Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Task D: Lateral-Longitudinal Control Analysis

Volume I: Executive Summary

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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

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Director, Office of Safety and Traffic Operations Research and Development

NOTICE

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List of Acronyms and Abbreviations

AHS	Automated Highway System
FLIR	Forward Looking Infrared
LDAR	Laser Imaging Detection and Ranging
LLCS	Lateral/Longitudinal Control Study
MDFRD	Maneuver Definition and Functional Requirements Document
MMWR	Millimeter Wave Radar
mps	meters per second
mph	miles per hour
PSA	Precursor Systems Analysis
RSC	Representative System Configuration
SCDD	System Concepts Definition Document
SCED	System Concept Evaluation Document
TBD	To Be Determined

Executive Summary of Study Results

1. INTRODUCTION

1.1. Purpose

This document is the Executive Summary of the results of the study of Lateral/ Longitudinal control issues under the Precursor System Analyses for the Automated Highway System (AHS). It is intended to provide a high-level overview of outcomes and conclusions for those not interested in the full depth of the documented results. Having read this document, the reader will have a broad understanding of our study methodology, our candidate system concepts, our evaluation results, and the most significant of the issues we uncovered during the course of the study.

For those interested in an in-depth treatment, there are three subsequent volumes that describe those results in much greater detail. They are:

1) Volume II: *AHS Maneuver Definition and Functional Requirements Document* (MDFRD) that describes the basic maneuvers and the specific functional requirements for each maneuver,

2) Volume m: *AHS System Concepts Definition Document* (SCDD) that presents the concepts under evaluation, and

3) Volume IV: *AHS System Concept Evaluation Document* (SCED) that documents the evaluation of the systems described in (2) against the requirements and criteria defined in (1).

The primary intent of the Precursor Systems Analyses is to identify significant risks and issues associated with various postulated implementations for an AHS. While the documents above elaborate requirements and candidate system implementations, the reader is cautioned to bear in mind that these reports do not document the product of a detailed design process nor an in-depth trade study. Instead, these reports provide a first look analysis at candidate system concepts in the context of preliminary requirements. The expectation of this study is that the results will form a basis for later work to be undertaken by the anticipated AHS Consortium.

1.2. Organization of the Study

Figure 1 on the next page illustrates the overall process used in this study. The boxes represent tasks, and the document icons represent the products of these tasks. The numbers enclosed in the various ellipses indicate the Statement of Work task number corresponding to each box.

The first task was to develop a taxonomy of maneuvers as independent of the system concepts as possible. This taxonomy provided the outline structure for capturing the functional requirements, and evaluation criteria of tasks two and three. The products of three tasks were captured in the *AHS Maneuver Definition and Functional Requirements Document* (MDFRD).

