities.

Position control

Radar in following vehicle obtains range and range rate data by detecting reflected signals returned from leading vehicle. Doppler ranging employs measurement of the vehicle's Doppler frequency, which is directly proportional to the velocity. The Doppler frequency is determined by filtering the reflected signal and measuring the offset between signals applied in two parallel filters. The Doppler method can be extremely precise because errors in the measured location are not inadvertently included in the differentiation calculations made to determine velocity and acceleration. The result of Doppler measurements is nearly instantaneous, minimizing signal processing delays associated with measuring the rate of change of location. Ranging radars are in development for use in adaptive cruise control applications.

Maneuver coordination

Absolute position location determined by GPS receiver. Entry and exit maneuvers must be performed using map-matching between known geographic locations and absolute position of the vehicle. Merge and split maneuvers must rely on obstacle detection/collision avoidance capabilities since inter-vehicle coordination is not provided. Emergency maneuvers are restricted at this level of instrumentation to in-lane braking.

Route guidance

Absolute position location determined by GPS receiver. Position accuracy can be determined to within 5-15 meters using differential GPS. Differential receivers are currently available and becoming cost competitive. GPS coverage is comprehensive within the continental United States and is currently implemented to provide Automated Vehicle Location (AVL) ITS services. GPS is a line-of-sight location determination system. The GPS system may be inhibited when used in center city areas where tall buildings will obstruct the view of the satellite system. Pseudo-satellites may be used to overcome this difficulty, adding cost by requiring infrastructure instrumentation.

Traffic operations

Existing ITS services may be exploited to obtain route availability and lane closure information. FM Radio Broadcast Data System (RBDS) is coming into use in the US. and has been introduced in Europe (known as RDS). The RBDS system allows co-transmission of digital data along with an FM radio signal. Traffic information is relayed to the FM radio station which in turn encodes the data and transmits it out on the subcarrier frequency (57 kHz).

RBDS transmission range is limited to the transmission range of the FM station, limiting use to areas within range of the transmitting station. RBDS is designed to transfer limited text data or message information to the motorist from the infrastructure. The data rate is up to 1200 bps. RBDS receivers are available from a number of sources, including Delco Electronics. These receivers typically display information received on the RBDS subcarrier on an alphanumeric readout on the face of the radio. Interface to vehicle processing and format of messages are key factors to integration of traffic flow information into automated vehicle control.

Advantages

- Infrastructure instrumentation to support communications backbone is not required.
- Majority of functionality transportable to non-AHS roadways.

Disadvantages

- Minimum headway dependent on sensitivity, accuracy, and response time of ranging sensors.
- Maximum lane capacity is constrained by headway limitations.
- Majority of instrumentation cost born directly by vehicle/owner.

2.2.2.2. Commercial technology

The second approach proposes a system in which commercially available public access communications systems are used to provide vehicle-infrastructure and infrastructure-infrastructure links. This solution builds on the ITS-based technology by adding coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Vehicle is autonomous, using adaptive cruise control technology based on radar ranging to maintain vehicle headway. No communication between vehicles is used to coordinate braking or acceleration.

Maneuver coordination, route guidance, traffic operations

These functions can be implemented through integration of mobile wireless radio such as analog or digital cellular with land based networks. A currently emerging information transfer protocol, Cellular Digital Packet Data (CDPD) technology transfers data over a digital packet switched network overlaid onto the cellular radio network. Connectivity to land networks such as the internet is used to provide direct access to host databases, such as centralized navigation information. CDPD can support non-time critical data transfers between a vehicle and the infrastructure to download navigation information and transfer origin/destination requests. The route guidance function is tolerant of the relatively long message latency inherent in the CDPD protocol, which inserts message traffic in idle spaces within analog or digital cellular networks.

CDPD can also provide intra-vehicle coordination for non-emergency lane changes, entry/exit, join and split maneuvers. The response time for emergency maneuvers is limited by the access times of the system, which must wait for a lull in message traffic to transmit data. Emergency maneuvers may be limited to stopping without changing lanes to avoid collisions. The latencies and access times also limit the applicability of CDPD to control loop data transfers, so headway maintenance is not expected to be compatible with this communication technology.

Advantages

- Low cost commercially available technology which provides two-way link between vehicle and infrastructure.
- Provides non-emergency vehicle-vehicle coordination.
- Increased capability over ITS/autonomous vehicle solution with little added cost.

Disadvantages

- No improvement in vehicle headway over autonomous vehicle.
- Increased infrastructure cost due to support of data base and access to land lines.

2.2.2.3. Existing technology

The third approach proposes a system in which existing vehicle-to-vehicle and vehicle-to-infrastructure communication technologies are implemented. Infrastructure-to-infrastructure communi-cations are not used to link vehicles with the TOC. This solution allows transfer of velocity and acceleration information between vehicles in addition to coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using an infrared link. Information is transmitted at infrared light frequencies through the atmosphere. The infrared link is limited to short point-to-point transfers, allowing transmissions to be confined to a limited reception area ideal for vehicle-vehicle communications. All vehicles in the system can use the same IR frequency, since the infrared receiver must be within the line-of-sight range of the infrared transmitter. Each vehicle within a coordination unit must receive information from the vehicle in front of it and retransmit the information to the vehicle behind it as necessary. Analysis by PATH has shown that the propagation delay introduced by the daisy-chain information path will not impact the expected control loop performance for close vehicle following.

Maneuver coordination and route guidance

Introduction of two-way infrastructure-vehicle communications allows origin and destination requests to be coordinated to optimize traffic flow. Autonomous vehicles may enter the automated lanes and merge with the traffic flow safely using absolute vehicle position and obstacle detection, but accommodation of the entering vehicle may have a negative impact on traffic flow. Communications will allow surrounding ve-hicles to adjust vehicle spacing and velocity in a coordinated manner to optimize traffic flow.

Vehicle-roadside communications (VRC) is an existing technology which employs a roadside transceiver (beacon) which interrogates and accepts responses from a small, inexpensive vehicle based transceiver (tag). VRC systems provide low power data transfers which are localized to within about 100 feet of each beacon. Beacons can be placed at intervals along the roadway or at specific points where communications are necessary, such as AHS entry and exit points. VRC technology is currently under deployment for both automated toll collection and commercial vehicle operations. It is compatible for adaptation to AHS because the active tags permit two-way communications. Passive tags associated with other toll-tag technology rely on reception of back-scattered energy from passive tags, which will not support entry and exit requests transmitted actively by a vehicle to the roadside beacon.

Continuous communications connectivity between the vehicle and the infrastructure will require installation of roadside beacons at close intervals. The infrastructure investment may not be cost effective in rural areas due to lower traffic volumes. It may be expected that coordination of join and split maneuvers would be less capacity critical in less dense population centers, obviating the need for continuous connectivity.

Traffic operations

Integration of TOC processors with roadside beacons can provide route availability and lane closure information to vehicles enroute. The VRC link permits two-way communications with the vehicle, and real-time speed, headway, or other traffic flow commands can be transmitted to vehicles to adjust traffic flow to existing conditions.

Advantages

- Vehicle-vehicle link allows close-vehicle-following to be implemented inexpensively.
- Technologies are low cost, proven, available.

Disadvantages

- Possible degraded performance of infrared in low visibility.
- Increased infrastructure cost to implement beacons at close intervals.

2.2.2.4. Advanced technology

The fourth approach proposes a system in which developing advanced radio technology is used to support vehicle-vehicle and two-way vehicle-infrastructure communications. Fiber optic cable is currently being deployed and is proposed to support the infrastructure-infrastructure link. This solution allows transfer of velocity and acceleration information between vehicles in addition to coordination of maneuvers, entry/exit functions, and traffic flow.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using RF radio link. Advanced digital radio techniques are being developed which allow system integrators to select modulation techniques and message protocols with a standard hardware configuration. This technology is in development for deployment to passenger vehicles. The potential for interference between users must be considered in the communications link design. This issue can be addressed by implementing frequency hopping to allow simultaneous use by multiple, independent networks. The control loop algorithm will require low message latency, which can be achieved amongst multiple users by implementing a time-slot access architecture.

Maneuver coordination

The digital radio which supports vehicle-vehicle communications for the control loop function can be extended to handle steady-state and emergency maneuvers within a coordination unit. The access protocol design would assign access slots in a manner which provides priority processing for emergency commands. Maneuver coordination which is limited to vehicle-vehicle communication of maneuvers may be restricted to single lane AHS applications. The ability to change lanes or swerve outside of a lane boundary will require intra-coordination-unit transfer of maneuver commands. Integration of the infrastructure-vehicle and vehicle-vehicle links would allow emergency maneuvers to be coordinated among multiple coordination units and across multiple lanes. This can be accomplished by providing connectivity between the vehicle-vehicle link and the infrastructure by placing radio transceivers at periodic intervals along the roadside.

