The RPEV's ability to perform maneuver planning and execution should be comparable to that of the standard interface. The pallet-based system could find it more difficult as it has to perform such functions for a pallet+vehicle(s) system, not just a vehicle(s).

Transition from automatic to manual control

	Ranking
Standard	5
Pallet	8
RPEV	5

The RPEV's ability to transition from automatic to manual control should be comparable to that of the standard interface. The pallet would always be under automatic control while in motion. After the pallet is brought to rest, the vehicle(s) is(are) unlocked, detached, and unloaded. This activity is performed off the AHS facility in a pallet detach area adjacent to the entry/exit area. This would be safer than for the standard interface.

Check-out

	Ranking
Standard	5
Pallet	8
RPEV	5

The check-out procedure for RPEV should be comparable to the standard interface, as the RPEV would have been queried about its available battery power during check-in. Check-out requirements for pallets would be reduced substantially relative to the standard interface as the vehicle is not checked-out, the pallet is; and the pallet would always be under automatic control. Check-out would be handled off-line, while the pallet is in a stationary position.

Flow control

	Ranking
Standard	5
Pallet	4
RPEV	5

The RPEV's ability to perform flow control should be comparable to that of the standard interface. The pallet-based system could find it more difficult as it has to perform such functions for a pallet+vehicle(s) system, not just a vehicle(s).

Malfunction management

	Ranking
Standard	5
Pallet	7
RPEV	6-7

For RPEVs there certainly would be additional items to manage under malfunction conditions compared to the standard interface situation, such as the roadway inductor or the pickup inductor. However, the RPEV would obtain access to the AHS facility upon check-in only after the system verified that the on-board battery had sufficient power to complete the entire trip. The RPEV is an electric vehicle, however, and EVs are considered more reliable than ICEVs in numerous respects because they contain fewer components and require less maintenance. There are advantages and disadvantages of pallets over the standard interface with respect to the criteria of malfunction management. Advantages include (1) control of pallet maintenance by a central authority results in better maintained pallet compared to a privately owned AHS vehicle (standard interface), (2) higher utilization of the pallet compared to a private AHS vehicles allows greater investment in each pallet (i.e. one can afford more redundancy and/or more expensive/higher reliability systems), and (3) because pallets only operate on the AHS, they can be optimized for that environment. Disadvantages include (1) higher center of gravity which likely results in a less stable "traveling unit", i.e. vehicle-pallet, (2) additional functions (e.g., vehicle load/unload and associated facilities, vehicle lockdown on the pallet, etc.) that are pallet-unique provide additional opportunities for malfunctions, and (3) there will probably be a need for additional response teams to recover pallets with minor malfunctions. On the whole picture, advantages likely outweigh disadvantages. Other advantages would be associated with the pallets if they were RPEV as well.

Emergency handling

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV solution may encounter additional situations of an emergency type that would not ordinarily be encounter by the standard interface, e.g., a large scale electrolyte spill from the battery, but its ability to perform emergency handling should not be inferior to that of the standard interface. For example, if automated control should temporarily cease as well as roadway power, then the RPEV should be able to egress from the AHS facility under manual control using its on-board battery for power, since permission to access the AHS facility was given only if the vehicle had sufficient battery power to complete its journey. Emergency handling for a pallet-based AHS is rated inferior to that of the standard interface solution. It is assumed that the pallets are driverless and that the on-board driver/vehicle would not gain control of the pallet. A shut down of the AHS facility would then result in stranded pallets with attached vehicles that would require some means of removal from the AHS facility unless there were available to the driver the means through which he/she could manually unload the vehicle from the pallet and drive away. There would still be the gauntlet of stranded pallets around which the vehicles would have to maneuver. Major delays could be likely.

2.4.3.3. Evaluation relative to uses for an AHS

The three vehicle/roadway interface characteristics are evaluated relative to the list of example uses for an AHS listed in Table 2-1 of the AHS System Objectives and Characteristics.

Heavily congested urban highway

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in a heavily congested urban highway environment should be comparable to that of the standard interface. The pallet-based system is rated inferior to that of the standard interface because of the very complex logistics at and near entry and exit facilities associated with loading, unloading, storing, and recirculating the pallet around urban area. Such disadvantages for the pallet would still exist even with an RPEV-based pallet. In addition, without exclusive entry and exit facilities, pallet-carrying vehicles would have to weave through ordinary conventional traffic streams which could pose additional problems. So the need for exclusive entry/exit facilities would require infrastructure modifications and possibly additional land.

Exclusive transit vehicle lanes

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an exclusive transit vehicle lane environment should be comparable to that of the standard interface. Generally, pallet-based systems should be able to support this use for an AHS, however, the process of loading, attaching, unloading, and detaching such a large vehicle as a bus could pose some logistics challenges. Issue of need for exclusive entry/exit facilities as in "Heavily Congested Urban Highway" use above is also issue here. Another issue making the logistics more complex is that of the short-haul/long-haul aspects of the bus trip. That is, the trip from origin to destination may include several short-haul runs along the route to pickup passengers. There could be bus stops on the highway (which would require infrastructure modifications to build) or the bus could exit the facility as needed to pickup passengers then get back on. This latter approach, however, would require entry/exit facilities at each of these points as well as having a bus-carrying pallet negotiate the arterial network to pickup passengers and return to the highway. Further research is needed to fully understand the complex logistics and tradeoffs associated with this scenario.

Only HOVs in rush hour

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an only HOV-in-rush-hour environment should be comparable to that of the standard interface. The same problems associated with the complex logistics of pallet-based systems described above in the "Exclusive Transit Vehicle Lanes" category are also present in this case with the additional issue of requiring pallets of different sizes (buses, vans, passenger vehicles) (See "Support Wide Range of Vehicle Classes" category) that could make already complex logistics associated with pallets substantially more complex when associated with the non-uniformity in the size of the vehicles that require pallets. Pallets of various sizes must be available as demanded.

Exclusive commercial vehicle lanes

	Ranking
Standard	5
Pallet	3
RPEV	5

The RPEV's ability to support the use of AHS in an exclusive commercial vehicle lane environment should be comparable to that of the standard interface. Generally, pallet-based systems should be able to support this use for an AHS, however, the process of loading, attaching, unloading, and detaching such a large vehicle as some heavy-duty trucks could pose some logistics challenges. Issue of need for exclusive entry/exit facilities as in "Heavily Congested Urban Highway" use above is also issue here. Docking facilities would require modifications for detachment and unloading of the vehicles from the pallets. The truck-carrying pallet would still have to travel from the highway exit to the docking facility through the arterial network. Further research is needed to fully understand the complex logistics and tradeoffs associated with this scenario.

Sparse rural areas

	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 associate 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 truck traffic are major users of rural roadways (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).

Roadway-powered electric vehicle

	Ranking
Standard	1
Pallet	1
RPEV	10

This category is unusual since the category itself is identical with one of the solutions. Obviously, the RPEV gets the highest ranking for its own category. As previously discussed, anther solution to this vehicle/roadway characteristic could be a hybrid case for both the vehicle as well as the pallet system, i.e. to use roadway power for a portion of their means of propulsion. In these cases, the rankings for both the standard and pallet solutions would be 10 if roadway power is used for traveling on the AHS. Otherwise, the vehicle associated with the standard vehicle/roadway interface is assumed to be a "standard" internal combustion engine vehicle and so would earn the lowest ranking; and the pallet would be assumed not to be powered by roadway electrification and would also receive a ranking of 1.

2.4.4 Description of Correlation Between Solutions

The level of correlation and compatibility between each of the solutions for the vehicle/roadway interface with any of the suggested solutions listed in the Concept Development and Analysis Guidelines are listed below with justification and analysis. Values for the correlation levels are given, according to the guidelines as follows: AR (absolutely required), SR (strongly related), WR (weakly related), and I (independent).

2.4.4.1. Distribution of intelligence/sensing/processing

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Most important compatibility issue to consider is the additional complexity associated with the RPEV (vehicle or pallet) vis-à-vis the buried roadway inductor and also having intelligence embedded in the roadway infrastructure.

2.4.4.2. Communications

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

No apparent incompatibility problems associated with any of the solutions to this characteristic. Communications between the vehicle and the roadway will make much stronger the ties between them.

2.4.4.3. Separation policy

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Pallets and platoons, while not necessarily incompatible, certainly make for more complex logistics as pallets of different, non-uniform lengths would be required to accommodate vehicle platoons of varying lengths. A single pallet long enough to accommodate the longest platoon of vehicles allowed would reduce the logistics issue but would use more energy (e.g., a fifteen vehicle pallet carrying a single vehicle).

2.4.4.4. Obstacle response policy

	Level of Correlation
Standard	SR-AR
Pallet	SR-AR
RPEV	SR-AR

Almost all suggested solutions are vehicle-based. Should probably speak more generally in terms of the traveling unit and not the vehicle, at least until pallets are eliminated from consideration for inclusion in AHS concept. For the pallet alternative, all such traveling unit-based solutions need to be pallet-based solutions instead of vehicle-based solutions.

2.4.4.5. Vehicle classes

	Level of Correlation
Standard	WR-I
Pallet	SR-AR
RPEV	SR-AR

Vehicles of different classes (passenger cars, vans, light-duty trucks, buses, heavy-duty trucks) are associated with vehicles of different sizes and the need for non-uniform size of pallets, again a more complex logistics scenario.