Route guidance

The infrastructure connectivity provided to support maneuver coordination can also be used to transfer route guidance information. The two-way infrastructure-vehicle link permits transfer of origin/destination data from the vehicle to roadside processors. The entry/exit commands can be processed at the roadside an returned to the vehicle. Supporting several communication paths with a single radio technology will reduce vehicle instrumentation and minimize the number of interfaces.

Traffic operations

Data collected at roadside sensors can be transmitted to the TOC via fiber optic cable providing the infrastructure-to-infrastructure link. Land lines may also be used to disseminate traffic flow information such as route availability, lane closure, travel speeds, and headways for automated vehicle control. Dedicated fiber optic lines provide a very high bandwidth (up to several gigabits per second) connection between infrastructure elements. Benefits of fiber optic include low equipment and maintenance costs, and data transfer that is reliable and immune to interference. Fiber optic is also capable of transmitting uncompressed video over several channels simultaneously, an ideal feature for transfer of incident detection and environmental sensor outputs. Installation can be expensive, time consuming, and disruptive due to trenching for conduit burial for retrofit applications. Another negative feature is the susceptibility of cable to damage during maintenance operations.

Advantages

- Coordinated braking is possible with vehicle-vehicle RF communications, allowing minimum headway and maximum capacity.
- Supports coordination of traffic flow over network of AHS lanes, entries, exits, and interchanges.

Disadvantages

- Higher risk approach due to developmental stage of radio communications.
- Increased infrastructure cost and system complexity.
- Increased infrastructure maintenance and operation responsibilities.

2.2.2.5. Dedicated technology

The fifth approach proposes a system in which existing spread spectrum radio technology is used to support vehicle-vehicle and two-way vehicle-infrastructure communications. This solution may be dependent on procuring frequency assignments for AHS use, similar to recent assignments for ITS communications at 220 MHz.

Position control

Velocity and acceleration data are communicated to a following vehicle by the vehicle immediately in front using spread spectrum RF radio link. Inexpensive transceivers operating in several unlicensed bands are commonly available. The use of different spreading codes enables multiple radios to share the same frequency band with minimal interference. Operation in these bands eliminates the need for frequency planning and coordination associated with conventional radio and microwave links. Some of the commercially available transceivers provide an interface to the RF front end, allowing unique access protocols to be developed. The control loop communications function is expected to require short duration, dedicated access time slots, for example.

Maneuver coordination

The spread spectrum radio which supports vehicle-vehicle communications for the control loop function can be extended to handle steady-state and emergency maneuvers within a coordination unit. The protocol design would assign access slots in a manner which provides priority processing for emergency commands. Integration of the infrastructure-vehicle and vehicle-vehicle links can be accomplished by providing connectivity between the vehicle-vehicle link and the infrastructure by placing spread spectrum transceivers at periodic intervals along the roadside.

Unlicensed spread spectrum transmissions are currently restricted to 1 watt output power, limiting range to 1 to 2 miles between radios depending on local topography, vegetation, and structures. For communications between vehicles and the infrastructure, this limitation will dictate a spacing of 1/2 to 1 mile between infrastructure radios. Interference from other spread spectrum radio sources such as a wireless LAN in a building near the highway is possible since anyone is able to operate in this unlicensed band. Dedication of a portion of the available bandwidth to AHS would eliminate the potential for unintentional interference from other users.

Route guidance

The infrastructure connectivity provided to support maneuver coordination can also be used to transfer route guidance information. Implementation of contention access or round robin protocols may be suitable for this function. The two-way infrastructure-vehicle link permits transfer of origin/destination data from the vehicle to roadside processors. The entry/exit commands can be processed at the roadside an returned to the vehicle. Supporting several communication paths with a single radio technology will reduce vehicle instrumentation and minimize the number of interfaces.

Traffic operations

Connectivity between roadside transceivers and the TOC can be implemented to support the infrastructure-to-infrastructure link. The spread spectrum radio link can be used to disseminate traffic flow information such as route availability, lane closure, travel speeds, and headways for automated vehicle control. The bandwidth of commercial spread spectrum technology is expected to support compressed video for transfer of incident detection and environmental sensor outputs.

Advantages

- Technology is low cost and readily available.

- Coordinated braking is possible with vehicle-vehicle RF communications, allowing minimum headway and maximum capacity.
- Supports coordination of traffic flow over network of AHS lanes, entries, exits, and interchanges.

Disadvantages

- Some risk of unintentional interference unless dedicated band is assigned.
- Commercially available transmitters have limited output power and short range, requiring frequent spacing along infrastructure.
- Similar infrastructure maintenance and operation responsibilities to solution 4.

2.3 LONGITUDINAL SEPARATION POLICY

2.3.1 Description of Characteristic

2.3.1.1. Definition

This concept characteristic specifies the distance two longitudinally adjacent automated vehicles on an AHS should be separated from each other. The longitudinal separation can be specified in either spatial or temporal term, i.e. spacing or headway respectively. Note that an AHS is defined as a vehicle-freeway system that supports fully automated driving on a dedicated lane. Consequently, the focus of this Concept Characteristic is on such an AHS.

2.3.1.2. Mixed traffic or deployment addressed elsewhere

Longitudinal separation policies during possible intermediate AHS deployment steps are beyond the scope of this discussion. Some of these stages may involve mixing automated vehicles with manually driven vehicles in the same lane. More detailed discussion can be found under the Concept Characteristic of Mixed Traffic Capability.

2.3.1.3. One vehicle class only

If multiple classes of vehicle share a common lane, then two adjacent automated vehicles may be of different classes. The longitudinal separation policy should also address their separation but this is addressed in the Concept Characteristic of Vehicle Classes in a Lane. The focus of this Concept Characteristic is the separation of longitudinally adjacent vehicles of a common class. Vehicle classes include automobiles, buses, trucks, etc. (Automobile carriers, such as those required in driveless Pallet systems, are considered as trucks in the following discussion.)

2.3.1.4. Effect on other operating requirements omitted

This policy has many implications on other operating requirements, e.g., merging, entering, lane-changing, diverging, and exiting. The longitudinal separation policy not only needs to specify how far automated vehicles should be separated during these events but also impacts how the companion maneuvers are performed. Such implications will not be considered here but will be considered in the Concept Synthesis stage.

2.3.2 Importance

Longitudinal separation policy is a fundamental operating requirement for an AHS. It impacts many overall AHS Objectives and Characteristics, most notably safety, capacity, environmental impact, human factors.

Major Benefits: Longitudinal Separation for Reduction of Rear-end Crashes and Capacity Gain

As the density and speed of vehicles using the road system increase, the likelihood and the likely severity of collisions will increase. The capabilities of drivers are the principal limitation. Automated longitudinal separation has a direct impact on a major collision type: rear-end collision.

It has been estimated that driver errors are responsible for from 70% to 90% of the collisions that occur on the current US roadways. Let us concentrate on those rear-end collisions occurring on the US Interstate Highways. Out of the 5,992,937 crashes that occurred on the US roadway system during 1992, 287,453 (4.8%) of them occurred on US Interstate Highways.

Among these 287,453 crashes, 103,578 (36%) were rear-end crashes. Out of the 3,788 fatal crashes that occurred on those highways during the same year, 454 (12%) of them were rear-end crashes. Although these interstate rear-end crashes tend to be low injury producing events and tend to result in minor to moderate vehicle damage, they are a major safety problem and create much traffic congestion. Causal factor analyses (Collision Avoidance Studies) estimated that 82% of these rear-end crashes are due to driver inattention and following too closely. (See Calspan PSA Reports.) The longitudinal separation policy, supported by the automation technology, can contribute directly to the reduction of such crashes and the resulting fatalities, injuries, property damage and traffic congestion.

Limited ability of drivers to follow other vehicles produces a major limitation on lane capacity. The limitation of drivers' ability to perceive changes in vehicle spacing, relative motion and acceleration and their limited speed and precision of response ensure that lane capacity cannot generally exceed 2200 vehicles per hour under manual control. Traffic flow is the product of speed and density. The longitudinal separation policy, supported by the automation technology, addresses directly the density and hence, can contribute directly to the increase of lane capacity.

Note that longitudinal separation may depend on speed, weather, traffic conditions, lighting conditions, etc.