2.4.4.6. Mixed traffic capability

	Level of Correlation
Standard	WR-I
Pallet	SR
RPEV	SR

While there are no compatibility problems associated with RPEV, another mode is present to consider when studying the capability of mixed traffic travel. There is AHS/RPEV, non-AHS/RPEV, AHS/non-RPEV, and non-AHS/non-RPEV. Nothing in the roadway electrification technology precludes RPEVs and non-RPEVs from sharing the same lane. Mixing pallets and non-pallets (standard vehicles), however, has problems (See Operate in Mixed Traffic with Non-AHS Vehicles).

2.4.4.7. Lateral control

	Level of Correlation
Standard	WR-I
Pallet	WR-I (ICE pallet) or SR-AR (roadway powered)
RPEV	SR-AR

The inductive coupling system can transfer the maximum current to the vehicle when the vehicle is properly centered above the roadway inductor. The magnetic field created by the roadway inductor is very strong and distinctively shaped. It forms a good position reference for a steering assistance or control system. This would help keep the vehicle more directly above the centerline of the lane to received the maximum amount of power transfer. The roadway inductor, however, would likely not be present for the entire length of the AHS lane, and so it could not provide lateral control for the entire trip length on the AHS. Alternatively, the 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. If lateral control solution is primarily infrastructure based then potential conflicts between the two technologies using the same roadway need to be addressed. This subject needs to be more thoroughly investigated as a means for automatic vehicle steering.

2.4.4.8. Longitudinal control

	Level of Correlation
Standard	WR-I
Pallet	WR-I
RPEV	WR-I

No apparent compatibility problems associated with the three vehicle/roadway interface solutions (primarily vehicle-based). Such vehicle-based solutions would need integrating with the pallet for that solution.

2.4.4.9. Entry/exit

	Level of Correlation
Standard	WR
Pallet	AR
RPEV	WR

The pallet-based alternative leads to complex logistics problems at entry/exit points. If the pallet solution were used in conjunction with non-exclusive entry/exit facilities using a transition lane to access the AHS lane after weaving through conventional traffic lanes (See Operate in Mixed Traffic with Non-AHS Vehicles category), the logistics of handling such a scenario would be very complex. As indicated in the discussion above on "Beneficial Effect on Conventional Roadways", a pallet-based system will likely be a heavy consumer of land space adjacent to entry/exit points to the AHS facility for loading, attaching, unloading, detaching, and storage and for achieving the entry and exit functions.

2.4.4.10. Lane width

	Level of Correlation
Standard	WR-I
Pallet	WR-I
RPEV	WR-I

Compatibility problems associated with the three vehicle/roadway interface solutions are more directly associated with the use of alternative vehicle types.

2.4.4.11. Design speed

	Level of Correlation
Standard	WR-I
Pallet	WR (ICE pallet) or SR (roadway powered)
RPEV	SR

While power can be drawn inductively with no problem at high speeds, there is a tradeoff among speed, length of roadway inductor, and amount of power transferred. For example, a bus with a 10 foot pickup inductor sitting in a stationary position for one second over a 10 foot roadway inductor will draw a certain amount of power, P. The same bus traveling 60 mph (88 feet per second) passing over a 10 foot roadway inductor will take 0.11 second and thus, will draw less than P power. Alternatively, to draw the same amount of power will require a considerably longer roadway inductor (higher capital costs!). These tradeoffs must be studied in order to make more informed decisions about design speed.

With respect to pallets, the kind of vehicle-to-pallet attachment and locking mechanism could be affected by pallet speed. An RPEV-pallet would encounter the same design speed-related problems as an ordinary RPEV.

2.4.5 Conclusions

Based on this investigation of the roadway interface concept characteristic considering in detail the three solutions (standard, pallet, and roadway electrification) as well as the follow-up discussion of these issues at the Concept Characteristics Review Meeting during the June 27-28 meeting, it was decided by the C! Team that both pallets and roadway electrification would not be recommended for continuing study as a potential concept discriminator during the remainder of the concept downselect process of WBS C1. This would not, however, mean that either pallets or roadway electrification would or should not be studied further in the context of applications of various AHS concepts. Indeed, roadway electrification is specifically enumerated as an application scenario in the Objectives and Characteristics document. Regarding pallets, however, there are numerous issues to resolve regarding the apparently very complex logistics and the formidable setup requirements to handle the entry/exit activities required to minimize chances of a delay or at least of prospects of a sizeable delay with pallets. The smaller the delay the larger the size of the logistics operation necessary to handle pallet entry/exit operations. The smaller the logistics operations the larger the time delay would likely be. A complex and sizeable logistics operation would be a big land use consumer. Thus, land use is involved to a great degree in the tradeoffs that need to be made. Also, a large logistics operation would likely be very costly with the potential requirement to purchase additional real estate. Moreover, additional delay means increased travel times which also means increased cost. A rural application could have more logistics problems than for an urban application, jurisdictional issues associated with interstate crossings, competition with Amtrak.

2.5 OBSTACLE RESPONSE POLICY

There were three main considerations in deciding obstacle response policy. The first involves trade-offs in the amount of prevention vs. detection of obstacles. The second involves trade-offs in the amount of manual vs. automated detection. The third involves the vehicle maneuver capability in an obstacle avoidance response. As in longitudinal and lateral control, the technology to perform the obstacle detection task was not specified since development of this technology is still in its early stages (i.e. for the reliability required in AHS).

In considering prevention vs. detection, the most difficult type of obstacle that could occur in each particular case was examined. It was immediately apparent that there are many difficult obstacles (e.g., tire and vehicle parts, large birds, animals, fallen or wind-blown objects) which cannot be fully prevented, even though the probability of their occurrence could be made very small. Thus, any concept must retain full object detection capability for all types of objects, regardless of the degree of attempted obstacle prevention.

A similar examination led to the conclusion that there are few choices in the amount of manual help in the detection process. The natural tendency is to automate the detection of "easy" obstacles, and let humans detect the "hard" ones. The fallacy in this is that humans would have to detect all obstacles in order to decide which ones are the "hard" ones. This would make automatic obstacle detection redundant at best. Thus, the only possible choices are fully manual detection or fully automated detection.

The obstacle avoidance maneuver capability is related to the sensing capability. The possibilities are: (1) remain in the lane and stop or overrun the obstacle; and (2) steer around the obstacle. With manual obstacle detection, either choice is valid. With automated obstacle detection, the ability to steer around an obstacle is related to the field of view of the sensing system. Forward-looking, side-looking, and possibly rearward-looking sensors would be required for fully automated obstacle avoidance with steering capability. The trade-off is to use only forward-looking sensors for fully automated detection of obstacles in the vehicle lane. Once an obstacle is detected, the vehicle would have to stop and temporarily switch to manual detection to steer around it, or wait for the obstacle to be removed.

The above considerations led to the following three choices for the obstacle response policy:

2.6 VEHICLE CLASSES IN A LANE

This concept characteristic is an operational characteristic that defines one facet of the operational system requirements. This particular facet concerns whether or not an AHS lane should be restricted to a single vehicle class.

Possible solutions include:

Single Class Only—Only one class of vehicle is allowed into a given lane. A class definition would need to be specified.

Mixed Class—Different class vehicles could freely mix within a lane.

Platoon (Homogeneous)—Packets would be composed of a single class of vehicles, but mixed platoons would be allowed in the same lane.

Platoon (Sorted)—Packets would be composed of mixed classes of vehicles, but would be sorted on some key characteristic such as stopping distance. The length of platoons would vary as a function of the Markovian arrival of different classes of vehicles.

Note that if platooning is not allowed, then the first two solutions are the same as the last two. (In other words, if separation speeds are set independent of modes of operation (e.g., predefined separation (15 ft.), etc.) then "platoon" is undefined)

2.6.1 Solution Description

This section will describe the four possible solutions identified above. Each solution description will include a discussion of the solution definition, estimated performance, and any implication for the overall system architecture.

2.6.1.1. Single class only

Description

This solution would require all vehicles in a single lane to be of a common class. Class would be identified during check-in at which point a lane assignment would be made.

Estimated performance

This system could obtain high systems performance in terms of speed and safety, although it would get limited use by restricting itself to a subset of the desired users.

Architecture implications

The check-in station must be able to identify vehicle characteristics and/or Class to grant entrance approval or lane assignment. Inter vehicle communications are minimized as individual vehicles do not need to cooperate or be aware of special vehicle classes. Road Infrastructure requirements can be optimized for the particular vehicle class. Operational limits and system performance can be optimized for a restricted set of parameters.

2.6.1.2. Mixed classes

Description

In this solution, more than one class of vehicles could operate in any lane. Vehicles may need to transfer information to surrounding vehicles on stopping distance, obstacle sensing fields, etc. to assure safe operations. No additional requirements are placed on the check-in station sort incoming traffic.

Estimated performance

This would give the highest number of users access to the system. However, the system would have to operate at the lowest common denominator of the vehicles currently in the lane.

Architecture implications

Vehicles may need to transfer information to surrounding vehicles on stopping distance, obstacle sensing fields, etc. to assure safe operations. No additional requirements are placed on the check-in station sort incoming traffic.

2.6.1.3. Platoon (homogeneous)

Description

During entrance check-in, vehicle classes would be noted. Information would be returned to the entering vehicle regarding the vehicle(s) in front to allow platooning. Incompatible vehicles would have to maintain greater than normal operational separation. In this fashion compatible platoons could be assembled with homogeneous vehicles, and differing platoons could be separated appropriately.

Estimated performance

All vehicle classes can be accommodated. The operational envelope (speed, etc.) would be between an optimally set number and a lowest common denominator although biased toward the lower end because of platoon passing/resorting constraints.