2.3.3 Describe All Realistic Solutions

i) Realistic Solutions and Their Performance Strengths and Weaknesses
ii) Design and Architecture Implications

2.3.3.1. Realistic solutions

i) Free-Agent
ii) Platooning
iii) Free-Agent with Gap Management
iv) Platooning with Gap Management
v) Slotting

The Free-Agent and Platooning policies have received much attention in the literature. Their impacts on the longitudinal flow of an AHS lane have been the primary focus. However, AHS lanes need to accommodate lateral flow too, i.e. lane changes for flow balancing or successful exiting. To facilitate lateral flow of traffic, the distribution of vehicles and gaps on an AHS lane can be tracked, manipulated and managed. This leads to the enhanced longitudinal separation policies of Free-Agent with Gap Management and Platooning with Gap Management. The concept of slotting was heavily studied during the 60's and 70's. We consider only the quasi-synchronous slotting concept as a realistic solution.

Free-agent vs. platooning

The free-agent separation policy has two main characteristics:

i) a vehicle travels at speed limit or a lower but safe speed if there is no vehicle within the safety distance in front;
ii) otherwise, it follows the vehicle in front at a safe distance or travels at a lower but safe speed.

This has been viewed by many as the "basic" longitudinal separation policy that any AHS should support. Platooning and free-agent policies are contrasted as follows. Free-agent policy can be viewed as a special case of platooning having only one vehicle per platoon but a "safe" free agent vehicle spacing may be different from a "safe" inter-platoon spacing. We focus our attention on the additional features required by the platooned operations.

In platoon operations, vehicles are clustered together in groups of up to 20 vehicles, with short spacings between the vehicles within a platoon and a long spacing between two platoons. Intra-platoon spacings as short as 1m have been contemplated by proponents of platooning. This mode of organizing the movements of vehicles was conceived as a way of expanding the envelope of capacity and safety that can be achieved by road vehicles. The goals are as follows. There should be no collisions in the absence of malfunction. The short intra-platoon spacings are intended to ensure that when a collision between two longitudinally adjacent vehicles does occur (due to a malfunction), the relative speed at collision time and hence, the collision severity are both low. Note that the collision refers to only the initial collision and the initial low-impact collision may lead to more serious subsequent collisions. The long inter-platoon spacings are intended to guarantee no inter-platoon collisions. Under the free-agent separation policy, vehicles move without any clustered formation and the minimum longitudinal spacing is significantly longer than typical intra-platoon spacings, but maybe significantly shorter than typical inter-platoon spacings.

A major difference between the two different solutions is the short spacings between two adjacent vehicles in a platoon. Although these short spacings provide a high potential for a large capacity gain, the safety issues remain unresolved. Most of the technical results about the pros and cons of platooning are preliminary and much more research is required before definitive evaluation can be done. Particularly, models developed for studying platooning safety are far from being able to prove the safety of platooning in the real-world. In the existing studies on the impact of the initial collision, based on either analytical or simulation modeling, variations in values of model parameters can have dramatic effects on the shape, magnitude and distribution of impact speed of the initial collision between two longitudinally adjacent vehicles. Few computer simulation models have been developed to evaluate emergency maneuvering strategies and to simulate the possible subsequent collisions after the initial low-relative-speed impact. The proponents of platooning believe that platooning will be most likely able to provide more safety and capacity than the free-agent policy. The critics do not believe in the safety of platooning.

Lane capacity under platooning hinges upon the inter-platoon and intra-platoon spacings. That under the free-agent policy depends on the inter-vehicle spacings. Until such spacings have been selected, it is difficult to estimate the capacity that the corresponding AHS lane can achieve. Note that lane capacity alone does not determine the highway capacity. In those AHS that have more than one lane and require lane-changing, some lane capacity may have to be sacrificed to accommodate vehicles' lateral movements from one lane to another.

The platooning policy has several important parameters. First of all, the maximum allowable number of vehicles of a platoon, i.e. maximum platoon size, may vary according to, for example, traffic conditions, weather and safety requirements. The spacings, either the intra-platoon spacings or the inter-platoon spacings, may also vary with respect to, for example, the vehicle class, type of longitudinally adjacent platoons, weather conditions, and safety requirements. These spacings may change in real-time to accommodate speed changes or vehicle maneuvers. Variations of platooning exist. For example, platooning may be compulsory and planned; it may also be optional and spontaneous. In the former case, all vehicles on an AHS lane are required to platoon and the operating rules stipulate how a vehicle should relate to other vehicles in the clustered formations throughout its trip. In the latter case, however, a vehicle's driver decides if he or she wants to travel in a platoon and, after so deciding, he or she can break out of the platoon at any time. This variation is often called spontaneous platooning. In mixed traffic where automated vehicles are intermixed with manually driven vehicles in the same lane, only automated vehicles that happen to be longitudinally adjacent can form a platoon. Platooning in this mixed traffic has also been referred to as spontaneous platooning.

Free-agent and platooning policies with gap management

The idea behind gap management is to better organize and more efficiently utilize the space on an AHS lane. It is also to increase traffic flow stability. Recall that both free-agent and platooning policies do not address the unused gaps between two free-agents and platoons, respectively.

The physical distribution of vehicles and gaps has a great impact on the ability of vehicles to change lane and on the time needed to complete a lane change. Proper distribution can improve the lateral and hence, the overall AHS capacity. This function (i) plans for the proper distribution of vehicles (platoons, if applicable) and gaps. (ii) monitors and manages the position and the length of individual gaps between the traffic units to maximize the lateral capacity. (The traffic unit may be a platoon or an individual vehicle.) With platooning, this function also plans and determines whether and when to split one platoon into two (or more) or merge two (or more) platoons into one. It also determines where the split(s) should occur within a platoon.

Slotting

The idea behind slotting is to more simply organize the use of space on an AHS. It is also to increase traffic flow stability. The roadside control system creates and maintains moving slots on an AHS lane that partition the AHS lane at each moment in time. Each slot is occupied by a single vehicle or left empty. In a basic slotting concept, slots are always of a single fixed length, not variable. The single fixed length may be determined based on safety requirements, weather conditions, roadway conditions, lighting conditions, etc. Other than the safety spacings and the space physically occupied by the vehicle, there may be extra space within a slot set aside for maneuvering, e.g., lane changing. Variations of this basic slotting concept exist.

Other solutions

There are other possible solutions for longitudinal separation, e.g., platooning with mechanical intra-platoon linkage. In this longitudinal separation concept, two longitudinally adjacent automated vehicles in a platoon are physically linked by a rigid bar, instead of being electronically linked through sensing, communication, computing and actuation. Since the Request for Application (RFA) called for AHS concepts and designs involving only electronic linkage, as opposed to mechanical linkage, this concept is beyond the scope of Concept Characteristic Analysis and is not considered as a realistic solution. Note that this solution still requires the technological support for all other characteristics of platooned operations, e.g., longitudinal separation between two adjacent platoons in the same lane.

2.3.3.2. Design and architecture implications

Platooning vs. free-agent

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

- vehicle-to-vehicle communication system capable of transferring reasonably high bandwidth control information (in the range of kilobytes per second);
- ranging sensors with accuracy of several centimeters within the range of a few meters;
- software logic for joining and splitting platoon.

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

- safety-verified cooperative maneuvering protocol;
- very fast and precise throttle and brake control actuators.

Vehicle-following vs. point-following technologies

There are at least two fundamentally different ways of implementing any longitudinal separation policies: vehicle-following and point-following. In the former paradigm, longitudinal separation of a vehicle from its predecessor is directly observed by the vehicle. In the latter, a vehicle follows a moving point, i.e. a trajectory, that is calculated and instructed by the roadside control system. In this paradigm, proper longitudinal separation is achieved indirectly through proper functioning of the point-following mechanism. These two paradigms, due to their technological nature, are discussed in more detail under Longitudinal Control Approach. It should be apparent that, in general, the vehicle-following approach requires higher vehicle intelligence but lower infrastructure intelligence than the point-following approach. In other words, the former is vehicle-centered while the latter is infrastructure-centered. The latter paradigm requires sophisticated centralized sensing (for traffic and driving conditions) and control systems and hence, tends to be vulnerable to single-point failures on the roadside. In addition to the centralized sensing, separate obstacle detection capability is nevertheless needed on the vehicle.

Although in theory both platooning and free-agent policies can be implemented with either of the two paradigms, it is generally believed that, due to the short intra-platoon spacings, the vehicle-following approach is absolutely required for platooning. The free-agent policy may not absolutely require the vehicle-following approach and may be amenable to the point-following approach. Point-following has received much less attention than vehicle-following and it is unclear at this stage how strongly the free-agent policy is related to either of the two approaches.

Gap management

Gap management is a roadside function that addresses both longitudinal separation and system flow control. The primary purpose is system efficiency or capacity, rather than safety. Gap management involves a certain degree of centralized control and requires extra roadside intelligence that monitors, plans and manages vehicle/gap distribution on an AHS lane, but does not absolutely require the sophisticated centralized sensing of the point-following paradigm.