Architecture implications

Additional software would have to be added to the check-in station for platoon sorting and to the vehicles to remember their relative operating position vis a vis the rest of the platoon. Inter vehicle communications may be required. Roadway design would need to accommodate the lowest common denominator in terms of width, control frequency, etc.

2.6.1.4. Platoon (sorted)

Description

During entrance check-in, vehicle class would be noted. Information would be returned to the entering vehicle regarding the vehicle(s) in front to allow platooning. Vehicles would be sorted inversely according to a primary parameter such as stopping distance so that they could be platooned without violating operating constraints. In this fashion sorted platoons could be assembled with heterogeneous vehicles sorted by a primary feature such as stopping distance, gross weight, height, etc. Any negative discontinuity in the primary parameter would cause a new platoon to form with the lead vehicle noting the additional separation parameters. In this fashion, all vehicle classes could be accommodated with maximum efficiency while maintaining safe operations.

Estimated performance

All vehicle classes can be accommodated. The operational envelope (speed, etc.) would be between an optimally set number and a lowest common denominator although biased toward the lower end because of platoon passing/resorting constraints.

Architecture implications

Additional software would have to be added to the check-in station for platoon sorting and to the vehicles to remember their relative operating position vis a vis the rest of the platoon. Inter vehicle communications may be required. Roadway design would need to accommodate the lowest common denominator in terms of width, control frequency, etc.

2.7 MIXED TRAFFIC OPERATION

2.7.1 Description

Mixed traffic operation refers to the degree to which vehicles under manual control and those under automated control simultaneously share one or more lanes of a vehicle-highway. Figure 2.7.1-1 shows the spectrum of mixed-Traffic operation. At one end of the spectrum, there is no mixing: manually controlled vehicles (MCV) and automatically control vehicles (ACV) are segregated, with MCV assigned to MCV-dedicated lanes and ACV assigned to ACV-dedicated lanes. At the other end of the spectrum there is full mixing of MCV and ACV traffic: there are no dedicated lanes. In between these two extremes lie combinations of dedicated lanes and shared lanes.

Given this spectrum, the extreme and closed interval between the extrema correspond to isolation categories in terms of AHS concept characteristics: (i) no mixing, (ii) partial mixing, and (iii) full mixing of MCV and ACV. The relationship between each solution category and the existence of dedicated and shared lanes in a vehicle-highway system are shown in Table 2.7.1-I.

Note that these solution categories do not exclude the possibility of dynamically changing the designation of a lane from dedicated to shared and vice versa. That is, mixed traffic operation can have a temporal component. For example, during peak-hour usage of a vehicle-highway system in an urban area or in the event of an accident on either a dedicated or shared lane, it may be necessary to reallocate the number of lanes designated as dedicated and shared.

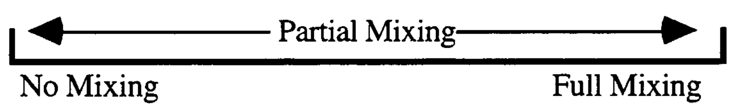

Figure 2.7.1-1. Spectrum of Mixed Traffic Operation Alternatives

Table 2.7.1-I. Relationship Between Each Solution Category and the Existence of Dedicated and Shared Lanes in a Lane

	Dedicated Lanes	Shared Lanes
No mixing	yes	no
Partial mixing	yes	yes
Full mixing	no	yes

2.7.2 Description of Realistic Solutions

An objective determination of whether a specific solution within one of the three mixed traffic operation solution categories is realistic cannot be performed in a void. Rather, a specific solution or category of solution is realistic in terms of a specific system context. Consider, for example, a rural and an urban segment of a vehicle-highway system. A solution characterized by full mixing may be deemed pragmatic for the rural portion of the vehicle-highway system due to cost considerations: it may be hard to justify on a per-kilometer basis the cost to build additional dedicated AHS lanes if the volume of traffic on these lanes is expected to be low. However, the same solution may not be pragmatic for use in the urban segment of the vehicle-highway system: the risk associated with system hazards introduced by fully mixed lane operation in high-density traffic may be too high from a public policy perspective. Hence, the same mixed lane operation solution may be realistic for zero, one, or more specific system contexts for the same candidate concept AHS.

2.7.2.1. No mixing

Pros: The sensing and control functions required of the vehicle-highway system may be less stringent than those for partial- or full-mixing lane operations due to the absence of manually driven or malfunctioning AHS-equipped vehicles in the dedicated AHS lanes under nominal conditions.

Cons: The AHS must be able to detect and compensate for rogue users of a dedicated AHS lane; a rogue user of a dedicated AHS lane is a vehicle that enters a dedicated AHS lane when it is either not AHS-equipped or failed or deceived the check-in test to enter the dedicated AHS lane. The rogue user of a manual-only lane is a vehicle operated under automatic control.

Strict separation of MCV and ACV can make it difficult to respond to an accident (e.g., vehicle-vehicle crash) or failure (e.g., AHS-equipped vehicles communication system fails or debris, such as a piece of wood falls onto the dedicated lane) occurs within a dedicated lane apprehend a reach the accident scene, rogue vehicle (for enforcement purposes), or malfunctioning vehicle.

The level of usage of lanes dedicated to AHS-equipped vehicles will be low in the early stages of AHS deployment. Moreover, in rural areas, it can be difficult to justify on a per-kilometer basis the cost to build additional dedicated AHS lanes or convert existing manual lanes to dedicated AHS lanes if the volume of traffic on the dedicated lanes is not expected to exceed a certain threshold.

2.7.2.2. Partial mixing

Pros: Partial mixing permits some degree of flexibility in making tradeoffs among system safety, cost, and throughput-capacity. For example, commercial and transit vehicles under manual or automatic control can be relegated to lanes reserved exclusively for their use, while all other vehicles, irrespective of their mode of control, share the remaining lanes. From a system safety perspective, such an arrangement removes the hazard characterized by two vehicles of greatly differing masses colliding at highway speeds.

In comparison to no-mixing lane operation solution, shared lanes can be used to reroute traffic, respond to an accident (e.g., vehicle-vehicle crash) or failure (e.g., AHS-equipped vehicle is communication system fails or debris, such as a piece of wood falls onto the dedicated lane), or apprehend a rogue vehicle (for enforcement purposes).

Cons: As in the no-mixing lane operation solution, there needs to be a capability in any existing dedicated lanes to detect rogue users.

The sensing and control functions required of the vehicle-highway system may be more stringent than that of no-mixing lane operation for the following two reasons: (i) in shared lanes, ACV must compensate for the unexpected or incorrect behavior of human drivers and (ii) MCV must compensate for unexpected or incorrect behavior of the ACV.

2.7.2.3. Full mixing

Pros: Manual-use lanes on existing highways can be used for AHS traffic.

Cons: As with no mixing, there is less flexibility to accommodate system safety, cost, and throughput-capacity issues than with partial-mixing lane operation solutions.

The sensing and control functions required of the vehicle-highway system may be more stringent than those for no- or partial-mixing lane operations for the same reasons cited above.

2.8 LATERAL CONTROL APPROACH

2.8.1 Characteristics

The purposes of lateral control are to automatically maintain the vehicle's position within a line, change lanes, help to avoid obstacles, or merge into or out of the automatic highway system.

To facilitate the above goals, the lateral control will need to perform the following basic functions: roadway definition, sensing, signal processing, control, and actuating. The AHS roadway is either defined by some kind of markers on the roadway or stored as a map in some devices. The raw information of the absolute, or relative vehicle position is recognized and transmitted through some media to the sensing devices. Based on the characteristics of the media, the raw information is then signal processed to obtain the necessary control variables. One common such variable is the current lateral deviation of the vehicle with respect to the road center. The number and nature of the variables depend on the requirements of the inputs of the control algorithm. The control algorithm takes this (these) input(s) and produce steering command based on a set of designed procedures. The algorithm is developed primarily based on the overall AHS lateral control system/operating requirements. An automatic steering actuator then interacts with the manual steering mechanism to perform the desired steering function. The vehicle reacts based on its dynamic characteristics, and the environmental disturbances.

The design and the complexity of the control function depends on the overall lateral functional requirements, such as maximum tolerable lateral deviation, minimum emergency response time. The major difficulties involving are 1. good tradeoff between lane-tracking accuracy and ride comfort when small lateral error is demanded, 2. good robustness against environmental disturbances and system uncertainties, and 3. high reliability for emergency responses. Additional control inputs such as incoming road curvature, relative vehicle orientations may be required to meet stringent functional requirements.

The choice of the automatic steering actuator depends on the control requirement flow-down, the ease of both user and manual system interfaces, as well as the cost and reliability.

The majority of the variations of the lateral control lies on the sensing system and the corresponding signal processing. There are many systems suggested based on different detection devices, media, and technologies. They are of different maturity level today, nevertheless most of them have the potential to provide the basic information necessary for the automatic lateral control. Although the selection of such sensing and signal processing system depends somewhat on the control function requirements, the eventual decision will be based more heavily on the *maturity* of each technology, future *potential* (e.g., upgradability) of each system, overall *reliability*, the total *cost* (or the marginal cost) of the sensing/processing system together with that of the corresponding infrastructure modification/maintenance, as well as the *schedule* of the product development.

It is of course preferable to require no additional infrastructure modification for the roadway definition. However, the schedule, the maturity, and the reliability of the corresponding sensing/signal processing system may demand some form of roadway infrastructure modifications.