Slotting

The slotting policy absolutely requires point-following longitudinal control technologies, particularly the sophisticated centralized sensing. Due to the need to set conservative slot lengths, slotting tends to have limited capacity potential.

2.3.4 Evaluate Solutions to Concept Characteristic

i) Against AHS Objectives and Characteristics
ii) Against Baseline Functions
iii) Against Uses for an AHS

2.3.4.1. Against AHS objectives and characteristics

Safety ranking

free-agent 5; platooning 6; free-agent with gap management 5; platooning with gap management 6; slotting 4

As indicated earlier, safety and capacity (and hence, mobility) differences between the platooning and the free-agent policies are unclear at this stage. Much more research is required. Gap management should not affect the safety of either the free-agent or the platooning policy. The vulnerability of the slotted systems to single-point failures on the roadside makes them somewhat less safe.

Capacity and mobility ranking

free-agent 5; platooning 9; free-agent with gap management; platooning with gap management 10; slotting 4

Platooning should provide considerably higher capacity than the free-agent policy if proven safe. Gap management should enhance capacity and mobility. Slotting always costs capacity because of the rigid space partitioning.

Convenience and comfort ranking

free-agent 6; platooning 3; free-agent with gap management 6; platooning with gap management 3; slotting 7

Platooning, when compared to the free-agent solution, may make some users feel uncomfortable, due to the short intra-platoon spacings. Gap management should not affect convenience and comfort levels. Slotting, due to the larger longitudinal spacings involved, may provide more user comfort.

Environmental impact

free-agent 5; platooning 7; free-agent with gap management 5; platooning with gap management 7; slotting 5

Platooning has been shown, through wind-tunnel simulation, to reduce aerodynamic drag by as much as 50%. The corresponding reduction of fuel consumption and pollutant emissions is estimated to be between 25% and 50%. (The ranking is based on per vehicle mile traveled on AHS. These reductions may be offset by the increase of fuel consumption and environmental impact due to increased traffic.) Gap management should not affect the environmental impact. Slotting should have similar environmental impact as the free-agent policy.

Cost ranking

free-agent 6; platooning 4; free-agent with gap management 5; platooning with gap management 3; slotting 32

Due to the higher technological requirements, platooning may incur higher vehicle costs as well as infrastructure costs than the free-agent policy. Gap management needs higher roadside intelligence and may increase the infrastructure costs. Although slotting can reduce somewhat the need for certain vehicle intelligence, it requires much more infrastructure intelligence.

Deployability ranking

free-agent 6; platooning 3; free-agent with gap management 5; platooning with gap management 2; slotting 3

Due to the extra features of platooning, compared to the free-agent policy, its deployment could be more difficult or requires a longer time. Gap management is a additional feature and hence, may require extra time for deployment. Slotting is generally considered difficult to deploy because the infrastructure needs to be extensively modified before demand buildup.

Availability ranking

free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; slotting 3

Due to the higher complexity of the platooning system, its availability could be lower than its free-agent counterpart. Gap management is not essential for safe operation of AHS. Therefore, it should not affect the system availability. Slotting increases the vulnerability of the roadside system and hence, decreases the availability, although the reduced vehicle complexity may increase the vehicle availability for a slotted free-agent system somewhat (but not for a slotted platooning system).

Supported vehicle classes ranking

Free-agent 6; platooning 4; free-agent with gap management 6; platooning with gap management 4; slotting 4

It is in general a consensus that mixing different vehicle classes in the same platoon is unsafe. Therefore, if the AHS does support a wide range of vehicle classes, grouping vehicles to form large platoons may be difficult and system operations could be more complicated. Gap management should not have any bearing on supported vehicle classes. Multiplicity of supported vehicle classes may increase the complexity of slotting. In this case, the slot length may be set for the shortest vehicle class, e.g., the automobile, and a long vehicle, e.g., a truck, may occupy more than one slot.

2.3.4.2. Against baseline functions

Check-in ranking

free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; 7

Due to the higher complexity of the platooning system, check-in function, if required, may involve more checking than the free-agent policy. The gap management feature should be have any negative impact. The slotting policy may require somewhat less of the check-in function, when compared to the free-agent policy, due to the reduced complexity of on-board functions.

Maneuver Planning and Execution Ranking

free-agent 6; platooning 5; free-agent with gap management 8; platooning with gap management 7 slotting 9

Maneuver planning and execution under platooning could be more complicated than under the free-agent policy. Gap management, due to its very nature, is conducive to maneuvering planning and execution. Due to its rigid space organization, slotting should be even more conducive to maneuvering planning and execution.

Flow control ranking

Free-agent 6; platooning 5; free-agent with gap management 8; platooning with gap management 7; slotting 9

Flow control for platooning could be more complicated than its free-agent counterpart. Gap management, again due to its very nature, is conducive to flow control. Slotting, again due to its rigid space organization, is even more conducive to flow control.

Malfunction management

Free-agent 6; platooning 5; free-agent with gap management 6; platooning with gap management 5; slotting 3

Due to the higher complexity of the platooning technologies, malfunction management could be more complicated than their free-agent counterpart. The gap management feature should not negatively impact malfunction management. The slotting policy is heavily dependent upon the proper functioning of the roadside sensing and control systems. In the presence of roadside failures, malfunction management may be severely affected.

Emergency handling

Free-agent 6; platooning 5; free-agent with gap management 7; platooning with gap management 6; slotting 4

Due to the short intra-platoon spacings, emergency handling in platooned operations could be more difficult than its free-agent counterpart. The presence of gap management should not have any negative impact on emergency handling. Moreover, it should make traffic coordination, either as a means to avoid collisions or as a way to manage traffic after collisions, easier. Due to the heavy reliance on the proper functioning of the roadside sensing and control systems, emergency handling under slotting, in the presence of roadside failures, may be more difficult than their non-slotting counterparts.

Against uses for an AHS

These five solutions fare identically with respect to the six Uses described in Table 2.1 of the System Objectives and Characteristics document. Therefore, rankings for all five solutions are identically 5. However, if the platooning is proven safe, then it should perform better in the heavily congested urban freeways due to its ability to provide much higher capacity, in which case rankings would be 7 and 5 for platooning and free-agent policies respectively. Their gap management counterparts would rank 8 and 6 respectively. Assuming that the slotting policy is safe and reliable, since it has lower capacity potential, it would rank 4.

2.3.5 Description of Correlation Between the Solutions

The correlation is discussed in the following subsections, each corresponding to the concept characteristic as numbered.

1) Platooning is strongly related to two solutions: a) Vehicle only and b) Vehicle Predominant with Some Infrastructure solution. The features and vehicle performance required by platooning discussed earlier would likely require more vehicle intelligence. The Free-agent policy can be implemented within either the vehicle-following or the point-following paradigm. If implemented by the former, it is also related to the two solutions above, but only weakly related. If implemented by the point-following approach, then it is strongly related to the solution of Infrastructure Predominant. The two policies with gap management relate to the Distribution concept characteristic in a similar way. However, gap management requires more infrastructure intelligence for additional centralized control. The Slotting policy is strongly related to the solution of Infrastructure Predominant.

2) Platooning absolutely requires Vehicle-to-vehicle Communication but is strongly related to Vehicle-to-infrastructure Communication. The Free-agent policy is strongly related to both Vehicle-to-vehicle Communication and Vehicle-to-infrastructure Communication. Gap management absolutely requires Vehicle-to-infrastructure Communication. The Slotting policy absolutely requires Vehicle-to-infrastructure Communication but is weakly related to Vehicle-to-vehicle Communication.

3) All five solutions are independent of the Roadway Interface solutions.

4) All the solutions for the Obstacle Response policy for sensing and avoidance, including sensing, prevention, avoidance, and response, are absolutely required. The requirements on these solutions are more stringent for Platooning and Platooning with Gap Management due to the hazard involved in a collision between a platoon with an obstacle. The response to a detected obstacle under either of these two policies may include "coordinated braking", in which the lead vehicle may delay its braking to ensure minimal likelihood of intra-platoon collisions. Under Slotting, obstacle detection and response heavily involves the roadside intelligence.

5) Both Platooning and Platooning with Gap Management are weakly correlated with the solution of One Vehicle Class for the Concept Characteristic of Vehicle Classes in a Lane. This is because accommodating multiple vehicle classes in a lane makes grouping of vehicles of a common type more difficult. The Free-agent and the Free-agent with Gap Management policies are independent of Vehicle Classes in a Lane. Slotting is at least weakly related to the solution of One Vehicle Class.

6) The solutions associated with the concept characteristic of Mixed Traffic Capability include segregation (physical isolation) of automated traffic from manual traffic ("segregation" for short), non-segregated AHS but dedicated AHS lane ("dedicated lane" for short) and mixing automated vehicles with manually driven vehicles in the same lane ("mixing in lane" for short).

All five solutions are weakly correlated with Segregation because accidents spilling into the automated lane of a non-segregated AHS have been shown to create significant safety hazards. This is under the assumptions that such spill-overs are not detected by the automated vehicles, not to mention collision avoidance, and that no safe driver intervention is possible. (Compared to Platooning and Platooning with Gap Management, the correlation between the Free-agent/Free-agent with Gap Management policies and segregation may be somewhat weaker because, with larger spacings typical of the Free-agent and Free-agent with Gap Management policies, drivers may serve as sensors and may be able to intervene more safely than they may under Platooning or Platooning with Gap Management.)

Slotting absolutely requires Dedicated Lane because it is very unsafe to mix automated vehicles with manually driven vehicles without sophisticated vehicle intelligence/sensing/processing. All other policies are strongly correlated with Dedicated Lane in that without lane dedication (i.e. mixing in lane) safe automation requires much more sophisticated technologies. Also, without lane dedication, an automated vehicle can join a platoon only if at least one of its two longitudinally adjacent vehicles is also automated. Platooning in such a mixed traffic has been referred to as Spontaneous Platooning. As pointed out earlier, the longitudinal separation between an automated vehicle and a manually driven vehicle is addressed in more detail in the Concept Characteristic of Mixed Traffic Capability.

7) All five solutions are independent of the Lateral Control Approach.

8) Due to the short intra-platoon spacings, both Platooning and Platooning with Gap Management absolutely require those approaches that include vehicle-to-vehicle communication system capable of transferring reasonably high bandwidth control information (in the range of kilobytes per second) and ranging sensors with accuracy of several centimeters within the range of a few meters, and very fast and precise throttle and brake control actuators. The Free-agent policy is weakly related to both the Vehicle-following and Point-following longitudinal control technologies. The Free-agent with Gap Management policy needs additional infrastructure intelligence. Slotting absolutely requires the Point-following longitudinal control technologies.

9) Platooning and Platooning with Gap Management are weakly related to the solution of Platooned Entry, either through a Transition lane or a Dedicated Station, for the Concept Characteristic of Entry/Exit. With the longitudinal separation policy of Platooning or Platooning with Gap Management, entering vehicles can form a platoon first before entering the automated

lane. By the same token, exiting vehicles can exit the automated lane in a group, as long as they have the same destination.

Free-agent, Free-Agent with Gap Management, and Slotting policies are independent of all the Entry/Exit solutions.

10) All five longitudinal separation policies are independent of the Lane Width Capability.

11) Although the actual separation under all five policies may be dependent upon the actual operating speed, all of them are independent of the design speed.

2.4 ROADWAY INTERFACE

2.4.1 Description of the Characteristic

The two core physical components of an Automated Highway System (AHS) are the vehicle and the roadway. The concept characteristic, Roadway Interface, designates the linkage or the connection between these two core components.

2.4.2 Description of all Realistic Solutions

Solutions to the vehicle/roadway interface characteristic depict the extent of interaction between the vehicle and the roadway. First order solutions for this characteristic consist of the following:

1) standard or normal interface

2) pallet

3) RPEV (roadway-powered electric vehicle)

2.4.2.1. Basic description

This section gives a brief description of each of the three vehicle/roadway interface characteristic solutions.

Standard or normal interface

The standard or normal interface simply consists of the vehicle tires on the roadway surface.

Pallet interface

The pallet interface consists of the vehicle attached to a pallet which would operate on the AHS roadway. The pallet could be sized for a single-vehicle or multi-vehicle configuration. A second order roadway interface, namely, the interaction between the roadway and the pallet system could be the standard interface of the pallet's tires on the roadway.

RPEV interface

The roadway-powered electric vehicle is an electric-electric hybrid vehicle. It has two power sources, both of whom are electric, the on-board battery and the inductive coupling system (ICS). The ICS consists of the roadway inductor, buried just beneath the road surface, and the pickup inductor, mounted on the underside of the vehicle. The coupling consists of the inductive power transfer from the roadway inductor to the pickup inductor. No physical contact exists between these two inductors. The on-board battery can store power emanating from (a) a conventional wall-outlet, for example, while the battery is being recharged overnight, (b) the ICS, as excess power during dynamic roadway charging, or (c) the ICS, as static roadway recharging, while the vehicle is parked over a roadway inductor segment. In addition to the roadway and pickup inductor, other RPEV system components include the distribution links to the electric utility grid, power conditioner located near the roadway, distribution network that carries power from the power conditioner to the roadway, onboard controller, onboard battery, motor controller, and electric drivetrain.

Energy from electrified roadway charging during driving may go directly to the onboard motor controller, and then to the motor. When the vehicle motive requirement is less than the power drawn from the roadway, the excess power would be directed to he onboard battery for later use. The amount of battery recharging from the roadway changes from day to day, as well as by time of day, by vehicle characteristics, and by driving cycle.

One desirable feature of RPEVs is that the electrified roadway can be shared by electric and non-electric vehicles. That is, nothing about the technology precludes the shared use of the roadway by RPEVs as well as non-RPEVs.

Roadway electrification, while being considered here as a solution to the vehicle/roadway interface characteristic, is more fundamentally an alternative means of propulsion that also requires an additional vehicle/roadway interface, namely, the ICS, relative to the standard interface. For RPEV there are thus, actually two types of interaction between the vehicle and the roadway. One interaction is the standard interface of the vehicle tires on the roadway surface; the second interaction, which does not involve any physical connection, is the inductive coupling system (ICS) consisting of the transfer of power from the roadway inductor to the pickup inductor.

In essence then this solution set is really a combination of two non-mutually exclusive characteristics, one being the vehicle/roadway interface and the second being the power source. This mixing allows the formation of the following additional solution alternatives:

(1) + (3) = hybrid vehicle powered by both an internal combustion engine (ICE) and roadway power. The interface is the standard one when power is drawn from the ICE and the pickup inductor is in its retracted position and is the ICS when power is drawn from the roadway.

(2) + (3) = roadway-powered pallet system in which the pallet interfaces with the roadway via its tires as well as the ICS.

Focus will be placed on the first three "pure" characteristic solutions.

2.4.2.2. Comparison of solutions

The comparison among the three alternative solutions is accomplished in two stages. Since the difference between the RPEV solution and the standard interface is the alternative means of propulsion associated with RPEV, the first comparison is made of RPEV relative to the standard interface concentrating on the additional features associated with or required of an RPEV. The second comparison will be made of the pallet alternative relative to both the standard and the RPEV solution. A more complete discussion of the alternative solutions follows.

Standard interface vs. RPEV

As indicated above, the core difference between the standard interface and roadway-powered electrification is that an RPEV is an alternative propulsion vehicle and it adds a second vehicle/roadway interface to the standard or normal one. It is assumed that the means of propulsion used relative to the standard or normal interface is the usual or standard internal combustion engine vehicle (ICEV).

The potential primary advantages/strengths of roadway electrification (AHS) over the standard interface/ICEV-AHS is the possibility for:

- obtaining environmental benefits beyond those that could be obtained by AHS alone
- providing support for sustainable transportation policies
- greater reliability of RPEVs over ICEVs in certain respects and resulting impact on maintenance requirements
- ability of magnetic field generated by inductive power transfer to form a good position reference for a steering control system; this would help keep the vehicle more directly above the centerline of the lane to received the maximum amount of power transfer.

Environmental benefits would be reductions in pollution and decreases in usage of certain fuels (petroleum-based). Whether such benefits are realized and the extent of the benefit is dependent on site as well as on several factors such as primary fuel source for generating the electricity used to power the RPEVs and user acceptance/market penetration.

The potential drawbacks/weaknesses associated with RPEVs compared to ICEVs are in the areas of:

- environmental concerns (EMF, acoustic noise, and battery disposal)
- cost/financing/ability-to-pay issues associated with building up of an electric vehicle market in addition to an AHS-market.
- ensuring deployability (user acceptance/market penetration)

- operation in inclement weather conditions (snow or ice)
- roadway inductors not likely to be present for entire length of AHS lane (cost reasons), and so would not provide lateral control for the entire trip length on the AHS. While AHS (non-RPEV) lateral control system can be used to track the vehicle to help insure that it closely lines up with the roadway inductor to maximize inductor power transfer, could have compatibility problems between AHS lateral control system and roadway inductor if lateral control solution is primarily infrastructure based.