2.8.2 Realistic Solutions

There are many possible solutions of the lateral control approach. They can be grouped in different ways. For example, grouped by where the control and sensing devices located, we have vehicle centered (located in the vehicle), or infrastructure centered lateral control. By the road markers: magnet nail, magnet strip, electric wire, resonance coil, guard rail, ... By the sensor transmitting media: magnetic field, electro-magnetic waves with different wave length, sound wave. By the power trans-mitted: active and passive. By the direction the sensor is pointing at: look ahead, look down, and look sideways. By the technology: vision, GPS, Differential GPS, frequency selective strip, acoustic, wireless communication, Infrared Beacon,...

To address the fundamental difference in the approaches of lateral information acquisition, the following method of grouping is chosen:

- Mechanical Guided Roadway: There is a physical link between the vehicle and the roadway in this category, for example, rail road is one of such case.

This is not a realistic solution of the lateral control approach.

- Indirect Guided Roadway: There is no physical link between the vehicle and the roadway in this category. The road is defined by markers either on the center/side of the roadway or on the roadside. The markers can be magnet nails or strips, electric wires, resonance coils, guard rails, different radar reflectors (strips, paints, mesh), optical or electro-optical reflectors, acoustic or ultrasonic reflectors, or even ordinary lane markers. The appropriate devices are used to detect the field strength, or to compare the incident and reflected signals. The corresponding physical properties are then used by some signal processing algorithm to determine the relative distance between the sensor and the markers. Some of the marker systems, such as the magnetic systems, have inherited ability to code information (e.g., future road map) on the roadway. Some of the systems requires active elements either on the roadway or in the vehicle. Some are totally passive. However, they are similar in terms of their eventual potentials and basic limitations. This is a realistic solution of the lateral control approach.
- Direct Imaging: There is no physical link between the vehicle and the roadway in this category. This category involves primarily machine/ computer vision systems with cameras and image processing. Relative geo-metrical relationships between the vehicle and the roadway can be extracted from the image of the roadway divided markings captured by the camera. Besides the information similar to those obtained from the indirect guided roadway system, direct imaging systems have the potential to apprehend more roadway knowledge, such as roadway obstacle detection and sign recognition. Furthermore, the extensive research conducted on this lateral control approach warrants its consideration separately from the indirect guided roadway category. This is a realistic solution of the lateral control approach.
- Beacon System with Road Map: There is also no physical link between the vehicle and the roadway in this category. Instead of obtaining the relative vehicle information with respect to the roadway markers, the systems in this category acquire absolute vehicle locations through some kind of global or roadside beacon systems, for example, GPS, Differential GPS, or wireless communication. Relative geometrical information between the vehicle and the roadway can be obtained by comparing the current and previous absolute vehicle locations with respect to the map. It can also be a realistic solution of the lateral control approach.
- Dead Reckoning with Inertial Navigation: These systems utilize vehicle based motion sensors such as gyros, accelerometers and wheel encoders to estimate the vehicle's location on the roadway. To function as a lateral control system, this technology would be combined with a map or some discrete beacon system to obtain the vehicle's absolute position. Due to the error accumulation in these sensor over time, it is unlikely this type of system alone could solve the entire lateral control problem. However such a system may be effective when combined with other lateral control alternatives, particularly those which provide vehicle position estimates that are relatively widely spaced in time or distance. To that effect, we still consider it to be a realistic solution of the lateral control approach.
- Infrastructure Based Lateral Control: This concept involves systems which individual vehicles' lateral sensing and/or control functions are the responsibility of the infrastructure. Although centralized sensing/control capability seems to be attractive from the simplicity point of view, it is in fact a non-efficient method of performing the automatic lateral control functions. Moreover, the infrastructure based lat-

eral control system requires several communication technologies that are not currently available and will not be available in the near-term. These requirements include continuous communication for real-time control of the vehicles with absolutely no interruptions or loss of information; and a sophisticated network of computers able to 'hand-off' sensing/control functions of vehicles with absolutely no interruptions or loss of information. Furthermore, the latency of the communication as well as the 'local' uncertainties and variations of each vehicle/components/environment make the infrastructure based lateral control system more costly than any of the above suggested systems. As a general rule, remote servo control system is always more costly and difficult to build. Combining the above arguments and the possibility/ability of simultaneously creating thousands of accidents should a failure in the infrastructure occur disqualify this system to be a realistic solutions.

Why the possible solutions are defined as above? Notice that the members in each generic group possess similar system potential and have common limitations. For example, the best can be obtained from the indirect guided roadway system will be the exact knowledge of the current vehicle geometric relationship with respect to the road marker along with an incoming road map. On the other hand, the direct imaging systems have more potential simply because the image contains more information than just the relative relationship. But the complexity of imaging processing and the reliability in the inclement weather will be a common problem area for the direct imaging system for some time to come. The differences of future potential among system within a group are not very significant. The eventual choice among one group, should it be chosen as a candidate, will be based on the tradeoff of the level of maturity, the ease of coordination with other components in the vehicle or roadway, the overall reliability, the total cost of the sensing/processing system together with that of the corresponding infrastructure modi-fication and maintenance, as well as the schedule of the AHS development.

Moreover, the above categories are not absolutely exclusive. For example, a member of the direct imaging category that looks directly down at the lane maker next to the vehicle during bad weather very much resembles an indirect guided roadway system. A beacon system with long sampling interval and a discrete marker system with very low vehicle speed are similar in nature to a dead reckoning system without inertial navigation. A system in the indirect guided roadway category may resemble a dead reckoning system during lane change maneuvers if the lateral position sensor has a restricted sensing range. If we bring in the fact that each solution group has similar limitations, a tentative conclusion may be that some combination of the above realistic solutions is yet another feasible solution.

The realistic solutions of the lateral control approach are the following vehicle centered approaches:

- Indirect Guided Roadway
- Direct Imaging
- Beacon System with Road Map
- Dead Reckoning with Inertial Navigation
- Some form of Combination of the Above.

2.8.2.1. Pros and cons

Indirect guided roadway

Pros:

- This category presents the most effective methods to obtain precision relative geometric information between the vehicle and the roadway.
- Most members of this category have less complicated components and rela-

tive simple signal processing algorithm.

- Most members can perform equally well at inclement weather or at low visibility.
- Several members can code information on the roadway with relative ease (e.g., road map).
- Most members are robust in terms of relative roadway information acquisition.
- Most members in this category can become mature in relative short period of time.

Cons:

- Most members of this category require some form of roadway infrastructure modification and maintenance.
- The systems in this category can at best provide the precise relative roadway/vehicle knowledge, and other geometric related information coded on the roadway. It can not really 'see' the roadway and surroundings. They all need other system's support for obstacle detection and emergency maneuvers.

The eventual choice among the members of this category will be based heavily on the maturity of each technology, future potential (e.g., upgradability) of each system, overall reliability, the total cost (or the marginal cost) of the sensing/processing system together with that of the corresponding infrastructure modification/ maintenance, the schedule of the product development, as well as some marginal effects such as the ease of road information coding, the range limitation of the measurements, and passive or active components.

<u>Direct imaging</u>

Pros:

- This category have the most potential of capturing roadway information for lateral lane control, obstacle detection and emergency control, roadway sign recognition, as well as longitudinal spacing control.
- This system requires almost no infrastructure modification, except maintenance.
- This system can detect small relative angle between vehicle and the roadway through vision geometric amplification.

Cons:

- There would be no information acquired from this system when it can not 'see'. The robustness of this lateral information acquisition system during inclement weather condition, low visibility situations, or poor lighting environment can not be guaranteed.
- The complexity of the image processing algorithm requires large computation power to achieve fast sampling rate, better accuracy, or higher robustness.
- The capability of this system in small longitudinal spacing situation (e.g., platooning) may be limited.
- The time for the fully maturity of the system in this category will be long.

<u>Beacon system with road map</u>

Pros:

- There may be no infrastructure modification and maintenance on the roadway.
- It is relative easy to implement roadway modification (e.g., detour) since the roadway is defined by the map,
- The system is available at bad weather (except when beacon system transmission has been affected) and low visibility.

Cons:

- Good accuracy and fast sampling rate depend on the development and availability of the beacon system.
- Accurate map is also necessary for tight control.

- Higher noise to signal ratio for the relative geometric information (especially relative angles) derived from the absolute knowledge of locations.

Dead reckoning with inertial navigation

Pros:

- The inertial sensors provides direct vehicle dynamic information for servo controls.
- Most inertial sensors can have multiple usage for other vehicle control functions.

Cons:

- Low robustness against sensor noise and environmental uncertainties because of the noise accumulation.
- Low robustness against road hazard and when perform emergency maneuvers.
- Some members of this category need roadside beacon installation.
- It could be costly to increase the accuracy of the roadside beacon system.

2.9 LONGITUDINAL SENSING AND CONTROL APPROACH

Options include:

1. Vehicle-based radar, with wide field of view, supplemented by video for longitudinal control and forward obstacle detection. Side-looking radar (proximity sensors) and vehicle-vehicle communications for steering around obstacles.
2. Vehicle-based video using cooperative target, supplemented by vehicle-vehicle communication for longitudinal control and vehicle avoidance. Down-looking infrastructure video, or side scanned infrastructure radar/laser for non-cooperative targets.
3. Down-looking infrastructure video, or side scanned infrastructure radar/laser for all targets (together with communications and control intelligence for infrastructure guidance of vehicles).
4. Vehicle-based radar in lead vehicle (as in 1 above). Cooperative target video for other vehicles.
5. Human driver in lead vehicle. Cooperative target video for other vehicles.
6. Vehicle-based video using cooperative target, supplemented by vehicle-vehicle communication for longitudinal control and vehicle avoidance. No detection of uncooperative targets.
7. GPS or beacon based vehicle position sensing and vehicle-vehicle communications for longitudinal control and vehicle avoidance. No detection of uncooperative targets.