Regarding deployability, the electric vehicle market may blossom in certain parts of the country, e.g., California or the Northeast, yet generate little if any interest in other parts of the nation. AHS would have to be flexible enough to accommodate both. As indicated above, an attractive RPEV feature is that the electrified roadway can be shared by electric and non-electric vehicles, i.e., no technological reason precludes the shared use of the roadway by RPEVs (AHS) as well as non-RPEVs (AHS).

Pallet interface vs. standard

The core difference between the pallet system and either the standard interface or the RPEV interface is the fact that the traveling unit is no longer the usual vehicle, but the pallet.

The primary advantage of the pallet system is its potential to provide much wider access to the AHS than with the use of standard vehicles. No retrofitting or purchasing of a new AHS-ready vehicle would be necessary, so everyone could potentially access the system. To use the system, however, would require some fee. The primary disadvantage of the pallet system is that it would require additional space, time, and facilities for storage, loading, unloading, and circulation throughout the AHS system. This difference is an important disadvantage relative to the standard or RPEV solution. A more complete set of strengths and weaknesses are provided as follows:

The potential advantages/strengths of the pallet-based system over the standard interface is the possibility for:

- safety-related benefits could accrue: improved control over system design could increase similarity/consistency/uniformity of traveling units and their operating characteristics; improved control over traveling unit maintenance would reduce likelihood of degraded performance, reduced interruption due to automatic check-in and -out being handled off-line; virtual elimination of problem of transferring control to the human operator, as transfer would be conducted under stopped conditions
- ease of use (no manual-to-automated-to-manual transfer in motion)
- universal access — all potential AHS users can access a pallet based system with their existing vehicles; pallet, not the vehicle attached to the pallet that would have to be AHS-equipped; a substantial social equity advantage over possibly requiring expensive equipment on-board the vehicle. Would possibly substitute a pay-as-you-use or rent-a-pallet system for purchasing an AHS-vehicle up front
- would immediately be a high number of "AHS-ready-and-capable" vehicles, i.e. no need to wait for uncertain rates of market penetration development, and construction of pallets is still necessary and depends on market demand, but sharing of pallets among users eliminates the 1-to-1 correspondence between users of system and AHS-traveling units
- pallets would provide a portable AHS technology, pallets could be moved from one location to another
- high utilization factor (assisted by sharing of pallets by users) should justify better and more robust AHS features than an occasionally used, private AHS vehicle
- use of pallet system owned and maintained pallets should yield safer and better maintained AHS traveling units
- pallet-based system could be dedicated to using alternative/cleaner fuels even

when the vehicles being carried are still ICEVs
- could be valuable in applications where it is desirable to prevent potential driver intervention or tampering

The potential drawbacks/weaknesses associated with pallets compared to the standard interface are in the areas of:

- heavy consumer of land space for storage and performing entry/exit functions
- delays at entry/exit points due to load, attach, detach, unload, and circulate activities of vehicles would lead to bottlenecks and problems to achieve and maintain desired level of throughput, mobility, and convenience
- vehicle-pallet attachment could affect comfort of ride, especially at high speeds
- storing and maintaining a large pallet inventory (of different size pallets!) as well as recirculating empty pallets will be a complex logistical endeavor, made more complex for rural application because of longer trip lengths associated with such driving
- concentrate equipment investment costs and liability onto the pallet system entity/authority
- probably use more energy for a given trip than the vehicle being carried; significant volume of deadhead (empty) return trips complete waste of energy
- vehicle/pallet combination traveling unit heavier than vehicle alone and have a higher center of gravity, which would tend to make traveling unit less stable in lateral maneuvers
- emergency handling would have very complex logistics--could have stranded vehicle-carrying pallets on highway; if vehicle has way to remotely control pallet during emergencies (to move pallet) then this could detract from universal access aspect; alternatively, mechanism for manually detaching and unloading vehicle from pallet could help, but still must contend with stranded pallets on highway as well as driving around them
- ability to operate in partially automated mode with non-AHS vehicles could be very complex logistically
- added logistical complexities associated with non-uniform pallet sizes

An RPEV pallet-based system would combine the strengths and weaknesses outlined above for RPEV systems with those of the "pure" pallet system just described.

2.4.3 Evaluation of Solutions to Concept Characteristics

The three solutions to the vehicle/roadway interface characteristic are evaluated with respect to the following three sets of evaluation criteria: (1) AHS Objectives and Characteristics as detailed in the Automated Highway Systems (AHS) System Objectives and Characteristics 2nd Draft (May 22, 1995), (2) Baseline Functions listed in the Concept Development and Analysis Guidelines, and (3) example uses for an AHS as listed in Table 2-1 of the AHS System Objectives and Characteristics document. At this initial stage in the development of AHS concepts, i.e. individual characteristics not yet integrated with each other to form whole concepts, only a ranking of each solution relative to other solutions will be meaningful. In particular, since the pallet and RPEV solutions are the unusual or different solutions compared to the standard or normal vehicle/roadway interface, the ranking for the standard interface will be given a "5" unless otherwise ranked. Rankings given as a range instead of a single value was necessary when both advantages and disadvantages were present and no available and confident means to quantify the tradeoffs among them.

2.4.3.1. Evaluation relative to AHS objectives and characteristics

The three vehicle/roadway interface characteristics are evaluated against the twenty-three AHS objectives and characteristics and in relative terms with respect to each other.

Improve safety

	Ranking
Standard	5
Pallet	7
RPEV	5

The use of an AHS with pallets would cause a shift of safety management from individual vehicles to the infrastructure. Several benefits could accrue: (1) improved control over system design could increase similarity/consistency of vehicles (i.e. traveling units) and their operating characteristics, (2) improved control over vehicle/traveling unit maintenance would reduce the likelihood of degraded performance, reduced interruption due to ACI/ACO being handled off-line, and (3) virtual elimination of the problem of transferring control to the human operator, as transfer would be under stopped conditions. Because of improved control over the designed-in capabilities, maintenance, and check-out of the critical on-board AHS systems, pallets should result in a net increase in safety over the standard interface. The pallet, however, could be more susceptible to breakdowns if it were to have more mechanical equipment than the standard interface. Roadway electrification would be rated the same as the standard interface. The concern that an RPEV would run out of battery power to complete its trip, thus, causing an added safety hazard on the AHS could be addressed during the check-in procedure, as the RPEV would be allowed to enter the AHS only if the vehicle had enough battery power to complete its trip. If the on-board battery was at too low a charge state, the vehicle would be denied access to the AHS.

Increase throughput

	Ranking
Standard	5
Pallet	2
RPEV	5

Roadway electrification would be rated the same as the standard interface. The pallet alternative is rated substantially below the standard because there could be significant entry-exit issues that could lead to bottlenecks and problems to achieve and maintain the desired increased level of throughput. Entry/exit issues are where and how pallets would be loaded, unloaded, and circulated throughout the AHS system.

Enhance mobility

	Ranking
Standard	5
Pallet	2
RPEV	5

There should be no constraint on the Rev's ability to enhance mobility relative to the standard interface. The pallet alternative is rated substantially below the standard because there could be significant entry-exit issues that could lead to bottlenecks and problems to achieve and maintain the desired enhanced level of mobility, specifically, shorter and predictable travel times. Entry/exit issues are where and how pallets would be loaded, unloaded, and circulated throughout the AHS system.

More convenience and comfort

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the Rev's ability to provide comfort and convenience relative to the standard interface. Comfort could be slightly less in the pallet case depending on the exact nature of the vehicle-pallet attachment. Moreover, convenience could suffer due to potential delays at entry/exit points as discussed above.

Reduce environmental impact

	Ranking
Standard	5
Pallet	3-7
RPEV	8

The areas of environmental impact that need to be considered are (1) pollution, (2) fossil fuel usage, (3) electromagnetic field (EMF) exposure, (4) acoustic noise levels, and (5) battery disposal.

Emissions—Relative to an ICE (standard interface), considering only vehicle-source emissions, an RPEV's emissions are extremely low, basically a zero-emission vehicle, on a gram per kilometer basis. One has to take into account, however, contributing stationary-source emissions as well to develop a more complete emissions picture, i.e. contributing stationary-source emissions for both the RPEV and the ICEV. While it is much easier to monitor and control the emissions of relatively few power plants compared to millions of ICEVs, the fuel source at the power plants will play a significant role in determining the overall emissions picture for an RPEV. A power plant using coal or oil to fuel it will emit substantially higher pollution levels than a natural gas-fueled power plant. For the PATH-SCAG study (1989-1992) investigating the emissions and utility industry impacts of roadway electrification in which roadway electrification was deployed on a subset of the Los Angeles metropolitan area freeway system, it was assumed that natural gas would be the fuel source for over 80% of electricity-generated for Southern California in the year 2025. The result was a moderate reduction in emissions across all major pollutants (hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter). Further research is required to account for the variation in powerplant fuel sources in order to determine with more certainty the extent of the emissions reductions associated with RPEV.

Fossil Fuel Consumption—Fossil fuel usage depends primarily on the fuel source used in the electric power plant. In the case study cited above with natural gas providing over 80% of the fuel source for the electricity generated for the SCAG region, the net impact on fuel usage was that petroleum consumption decreased moderately, whereas natural gas usage increased more substantially. The reduction in petroleum-based fuels helps reduce the U.S.'s dependence on foreign sources of these fuels.

Electromagnetic Fields—While tests conducted during the PATH/SCAG research effort, however, provide evidence that RPEVs are EMF safe, more EMF exposure research and its biological impacts on humans is needed. There is no irrefutable proof either way that EMF is safe or causes harm.

Tests were performed on the roadway powered bus at Richmond Field Station (RFS) at U.C. Berkeley. The strength of the magnetic field through which the ICS transfers power from the roadway to the vehicle varies depending on roadway current and distance from the roadway centerline. EMF measurements were studied from both static and dynamic testing of the PATH roadway powered bus and conventional vehicles on the Richmond Field Station test track.

Test results from the PATH bus and conventional vehicle powered roadway experiments indicated that in a unshielded situation, the magnetic flux density (the measure of EMF strength) was 300 milligauss (mG), and 1.5 to 3.0 mG for a shielded position for a 240 amp roadway. These measurements were taken at 40 inches above the roadway to approximate the EMF exposure at the driver's position in the vehicles. Shielded test findings indicated lower EMF exposure for the roadway powered vehicle since the magnetic field passes through the pick-up unit in an RPEV whereas it passes through the steel chassis in a conventional vehicle.

To put these powered roadway EMF readings in perspective, the magnetic flux density for several electrical appliances and electrical power delivery by field strength and degree of EMF exposure (in mG), are compared to both the shielded and unshielded powered roadway cases. The results indicate that for an electric shaver, electric blanket, toaster, transmission line at 115-230 kv, and the center of a living room, the EMF exposures are respectively 1,000-10,000 mG, 75-150 mG, 75-150 mG, 10-100 mG, and 0.5-10 mG. Unshielded and shielded conditions on the powered roadway yield approximately 200-800 mG and 1-5 mG, respectively. The unshielded situation is one in which a human being is exposed to the magnetic field directly without the normal shielding offered inside the vehicle by the steel of the pickup inductor or the vehicle floor and sides. The RPEV estimates of EMF were also found to be significantly below the standards for EMF exposure set by the International Radiation Protection Association (IRPA) and the International Non-Ionizing Radiation Committee (INIRC). Thus, at this time evidence regarding EMF exposure with respect to the powered roadway suggests that there is little need for environmental concern.

Acoustic Noise—As in case of emissions, fuel usage, and EMF, more work is needed in the area of acoustic noise impacts. Acoustic noise levels were investigated on the test track for the roadway powered bus at RFS. In these tests, the interior noise level was found to be 40-45 decibels. Conventional vehicles of different makes and sizes were also examined for acoustic noise under test track driving conditions. For the conventional vehicles 40-70 decibel readings were experienced. To put this in perspective, a library has an acoustic noise level of approximately 35 decibels, an office - 65 decibels, a heavy truck - 90 decibels, a jack hammer - 105 decibels, and a jet plane - 125 decibels. Experts consider noise levels of 135 decibels to be painful to the ear. The acoustic noise measurements for conventional vehicles were considered high enough to warrant further testing of lower roadway currents and higher frequencies. The use of higher frequencies in the inductive coupling design would lower interior noise levels since it permits use of lower roadway currents, and humans are less sensitive to higher frequencies.

Battery Disposal—Whether lead acid or other batteries are utilized in RPEVs, increased unrecycled battery disposal is likely to produce more impacts on the environment. The concern for water quality that would be jeopardized by the increased likelihood of battery leach water in groundwater supplies warrants attention for "cradle-to-grave" battery management. Similarly, incineration of lead waste products raises questions regarding air quality deterioration and associated health damages. Thus, it is important that behavior be reinforced towards participation in currently established recycling efforts to offset the potential for increased hazardous waste from illegal disposal of batteries.

The ranking for pallets vary depending on whether they are battery/roadway powered themselves or powered by an ICE. Thus, if roadway powered then the pallet would experience at least some of the environmental benefits as an RPEV. Pallets will, however, probably use more energy for a given trip than the vehicle being carried. Moreover, they may also have to make a significant number of trips empty, deadhead trips, which would be a complete waste of fuel/energy. There is also a tradeoff between energy use and the size of the available pallets. If pallets were available in all sizes (e.g., pallet platoons to hold from 1 to 15 vehicles) to meet the demands of any particular situation then this would make for very complex logistics. If, however, there were a "one size pallet fits all" then this would use more energy. That is, it is more energy efficient to have a 1-vehicle pallet transport 1 vehicle then for a 10-vehicle pallet to transport that single vehicle.

<u>Operate in inclement weather</u>

	Ranking
Standard	5
Pallet	4
RPEV	4

A potential problem area with RPEV is its ability to perform in bad weather, in particular, in snowy weather and its impact on the transfer of power from the roadway to the pickup inductor. A major question is how will snow affect power output? The complex logistics associated with entry/exit for pallets could be exacerbated during inclement weather, in particular during snowy conditions.

Ensure affordable cost & economic feasibility

	Ranking
Standard	5
Pallet	5?
RPEV	5?

A recent study of the regional impacts of roadway electrification (PATH/SCAG Study) included an economic analysis of RPEVs compared to their gasoline counterparts. Assumptions were made about the specifics of an RPEV scenario deployed on a subset of the freeway system in the metropolitan Los Angeles region in the year 2025. Baseline user cost comparisons of gasoline vehicles and RPEVs indicated that RPEVs may offer some economic advantage to users over the life of the vehicle if roadway infrastructure costs were subsidized. Of course, the capital costs associated with the roadway infrastructure modifications associated with implementing the technology could be sizeable. Recent Precursor Systems Analysis (PSA) estimates are in the range of $500 thousand-$1.5 million per lane mile. Much further work is necessary in this area. No cost analysis was performed on pallet-based AHS systems in the PSA set of projects. While the pallet-based scenario developed in the PSA research envisioned the pallet as the traveling unit, thus, no changes necessary to any vehicle, there would likely be pay-as-you-use costs associated with the pallet-based systems. This whole area requires much further research.

Beneficial effect on conventional roadways

	Ranking
Standard	5
Pallet	3
RPEV	5

There should be no constraint on the RPEV's ability to support a beneficial effect on conventional roadways adjacent to the AHS facility compared to the standard interface. A pallet-based system will likely be a heavy consumer of land space adjacent to entry/exit points to the AHS facility for storage and for achieving the entry and exit functions. This effect of pallet-based systems would likely have a detrimental impact on conventional roadways.

Easy to use

	Ranking
Standard	5
Pallet	3-7
RPEV	5

There should be no constraint on the RPEV's ability to support an easy-to-use system compared to the standard interface. In some respects, the pallet-based system will be much easier to use than the standard vehicle/roadway interface, since the driver does not have to worry about any transition from manual to automated and back again while the vehicle is in motion. Performing entry and exit functions could involve complex logistics and detract from ease of use. In circumstances of extreme malfunction, the pallets could become stranded on the highway waiting for external assistance for egress from the AHS (See Disengage the Driver from Driving category below) unless there were a way for the driver to manually unload the vehicle from the pallet and drive away manually. Of course, even under such circumstances, working one's way through the obstacle course of stranded pallets would be a challenge.

Infrastructure compatible

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of infrastructure compatibility.

Facilitate intermodal/multimodal transportation

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to facilitate intermodal/ multimodal transportation relative to the standard interface. The more that pallets (whether ICEV or RPEV based) support vehicles of different classes, the more complex the logistics become (See discussion in the following categories: Reduce Environmental Impact, Support TDM Policies, Support Wide Range of Vehicle Types, Enhance Operations for Freight Carriers, and Support Automated Transit Operations).

Ensure deployability

	Ranking
Standard	5
Pallet	4-6
RPEV	4

The chicken-or-the-egg problem concerning the linkages between market penetration and available AHS-ready vehicles is exacerbated in the case of RPEV since now the linkage also includes building up of an electric vehicle market (public acceptance). With respect to pallets there is universal access as all potential AHS users would be able to access a pallet based system with their existing vehicles. There would immediately be a high number of AHS-ready-and-capable vehicles without having the need to wait for uncertain rates of market penetration. Development and construction of pallets is still necessary and depends on market demand, but sharing of pallets among users eliminates the 1-to-1 correspondence between users of system and AHS-traveling units. There would, however, be issues associated with partially automated pallet based systems that would be necessary in the early stages of deployment (See Operate in Mixed Traffic with Non-AHS Vehicles category below).