2.10 ENTRY/EXIT

2.10.1 Objective

This section discusses the physical requirements and operational characteristics necessary to accommodate AHS operation and that may have an influence on technology selection and/or evaluation.

2.10.2 Roadway Configuration

AHS deployment can be implemented in one of the following configurations:

2.10.2.1. Configuration 1

A dedicated highway with all lanes automatically controlled.

2.10.2.2. Configuration 2

A dual-use highway with automatically-controlled vehicles (ACV) that would be operated only on dedicated automatically-controlled lanes (ACL) and manually controlled vehicles (MCV) that would be operated only on dedicated manually-controlled lanes (MCL). A MCL may have to accommodate ACV's for a certain length along the route.. Such a lane will be referred to as a Mixed Type Lane (MTL).

Each of the above configurations can be deployed in an urban setting or in a rural setting.

2.10.3 Base Line Functions

The following baseline functions will be involved in the operation of the AHS System:

1. Physical access to the automatically-controlled lane(s) from the surrounding roadway network.
2. Check-in procedures; i.e. verification that the vehicle is properly equipped to be operated on the ACL and meets certain safety and reliability standards.
3. Transition from manual to automatic control and merging into an ACL.
4. Exiting the ACL and transition from automatic to manual control.
5. Physical egress from the automated lane(s) to the surrounding roadway network.
6. Malfunction and emergency management; physical and operational accommodation of malfunction in one or more system's components and in dealing with emergency situations.

2.10.4 Alternative Solutions

2.10.4.1. Physical access to the ACL

ACV's can access the AHS system via one of the following options:

Option 1A: Dedicated ramps that directly feed the ACL. Applicable to all configurations.

Option 1B: Common ramps used by all vehicles; automatically-equipped as well as manual. Applicable to Configuration 2 only.

The adopted system concept will have to accommodate either option. As such, this function is not a concept discriminator.

2.10.4.2. Check-in procedures

It is assumed that ACV's will be tested and certified for operation on ACL's off-site. Some means of certification will be tagged to the vehicle. Options available for checking-in ACV's to the AHS system include:

Option 2A: Automatic check-in. On the fly check-in through electronic reading of a magnetically-coded tag placed in or on the vehicle. *A vehicle-based or an infrastructure-based* verification system would indicate to the driver whether the vehicle is or is not fit to use the AHS.

This process should preferably take place before the vehicle reaches the AHS facility to allow the driver to take the necessary action (i.e. proceed to use the AHS facility, proceed as a MCV, or abort and go back) without impinging on the operation of the highway.

Option 2B The ACV would be equipped with self-diagnosing instrument(s) that the driver can test before approaching the AHS facility, i.e. similar to an airplane's "check-in" before take-off.

If all systems are O.K. the driver can proceed to use the AHS facility. Otherwise he or she can proceed as an MCV, or abort.

The above two options are believed to be concept discriminators.

2.10.4.3. Transition from manual to automatic control and merging into ACL

The ACV would transition from manual control to fully automatic control and merge into the ACL under the AHS system in accordance with one of the following options:

Option 3A: on the entry ramp while the vehicle is stationary. The ACV would come to a complete stop on the entry ramp, wait for *a vehicle-based or an infrastructure-based* sign or signal to switch to automatic control and proceed to merge into the first ACL. If there is more than one ACL, then a separate mechanism would need to be developed to accommodate inter-ACL switching. This option would only be applicable to the dedicated ramp option (1A) discussed above.

Option 3B: on the entry ramp as the vehicle is in motion. Again *a vehicle-based or an infrastructure-based* sign or signal should be communicated to the driver to switch to automatic control and proceed to merge into the first ACL. Since this would be on the fly operation, a transition lane (similar to acceleration lanes associated with regular entry ramps) should be provided. This option would also be only applicable to the dedicated ramp option (1A) above.

Option 3C: -on a transition lane as the vehicle is in motion. This option would be applicable to the common ramp option (2A) discussed above. The ACV would enter the roadway on a common ramp with all other vehicles, maneuver its way to a transition lane next to the ACL. A *vehicle-based or an infrastructure-based* sign or signal would instruct the driver to switch to automatic operation and proceed to merge into the first ACL. Whether this transition lane would be dedicated to ACV's or used by all vehicles is dependent on the mode of operation of the ACL lane (i.e. free agent, single-class platoon, mixed platoon, etc.), on the number of ACL lanes, and on the speed of traffic on one or more of the ACL's.

The adopted system concept should accommodate either option 3A or 3B, and option 3C.

2.10.4.4. <u>Exit from the ACL and transition from automatic to manual control</u>

The exiting process is initiated by the trip planning function through which the vehicle and the driver are notified that they are approaching the desired exit or the terminus of the AHS system. Such notification can be *vehicle-based or infrastructure-based or both.* Since ACV's would be traveling at a high speed on the ACL, a transition/deceleration lane should be provided for both roadway configurations, i.e. it would not be possible to exit the ACL directly to an off ramp in case of Configuration 1.

Transition from automatic to manual control could take place on the transition lane or, in the case of a dedicated AHS facility, on the exit ramp as the vehicle is in motion or when it comes to a complete stop.

The length and use of the transition lane in function 3 and 4 above is believed to be a critical element in the development of the AHS system, especially in urban applications where inter-spacing between interchanges would be relatively short.

2.10.4.5. <u>Physical egress from the AHS to surrounding roadway network</u>

Options available for egress from the AHS are similar to those available for access, i.e. dedicated ramp in case of Configurations 1 and 2 or common ramp in case of Configuration 2 only.

2.10.4.6. <u>Malfunction and emergency management</u>

Depending on the type and nature of the malfunction or emergency, options available for malfunction and emergency management range from shutting down the AHS operation entirely or partially, reverting to manually-controlled operation, or directing disabled vehicle to an emergency lane or shoulder.

2.10.5 Evaluation of Alternative Solutions

Table 2.10.5-I presents a brief listing of advantages and disadvantages of pertinent options.

2.11 LANE WIDTH CAPABILITY

2.11.1 Describe the Characteristic

This concept characteristic addresses the width of an automated lane. Three general solutions exist — normal (current) width, narrower than normal (current) and wider than normal (current). Only the first two are considered realistic. Due to lack of specifics about technology capabilities, Narrower Than Normal, instead of the possible actual narrower lane widths, is considered a solution.

2.11.1.1. <u>Importance</u>

This concept characteristic addresses lateral separation but indirectly. Unlike longitudinal separation policy where the actually separation can be adjusted in real-time according to weather condition etc., lane width is considered part of infrastructure and cannot be adjusted easily in real-time.

Operations of AHS impose requirements on AHS lane width. The lane width, in turn, directly imposes requirements on the lateral control capability of an AHS vehicle. Note that lateral control is closely related to longitudinal control. For example, lateral control at low speed is easier than that at high speed. In other words, lane width, together with lateral control capabilities, may limit the operational speed of the AHS

Table 2.10.5-I. Entry/Exit Option Comparison and Evaluation

Function	Option	Advantages	Disadvantages
1. Physical Access	1A	Better control of AHS operations. Improved safety Control of interchange spacing. Control of length and operation of transition lanes	Could be very expensive Disruptive to highway operation during construction.
	1B	Low cost option	Disruptive to MCL's operation all the time Possible disruption to ramp operation
2. Check-in Procedures	2A	Automation compatible Assures driver of vehicle status Reasonable operating cost	System assumes responsibility for misdiagnosis Difficult to enforce
	2B	Automation compatible Relatively low capital and operating cost Driver assumes responsibility for vehicle status	Difficult to enforce
3. Transition to/from automatic controls	3A	Provide time for driver to adjust to transferring control to/from automatic operation Automation compatible	Potential time delays Need for queuing space
	3B	Fast, efficient and automation-compatible	May require more sophisticated drivers
	3C	Required for configurations 2 and 3 Compatible for mixed operation	Disruptive to MCL's operations Reduces throughput of MCL's

traffic on that lane. What follows concentrates on the operational requirements on AHS lane width.

The Operational Requirements Affecting Lane Width: Vehicle Type, Weather, Loss of Lateral Control, Emergency Maneuvering, and Degraded-Mode Operation (Manual Driving)

A lane must be sufficiently wide so that, in the absence of malfunction, any automated vehicle traveling in that lane stays completely within that lane. Note the effect of vehicle classes accommodated. A lane may be dedicated to the use of one particular vehicle class during certain hours, e.g., automobiles during commute hours, but may be shared by other vehicle classes during the rest of the day. Also note the effect of weather condition, especially the reduced tire-pavement friction and wind-gust, on the lane width requirements.

The possible safety hazards resulting from loss of lateral control, i.e. lateral control failure, during automated traveling should also be considered in determining the lane width. Emergency maneuvers for avoiding collisions after a failure, even with perfectly functioning lateral control, may require a wider lane width for safety.

The lane width should also be wide enough to support the degraded operating modes. In the extreme case of system shutdown, if automation-equipped vehicles are allowed to operate on AHS lanes manually during the system downtime, then those lane must be sufficiently wide for safe manual driving at a reasonable speed.

2.11.2 Describe All Realistic Solutions

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

2.11.2.1. Realistic solutions

i) Normal Width (for all vehicle classes)
ii) Narrower Than Normal for automobiles and light-duty vehicles only

The current standard lane width is 12 feet (3.7 meters). This width will be referred to as the Normal width. Since very little theoretical or empirical work has been done on the performance of possible lateral control technologies on heavy-duty vehicles, it is assumed that it is not realistic or beneficial to consider setting lane width at any value narrower than 3.7 meters for those lanes that will accommodate heavy-duty vehicles like trucks and buses. Therefore, the solution of "Narrower Than Normal" refers to the lane width for ONLY those AHS lanes that are dedicated to the use by automobiles or other light-duty vehicles. Due to lack of specifics about technology capabilities, Narrower Than Normal, instead of the possible actual narrower lane widths, is considered a solution. For convenience, a Narrower Than Normal lane should be at least 10% narrower than 3.7 meters and therefore should be at least one foot narrower than the normal width.

The only advantage of Narrower Than Normal width is the reduced land requirement. This should be weighed against its many potential disadvantages, which will become clear when these two solutions are evaluated against the Goals and Objectives, Baseline Functions, Uses and the solutions for other Concept Characteristics.

Other solutions

One other solution exists — Wider Than Normal (Current) Width. However, it is considered unacceptable. In other words, it is a requirement that the width of an AHS lane should not exceed the current standard. This means that the AHS technologies must be advanced enough and the operating rules must be conservative enough so that the AHS is safe while providing sufficient capacity gain. Given the assumption that it is not realistic or beneficial to consider setting lane width at any value narrower than the current standard, the current standard width is effectively the only solution for heavy-duty vehicles.

2.11.2.2. Design and architecture implications

The operational requirements that affect lane width include:

a) vehicle classes accommodated on the lane,
b) operation under inclement weather, particularly poor tire-pavement friction and gusting winds,
c) safety requirements after failures of lateral control,
d) safety of emergency maneuvering, and
e) safety and efficiency of degraded-mode operations (e.g., manual driving).

2.11.3 Evaluate Solutions to Concept Characteristic

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

Recall that Narrower Than Normal refers to only those AHS lanes that are dedicated to the use by automobiles and light-duty vehicles. Therefore, the rankings provided below effectively addresses lane width issues with respect to ONLY automobiles or or other light-duty vehicles.

2.11.3.1. Against AHS objectives and characteristics

Safety ranking

Normal 6; Narrower Than Normal 4

Capacity and mobility ranking

Normal 5; Narrower Than Normal 6

The reduced land requirement provides the opportunity for accommodating more lanes. However, on a two-lane AHS (i.e. two automated lanes in each direction) where only one lane is dedicated to automobiles, the impact on capacity gain could only be a small fraction of the total capacity. If the AHS requires a break-down lane, then the fraction will even be smaller. However, if land becomes so scarce that any marginal reduction of land requirement becomes crucial, then Narrower Than Normal should be very desirable.

Convenience and comfort ranking

Normal 5; Narrower Than Normal 4

Narrower lanes may create discomfort for automobile users.

Environmental impact ranking

Normal 5; Narrower Than Normal 5

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 capacity and hence, traffic.

Cost ranking

Normal 5; Narrower Than Normal 5

There are two different cost perspectives: infrastructure (land) costs and vehicle costs. If land becomes so scarce that any marginal reduction of land requirement becomes crucial, then Narrower Than Normal should reduce lane requirement and could be very desirable. However, Narrower Than Normal lane width would impose performance constraints on the vehicle and hence, make vehicle potentially more costly. How these two conflicting factors would determine the total costs is unclear at this stage.

Deployability ranking

Normal 5; Narrower Than Normal 4

Narrower lane Normal lanes would limit the vehicle classes that can be safely and efficiently accommodated. Also, lane narrowing may involve infrastructure modification.

Availability ranking

Normal 5; Narrower Than Normal 4

The more stringent lateral control requirements may result in more complex lateral control system and hence, vehicle availability may be lower.

Supported vehicle classes ranking

Normal 9; Narrower Than Normal 3

The normal lane width may not be able to accommodate some forms of Pallets. (For some pallet system designs, automobiles are loaded on the pallets sideways, i.e. the automobiles are facing side of freeway. Narrower Than Normal lanes will likely not be able to accommodate heavy-duty vehicles.

2.11.3.2. Against baseline functions

Check-in ranking

Normal 5; Narrower Than Normal 4

Due to the potential higher complexity of the lateral control system required for safe automated driving within narrower lanes, check-in function, if required, may involve more checking than its Normal counterpart.

Maneuver planning and execution ranking

Normal 5; Narrower Than Normal 5

Lane width should have minimum impact on maneuver planning and execution.

Flow control ranking

Normal 5; Narrower Than Normal 4

Since Narrower Than Normal lanes cannot accommodate heavy-duty vehicles, they restrict flow of the corresponding traffic and hence, may make flow control more difficult.

Malfunction management

Normal 5; Narrower Than Normal 3

Due to the narrower lateral separation between two adjacent streams of traffic, failures, especially those of lateral control, occurring on a Narrower Than Normal lane may create more serious safety hazards than their Normal counterpart.

Emergency handling

Normal 5; Narrower Than Normal 3

Due to the narrower width, emergency vehicles may have difficulty reaching the scene of an incident/accident.

2.11.3.3. Against uses for an AHS

Heavily-congested urban highway

Normal 5; Narrower Than Normal 7

With respect to the Use in Heavily Congested Urban Highway, Narrower Than Normal (automobile) lanes will reduce land requirement and hence, may in turn increase throughput.

<u>Exclusive transit vehicle lanes</u>

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes may be able to accommodate only vans and mini-buses.

<u>Only high-occupancy vehicles in rush hour</u>

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes cannot accommodate heavy-duty buses, as assumed earlier.

<u>Exclusive commercial vehicle lanes</u>

Normal 9; Narrower Than Normal 3

Narrower Than Normal lanes cannot accommodate heavy-duty buses, as assumed earlier.

<u>Sparse rural areas</u>

Normal 9; Narrower Than Normal 3

In sparse rural areas, there could be only one AHS lane in each direction. If the lane is Narrow Than Normal, then heavy-duty vehicles may have difficulty using the AHS.

<u>Roadway power electric vehicles</u>

Normal 5; Narrower Than Normal 5

Lane width should have no impact on this particular Use.

2.11.4 Description of Correlation Between the Solutions

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

1) Both Normal width and Narrower Than Normal lane width are correlated with a) Vehicle only and b) Vehicle Predominant with Some Infrastructure solution. But Narrower Than Normal is more so than Normal lane width.

2) Lane width is independent of Communication.

3) Lane Width is independent of Longitudinal Separation.

4) Lane Width is independent of Roadway Interface, except that some pallet systems may require Normal or even Wider Than Normal width.

5) Lane Width is correlated with the Avoidance Response solution of Obstacle Response Policy. The narrower the lane, the more difficult to safely avoid the obstacle.

6) Accommodation of heavy vehicles on a lane is strongly correlated with, if not absolutely require, Normal Width.

7) Mixing of automated automobiles with manually driven automobiles in a common lane is strongly correlated with, if not absolutely requires, Normal width.

8) Lane Width directly imposes performance constraints on the lateral control technologies.

9) Lane Width is independent of the Longitudinal Control Approach.

10) Lane Width is independent of the Entry/Exit policies.

11) Due to the correlation between lane width and operating speed, Narrower Than Normal lane width may allow a lower operating speed than otherwise. This in turn may warrant a lower design speed.

2.12 DESIGN SPEED

2.12.1 Description of Concept Characteristic

Design speed is an operating characteristic that defines the maximum allowable speed of traffic flow on a highway system under normal operating conditions. Specification of a design speed for an automated highway system (AHS) imply that the infrastructure and the automated vehicles within the system are capable of performing desired functions up to the selected speed. It also indicates that the goals and objectives of AHS can be met up to the design speed. Design speed has a considerable impact on the social and technical properties of an AHS concept.

The selection of a design speed does not assume that all traffic in an AHS must operate at the design speed at all times. Rather, the traffic speed in a specific location at a certain time is determined by the operating scenarios, vehicle, roadway and weather conditions. A higher design speed does suggest that an AHS operate at a higher speed for the majority of use. A higher design speed may increase the potential capacity of a highway system and reduce travel time but it also demands a higher level of performances and associated costs for all system components.

The design speed of AHS is critical with regards to its consequences on the operation of AHS because the traffic flow in AHS is closely coordinated and tightly controlled. For instance, a small percentage of relatively slow-moving vehicles in an AHS that fail to operate at a high design speed may potentially affect or paralyze a significant portion of AHS traffic. On the other hand, if a high design speed is successfully implemented and executed, the benefits of AHS will be highly visible and appealing.

Current interstate highway systems are designed for a speed of 65 mph or higher. The typical speed limits imposed on highways are not necessarily the design speed of the infrastructure. The determination of speed limits requires extensive and thorough consideration of social, economical and technical consequences. For example, highway safety and environmental impacts are the most frequently discussed factors in deciding a proper speed limit for highways. The same scrutiny should be applied in selecting the design speed for an automated highway system with the investigation of all relevant issues.

The selection of design speed should be based on the evaluation of the following factors:

1) Safety considerations, which includes

- effects of design speed on failure behaviors
- sensitivity of control systems to design speed
- evaluation of safety measures in collisions
- requirements of occupant restraint systems
- speed difference between AHS and adjacent manual traffic

2) Performance requirements and feasibility of vehicles and its components

3) Implementation and maintenance costs of vehicles and its components

4) Environmental impacts, such as fuel consumption and noises.