Provide high availability

	Ranking
Standard	5
Pallet	3
RPEV	5

There should be no constraint on the RPEV's ability to provide high availability relative to the standard interface. For pallets, under the universal access assumption that there would be no mechanism for transferring control from the pallet to the "on-board" vehicle, access to emergency vehicles and accommodation of rapid removal of disabled vehicles from the traffic stream would be made much more difficult a task.

Apply to rural roadways

	Ranking
Standard	5
Pallet	2
RPEV	5

There should be no constraint on the RPEV's ability to support the application of AHS to rural roadways relative to the standard interface, except that the longer distances associated with rural driving would require more capital outlay for roadway modifications. Relative to the standard interface, pallets would likely exhibit an inferior performance. The longer distances associated with rural roadway driving would tend to exacerbate the dead-head or empty-pallet-return-trip event. Some of this empty trip problem could be remedied through extensive coordination of regional or state trips. Moreover, since commercial vehicles are major users of rural roadways, especially the interstates, the complexity associated with adapting pallets to such large vehicles as heavy-duty trucks would be exhibited here too (See Support Wide Range of Vehicle Classes category below). The issues associated with partially automated lanes and use of pallets would also be present here as well (See Operate in Mixed Traffic with Non-AHS Vehicles category below).

Disengage the driver from driving

	Ranking
Standard	5
Pallet	3
RPEV	5

There should be no constraint on the RPEV's ability to support the driver disengagement feature of an AHS relative to the standard interface. PSA pallet research developed a scenario in which there would be no transfer from manual to automated control and back again as in the case of the standard interface. Either the pallet would not be moving, e.g., during vehicle/pallet loading/unloading procedures, or it is moving, yet always under AHS/pallet system control. This situation would make for a safer environment than the standard interface in non-emergency situations, and truly the driver would be disengaged from the driving task. However, during emergency conditions when automated control is stopped, how would the vehicle/pallet get off the AHS unless there were some mechanism for transferring control of the pallet to the driver of the vehicle or some means to insure that the driver could manually unload the vehicle from the pallet and drive away? Communication between the driver/vehicle and the pallet or the pallet authority would also be crucial. The addition of such vehicle capabilities then puts limits on the universal access feature of the pallet technology. Having all control in the pallet means that any vehicle would be able to use the AHS since there would then be no need for any retrofitting of existing vehicles or purchasing of new AHS-ready vehicles. There is thus, a tradeoff between degree of access and ability to resume control during emergency situations.

Support TDM policies

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support TDM policies relative to the standard interface. Ensuring pallets of varying sizes to accommodate and enhance transit use would make pallet logistics more complex not because of the need for a large pallet but for the need for non-uniformity in pallet sizes.

Support sustainable transportation policies

	Ranking
Standard	5
Pallet	3-5
RPEV	6-7

RPEV may have advantages over the standard vehicle/roadway interface in the areas of it ability to support deployments that have long-term sustainable impacts on resources and the environment, compatible with policies to couple AHS with programs that encourage fuel efficiency and renewable energy technologies, implementing AHS on advanced propulsion system vehicles first, and emphasizing AHS support for public transportation. Pallet-based systems may also experience these benefits if they were roadway powered instead of ICEVs. However, another aspect of showing support for sustainable transportation systems is its ability not to lead to increased congestion and traffic burden in neighborhoods adjacent to entry and exit points to/from the AHS facility. Pallet-based systems would likely have difficulty in this area as such systems would be a heavy consumer of land space adjacent to entry/exit points for storage and for achieving such entry and exit functions (See Beneficial Effect on Conventional Roadways).

Provide flexibility

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of flexibility. The choice to use roadway electrification may be very site-dependent, yet the technology is flexible enough to allow non-RPEVs to travel on roadway electrified lanes. Given that the system consists of an RPEV/AHS and given that a particular region or state chooses to implement this system, neither of the three solutions exhibits any flexibility advantage or disadvantage over the other two solutions.

Operate in mixed traffic with non-AHS vehicles

	Ranking
Standard	5
Pallet	3
RPEV	5

One desirable feature of RPEVs is that the electrified roadway can be shared by electric and non-electric vehicles. That is, nothing about the technology precludes the shared use of the roadway by RPEVs as well as non-RPEVs. The vehicles operating in at least partially automated mode are assumed to nevertheless be traveling under roadway power. The mixing of vehicle-carrying pallets with ordinary vehicles again seems to make an already complex logistical situation more complex. Fully automated pallets would be driverless, whereas partially automated pallets would place more control with the driver of the vehicle being carried. Exclusive entry/exit facilities with barriers between the automated lane and conventional lanes for fully automated pallets have been suggested to avoid having vehicle-carrying pallets needing to weave through conventional traffic to access the automated lane, and generally make entry and exit simpler. With a partially automated pallet, how would entry/exit be handled? The same as before? That would mean that conventional vehicles sharing the automated lane would be completely separated from their counterparts on fully conventional lanes. Should partially automated vehicle-carrying pallets be allowed to weave through conventional lanes for automated lane access? such complex logistics and tradeoffs need to be thoroughly understood and evaluated.

Support wide range of vehicle classes

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support a range of vehicle classes relative to the standard interface. While certain types of freight and cargo may be carried in light-duty vans and light-duty trucks which are comparable to standard-sized passenger vehicles, the already complex logistics associated with pallets could be made substantially more complex when associated with the largest of the heavy duty vehicles, such as 18-wheelers. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets, as pallets of various sizes must be available as demanded.

Enhance operations for freight carriers

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support freight carrier operations relative to the standard interface. While certain types of freight and cargo may be carried in light-duty vans and light-duty trucks which are comparable to standard-sized passenger vehicles, the already complex logistics associated with pallets could be made substantially more complex when associated with heavy duty vehicles, such as 18-wheelers. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets as pallets of various sizes must be available as demanded.

Support automated transit operations

	Ranking
Standard	5
Pallet	4
RPEV	5

There should be no constraint on the RPEV's ability to support automated transit operations relative to the standard interface. The already complex logistics associated with pallets could be made more complex when associated with larger vehicles such as buses, although the number of entry/exit points for buses that service freeways would tend to be considerably fewer than ordinary passenger vehicles and this would help simplify pallet logistics. The tendency for more complex logistics is not necessarily associated with the size of the vehicle, but the non-uniformity in the size of the vehicles that require pallets as pallets of various sizes must be available on demand.

Provide system modularity

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the criteria of system modularity.

2.4.3.2. Evaluation relative to baseline functions

The three vehicle/roadway interface characteristics are evaluated relative to the list of Baseline functions given in the Concept Development and Analysis Guidelines.

Check-in

	Ranking
Standard	5
Pallet	8
RPEV	5

The check-in procedure for RPEV will be only slightly more detailed than for the standard interface, as the RPEV would be allowed to enter the AHS only if the vehicle had enough battery power to complete its trip. If the on-board battery was at too low a charge state, which would be measured upon check-in, the vehicle would be denied access to the AHS. Check-in requirements for pallets would be reduced substantially relative to the standard interface as the vehicle is not checked-in, the pallet is; and the pallet would always be under automatic control. Check-in would be handled off-line, i.e. the pallet is checked-in while in a stationary position.

Transition from manual to automatic control

	Ranking
Standard	5
Pallet	8
RPEV	5

The RPEV's ability to transition from manual to automatic control should be comparable to that of the standard interface. The pallet would always be under automatic control, either in a stationary position or in motion. The pallet moves after the vehicle is loaded, attached, and locked into position on the pallet off the AHS facility in a pallet attach area adjacent to the entry/exit area. The vehicle/pallet unit would not be in motion during this transfer. This would be safer than for the standard interface.

Automated driving: sensing of roadway, vehicles, obstructions

	Ranking
Standard	5
Pallet	5
RPEV	5

No differences among the three solutions is apparent at this time relative to the baseline function of sensing.

Automated driving: hazard detection

	Ranking
Standard	5
Pallet	5
RPEV	5

The RPEV must be aware of more potential hazards on the road than in the standard case, e.g., deep snow or ice over the roadway inductor. Its ability to detect these additional hazards should not be any less than for the standard interface. No differences between the pallet solution either is apparent at this time relative to the baseline function of hazard detection.

Automated driving: maneuver planning and execution

	Ranking
Standard	5
Pallet	4
RPEV	5