5) Achievable highway throughput

6) Potential reduction of travel time

7) Operational variables, such as classes of vehicle and mixing of traffic.

8) Requirements and feasibility of infrastructure

9) Construction and maintenance costs of infrastructure

2.12.2 Description of Solutions

2.12.2.1. <u>29 m/sec (65 mph)</u>

It is appropriate to assume that an automated highway system should operate at a speed no lower than the current highway speed limit, 65 mph, or 55 mph in some urban areas. The AHS objective of increasing highway capacity is accomplished by automation (such as vehicle platooning and traffic management) without elevating the operation speed from the current system. Selecting a design sped close or equal to the current highway system also allows the interchange or mixing of automated and manual traffic if such mixing is desirable. A design speed of 65 mps is therefore chosen as one solution.

2.12.2.2. <u>43 m/sec (95 mph)</u>

This solution is proposed as a potential solution with an operating speed approximately 50% higher than the current interstate speed limit. Although it will reduce travel time by the same order of magnitude in the absence of congestion, it will not significantly increase the throughput of a highway system. In fact, it may actually reduce the throughput. (Throughput is generally defined as the product of speed and density. Increasing speed necessitates density reduction for safety.) It is also a driving speed that can be achieved by well-equipped and well-maintained passenger cars.

2.12.2.3. 56 m/sec (125 mph)

A third solution is proposed to approximately double the operation speed from that of current highway systems. This will further reduce the travel time in the absence of congestion. However, the potential throughput is likely to be lower than the level achievable at the speed of 43 m/sec. This speed can be achieved by high-performance passenger cars.

2.13 KEY CONCEPT CHARACTERISTICS

The analysis of the initial set of characteristics allowed the Concepts Team to refine the list. The goal was to focus on the most high level, essential dimensions, so that the number of combination concepts that result is manageable.

2.13.1 Refinement of Concept Characteristics and Alternatives

The specific modifications were as follows:

2.13.1.1. Distribution of intelligence/sensing/processing

This characteristic, also known as Allocation of Intelligence, was determined to be one of the key concept discriminators. The analysis showed that there are a great number of alternatives here, well beyond the original options — all in the vehicle, all in the infrastructure, or some in each. In fact, there are many viable ways to distribute the intelligence between the vehicle and the infrastructure, and the most promising approaches place intelligence in both places. Unfortunately, the 11 different alternatives make the total number of concept alternatives unmanageable. It soon became clear to the Concept Team that it is not feasible to do an exhaustive analysis of all alternatives. Based on the above analysis (see 2.1), the most promising alternatives were selected, supplemented by enough others to form a broad and representative sample of approaches. This does not mean that those that were not selected were eliminated for all time. The "re-concepting" approach allows the reintroduction of alternatives if the analysis points that way. The alternatives selected for analysis are discussed below.

2.13.1.2. Communications

The communications alternatives were seen to be driven by the allocation of intelligence. For example, a cooperative architecture would require heavy vehicle-to-vehicle communications, while infrastructure controlled would need extensive roadside-to-vehicle communications. Thus, the Concept Team agreed that the communications options discussed above in Section 2.2 would be used to provide a feasibility framework for the concepts, but that communication is not a concept-level characteristic by itself. As the concepts are fleshed out, communications architectures will be developed appropriate to the allocation of intelligence.

2.13.1.3. Separation policy (platoon, free agent, slot)

The analysis of the separation policy showed it to be a key driver in the nature of any concept. Each of platooning and free agent has advantages, so both should be continued as alternative options. The slot approach seemed less promising, in that it introduced complexity without great throughput gains. However, the team felt that further analysis needed be done before it could be definitively ruled out. Hence, separation policy was kept as a concept characteristic, with the original three options.

2.13.1.4. Roadway interface (normal, pallet, RPEV, other)

The normal interface, a rubber-tired, self-powered vehicle riding directly on the road, is a requirement of the AHS by its very nature. Then the issue becomes whether the AHS will also accept pallets and/or RPEVs.

This is an implementation and evaluation issue, to ensure that the concept is not designed in such a way to preclude pallets, or to interfere with the potential delivery of power from the roadway. This was consequently eliminated as a concept characteristic.

2.13.1.5. Obstacle response policy for sensing and avoidance

The analysis showed three approaches. If the technology does not exist for detecting obstacles, the human must be relied on for this function, in which case the vehicle will be automated until the driver sees a danger, at which time he will take over. The second approach is to use the collision avoidance capability that must be an any automated vehicle (that is not infrastructure controlled). If this could be tuned to recognize all hazards in addition to vehicles, this would naturally cause a stop at an obstacle. At that point, the driver would need to assume control, restart the vehicle and drive manually around the obstacle. The third option is full automation, in which the AHS (vehicle, roadside or combination) recognizes and avoids obstacles. The team agreed that this is a concept characteristic.

2.13.1.6. Vehicle classes in a lane (one class only, mixed classes)

Vehicle class mixing (e.g., cars and big rigs) was kept as a concept characteristic since the traffic dynamics change dramatically.

2.13.1.7. Mixed traffic capability (dedicated and mixed, dedicated only)

Whether or not manually operated vehicles are allowed to mix with automated vehicles profoundly changes the nature of the AHS, and hence, was kept as a concept characteristic. However, the analysis showed that there are different levels of mixing. At one extreme are manual vehicles allowed to travel in the same lanes as automated vehicles, but beyond that there are alternatives distinguished by the certainty that the manual vehicles will stay out of the automated lanes. This is based on the physical means for separating the lanes and the technique for the entering and exiting vehicles to merge. These alternatives are described in the next section.

2.13.1.8. Lateral and longitudinal control approach

Both of these techniques were seen to be implementation issues. The concept-level issues here are already covered in other characteristics, specifically whether or not the vehicles are infrastructure controlled, and whether or not slots (point-following) are used. Hence, both of these were eliminated as concept characteristics at this time.

2.13.1.9. Entry/exit (transition lane, dedicated station)

Of the many entry and exit characteristics, the key ones were dedicated ramp vs. transition lane. The choice of one or the other impacts the nature of the AHS, and so this was kept as a concept characteristic with these two alternatives

2.13.1.10. Lane width capability (normal only, normal or narrow)

The lane width will be determined locally, but each concept should be evaluated as to how well it supports a narrow lane once the concept is sufficiently well defined to estimate lane keeping accuracy. This was not used as a concept characteristic.

2.13.1.11. Design speed (speed limit, higher than speed limit)

This is something that will be imposed from without, rather than a design parameter of the AHS. The ongoing concept development should be sure not to preclude future speed limit increases on the AHS, but the baseline should be targeted at normal highway speeds. This was not used as a concept characteristic.

2.13.2 The Six Concept Characteristics

The evaluated concepts are built around the six key characteristics or dimensions that distinguish essentially different approaches to the Automated Highway System.

2.13.2.1. Allocation of intelligence

At the heart of AHS is the intelligence to control the vehicles and the overall system. Is the decision-making primarily in the vehicle or in the roadway or some of each? The answer has profound implications for requirements on sensing and communications, and on the nature of the AHS system as a whole. The locus of intelligence and control is largely the key description of the architecture. It will impact who pays the costs, how the automated highway evolves and whether a system optimum or individual optimum can be achieved. In this section the word "infrastructure" refers to infrastructure-based electronics, as opposed to vehicle-based electronics.

Autonomous

This is merely an automated vehicle. The infrastructure provides at most the basic ITS services (in-vehicle information and routing, but not control) and something for the vehicle to sense to determine its position in the lane. The vehicle does automatic lane, speed and headway keeping. Example implementations for lane keeping are the use of magnetic nails, a sensor on the vehicle that can read the roadway striping, and GPS with map matching. In any case, the roadway contains no more AHS-specific intelligence than the immediate location of the road. The vehicle senses its surroundings, including adjacent vehicles and lane, but does not communicate with the infrastructure (except possibly for standard ITS features such as routing requests or Mayday). Nor does it communicate with other vehicles.

In the simplest version, the vehicle can maintain steady state once in its lane, but anything else, including entry, exit, lane changes and obstacle detection and response, must be done by the driver. This vehicle senses and reacts (brakes and throttle) to the vehicle it is following in its own lane in order to maintain its fixed spacing. If there is no vehicle ahead of it, it maintains a set speed. If the vehicle carries additional sensors looking to the side or rear, they are only there to alert the driver. Obstacles in the vehicle's immediate path that are big enough to be seen by the forward-looking sensor will be sensed and cause the vehicle to brake as though another vehicle stopped suddenly ahead. However, there are no additional sensors to detect dangerous, but smaller, obstacles ahead or any obstacles, such as vehicles, approaching from the side.

A more sophisticated version supports automated lane changes, for example by the addition of side-looking sensors. However, there is no way to command the other vehicles to open a space, other than the usual signals between drivers.

Cooperative

This option is similar to the previous, in that there is minimal infrastructure intelligence, but there is the addition of local (e.g., line-of-sight) vehicle-to-vehicle communications for vehicle coordination. This allows coordinated lane changes and platooning. There is no infrastructure support beyond that in the previous alternative. Since this is all done locally, there is no region-wide traffic optimization, other than through digital ITS advisories. There is no entry or exit flow control.

There may be passing of information vehicle-to-vehicle or platoon-to-platoon, for example in an emergency, but they do not routinely act as conduits in a basic cooperative concept. More advanced versions of this option include data passing and aggregation, leading to a distribution of global intelligence throughout the vehicles on the roadway.

Infrastructure supported

This is an enhancement of the previous alternative. Here the cooperating vehicles are given location-specific information from the infrastructure electronics that is monitoring the global situation (flows and trouble spots, not individual vehicles). For example, all of the vehicles at a location may be given the information by a roadside beacon. In any case, the information sent will not be specific to any one vehicle or platoon, though it may be lane-specific. It will be in the form of general parameters, such as target speed or spacing, dependent on the current situation. The information could be static as well, such as: lane ends, merge left; speed limit 65; slow, curve ahead; exit 165. The vehicles are still maintaining their steady state and negotiating their lane changes, but now these are informed by the broader view maintained by the infrastructure. This allows the vehicles to concentrate on the local view of themselves and the surrounding vehicles, while the infrastructure concentrates on the global view.

Infrastructure managed

The major difference between Infrastructure Supported and Infrastructure Managed is that in this latter alternative, the infrastructure communicates with individual vehicles rather than groups of vehicles. Thus, the infrastructure manages anything other than steady state in the lane. Specifically, the vehicles maintain steady state including lane keeping, headway keeping, speed maintenance and platooning, but for any special request, such as lane change, entry or exit, the infrastructure takes command. Thus, this is a "request-response" approach, in which the individual vehicles ask permission of the infrastructure to perform certain activities, and the infrastructure responds by sending commands to that vehicle or to other vehicles (e.g., open up to allow a lane change). These are high level commands; the vehicles will determine the steering, braking and throttle needed to execute them.

Either the vehicle or the infrastructure may do vehicle navigation. The infrastructure may also take the initiative in emergency situations that it detects, or to reroute individual vehicles for flow control. In particular, individual entering vehicles may be sent to an alternate exit if their destination is congested. This allows much tighter overall system control than the previous alternative, but it requires tracking individual vehicles and extensive communications.

Infrastructure controlled

Here the vehicles are completely controlled by the infrastructure, which will continually track and send commands to individual vehicles. These commands may be in the form of steering, braking and throttle commands, or they may be acceleration, deceleration and turning commands. The vehicles have no intelligence beyond the ability to translate these commands into corresponding commands for their own actuators, and to monitor and adjust their response. They may not have sensors for roadway geometry or surrounding vehicles; if they do it is only as a means of data collection for the infrastructure.

This approach puts a heavy burden on the infrastructure in terms of real-time knowledge of the roadway and the vehicles, the computing power to manage the vehicles, and the communications power to be in continual control of all the vehicles. The update rate is very high, especially compared with the previous option in which commands were given on an exception basis.

2.13.2.2. Separation policy

The separation policy defines the relationship of each vehicle to the one in front of it. It defines the position that each vehicle will maintain. As such, it has major impacts on safety and throughput.

Free agent

The free agent vehicle maintains a safe distance from the vehicle it is following, and it travels at safe speed. This separation may be spatial (e.g., 3 meters) or temporal (e.g., 1 second). If there is no vehicle ahead within the safety distance, it will travel at the speed limit or at a lower but safe speed.

Even if the vehicles bunch up, with several closely-spaced vehicles following each other, this is not platooning, since the platoons do not operate as units, nor are they managed (e.g., there is no limit to their length), nor are spacings as tight as with an actual platoon.

The term "free agent" should not be construed to mean that they are free of outside influence. They may receive commands from the infrastructure or from other vehicles; the difference is that such commands are directed at individual vehicles rather than at platoons.

Platooning

Platoons are clusters of vehicles with short spacing between vehicles in the platoon and long spacing between platoons. Platoons as long as 20 vehicles have been considered. Intra-platoon spacings as short as 1m have been contemplated. This ensures that the relative speed is low if a malfunction causes a collision. The longer inter-platoon spacings ensure no inter-platoon collisions. Tight coordination within the platoon is required to maintain the close spacing. The platoon can be treated as a unit by the infrastructure or by other vehicles.

Slot

The roadside control system creates and maintains moving slots on an AHS lane that partition the AHS lane at each moment in time. Slots then are moving roadway segments, each of which holds at most one vehicle at any time. The vehicles are identified and managed by association with their slots. Vehicles that need more space (e.g., heavy trucks) may be assigned multiple slots. In a basic slotting concept, the slots are of fixed length.

Another way to think of slots is as a point-following technique. Vehicles are assigned to follow moving points rather than other vehicles.

2.13.2.3. Mixing of AHS and non-AHS vehicles in the same lane

Mixed traffic operation refers to the degree to which vehicles under manual control and vehicles under automated control share the roadway. At one extreme is full mixing, in which automated and manual vehicles under normal operations share a mainline lane. At the other extreme is dedicated automated lanes, with a physical barrier that makes it virtually impossible for a manually operated vehicle to enter. In between are configurations in which lanes are dedicated to automated use, but there is not complete physical separation. Thus, the distinction among the four alternatives below is the likelihood that a manually operated vehicle will find itself in a lane with automated vehicles.

Dedicated lanes with continuous physical barriers

The automated lane or lanes are physically separated from any manual lanes. For example, the innermost lane on a freeway may be converted to automated use, with a continuous solid barrier between this lane and the adjacent manual lane. Another example is a fully automated highway that is not adjacent to any manual roadway, either from new construction or by complete conversion to automation. This option generally would be implemented with dedicated automated on and off ramps.

Dedicated lanes with some gaps in the physical barrier

This variation on the previous alternative includes occasional gaps in the physical barrier to allow transition from the adjacent lane. This allows the adjacent lane to be a transition lane (see below). There is potentially greater danger of manual vehicle incursion in this alternative, since the gaps allow the possibility of a manually-operated vehicle entering through driver error or vehicle failure.

Dedicated lanes with virtual barriers

Virtual barriers are any demarcation that separates the dedicated automated lanes from other traffic, but does not physically prevent movement between lanes. The common example is yellow lines. This alternative is similar to HOV (carpool) lanes on many freeways, in which double double yellow lines, warning signs and enforcement prevent vehicles from entering the HOV lane except at designated gaps. In this alternative there is even greater danger of manually operated vehicles in the adjacent (presumably transition) lane inadvertently drifting into the automated lane.

Full mixing

Automated and manually-driven vehicles co-exist in the same through lane at all times. This is the only one of the choices in which the manual vehicles in the lane are not an abnormal or emergency situation.

2.13.2.4. Mixing of vehicle classes in a lane

Vehicle classes refer to levels of performance characteristics, such as passenger cars, heavy trucks and transit. For equity and economic viability the automated highway must accommodate all classes, but not necessarily in the same lane. Vehicles with poor performance will impact vehicles following; for example, a heavy truck going up a hill will cause the following traffic to slow. It may not be feasible to mix classes within a platoon.

Mixed

This alternative supports all classes in all lanes at the same time. It may or may not mix classes within platoons. It may or may not form vehicles into same-class blocks or otherwise manage the various classes on the lanes.

Not mixed

In this alternative only one class (or group of similar classes) is allowed in each lane. For example, there may be a lane for heavy trucks and buses and another for cars and light trucks. This may change with time of day, for example allocating more lanes for cars during rush hour.

2.13.2.5. Entry/exit

The key issue in entry and exit is how the automated vehicle transitions from manual and how it relates to other traffic on a dual-use highway.

Dedicated

This alternative has on ramps and off ramps that are used solely by automated vehicles and place the vehicles in the automated lane without passing through the manual traffic. The transitions between manual and automated operation occur somewhere on these automated ramps. It may or may not require the vehicle to stop.

Transition

If all vehicles use the same ramps, it is reasonable to assume that the automated vehicles will use the lanes farthest from entry. For example, in a standard freeway conversion, the lane closest to the center divider will be used for automated vehicles. The reason for this is that automated vehicles can operate in a manual mode and so can transition through the manual lanes without disrupting them, but the manual vehicles cannot transition through automated lanes.

A transition lane is the lane next to the first fully automated lane. Automated vehicles will enter this lane under manual control. They may go automated in this lane and then merge into the fully automated lane under automated control. This merge action is similar to that used currently to enter an HOV lane that is the left-most lane of a conventional freeway. The automated lane may be separated from the transition lane by virtual barriers or physical barriers with occasional gaps to allow transition.

2.13.2.6. Obstacle

There is no way to prevent obstacles on the roadway. They include such things as stalled vehicles, manual vehicles from adjacent lanes, dropped cargo, animals, and vehicle parts such as bumpers or hubcaps. Some hazardous objects are small and hard to detect.

Manual sensing and avoidance of obstacles

This alternative is essentially what is done today. The driver watches the road ahead and the sides of the road, and takes evasive action, such as braking, swerving or changing lanes, if a hazard is seen.

Automatic sensing, stop or manually avoid

The vehicle has the capability to detect obstacles in the road ahead and to brake automatically. For large (vehicle size) objects this may be provided by the sensor on the vehicle that maintains headway; it will see the obstacle as a stopped vehicle, and brake. This may be supplemented by other sensors on the vehicle and/or on the roadway. Once the vehicle stops, it is up to the driver to take control to steer around the obstacle if necessary.

Automatic sensing and automatic avoidance maneuver if possible.

Obstacles are sensed as in the previous alternative. If an obstacle is sensed, the vehicle will determine and execute the appropriate response, including braking and/or lane change. A variation would allow a swerve. Another variation would give the driver a "panic button" for those hazards that may be missed by the sensors (e.g., deer about to enter roadway; ladder or nails in the road).