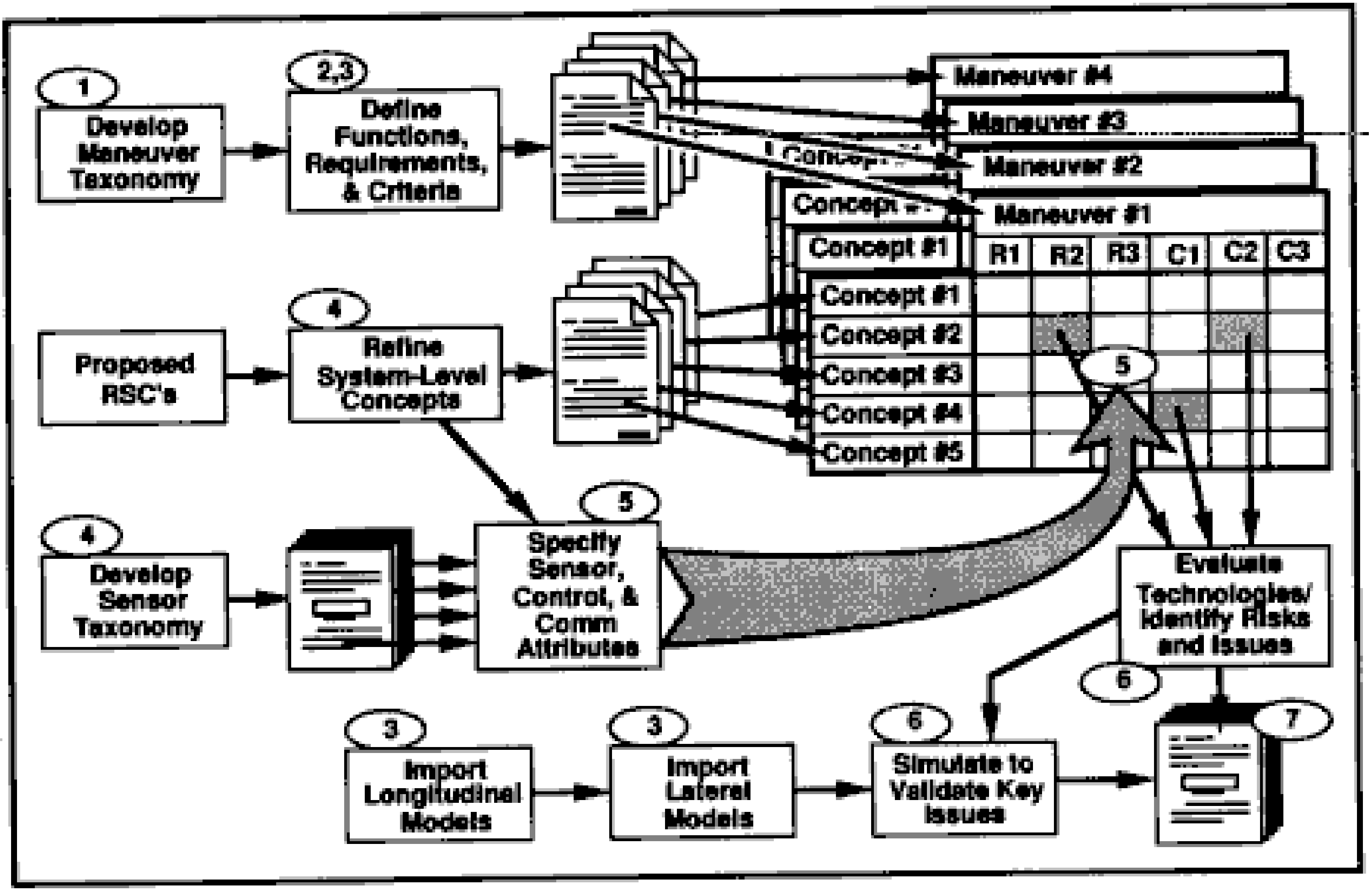

Figure 1. Lateral/Longitudinal Control Study Approach

The next task was to develop and refine our system concepts, and describe them in a clear enough way to permit meaningful evaluation and comparison of the concepts. This was done by first roughly describing each concept, and then showing how it fulfilled the functional requirements outlined in the MDFRD. The product of that effort is described in the *AHS System Concept Definition Document* (SCDD).

Concurrently with the above efforts, we undertook an effort to describe all the enabling technologies in a sensor taxonomy. That taxonomy classifies the relevant sensor types and describes the basic technology, provides an assessment of each of the enabling technologies, and in some cases projects where the technology is going and what issues surround the use of that particular technology. In it we also collected all the information we were able to in a reasonably short interval from our archives, from a brief literature review, and from various sensor vendors with whom we are in frequent contact. The purpose of the taxonomy is to provide a technical foundation for the evaluation portion of this effort described below. From that effort we drew an assessment of the sensor attributes needed to satisfy each concept. Since sensor technology is in many cases the dominant limitation on overall approaches, this mechanism for capturing, cataloging, and sharing data on sensor technologies may be particularly useful to the anticipated AHS Consortium.

The last step was to apply the evaluation criteria defined in the MDFRD to the concepts described in the SCDD and assess the merit of each of those candidate concepts. The primary objective was to capture along the way the issues surrounding implementation of an AHS and provide a first-look assessment of the broad merits of each of the candidates. This evaluation is recorded in the *AHS System Concept Evaluation Document* (SCED).

Some concepts require quantitative analysis to provide the basis for evaluation. The simulation environment we developed provided the tools for this analysis. As areas requiring quantitative backup were identified the various models and parameters for those models were developed. These models executed on various test scenarios to provide the needed quantitative data. A set of test cases was defined and executed to determine the maximum latency. This program did not have the time or scope of effort to simulate all aspects of all concepts, so due diligence was applied to the selection of particular conditions and concepts to be simulated.

The evaluation process can only be relied upon to identify clear winners and losers in a broad sense, and to ascertain significant risks and issues associated with each. It is important to note that there are too many unknowns at this time to definitively establish both the weights and the specific evaluation numbers. There is therefore a large margin of uncertainty surrounding the resultant numerical evaluations. Instead, they are intended only to provide insight into which concepts are strongest and merit further consideration, which are weakest and may be dismissed. It is important to view the numerical results as "fuzzy indicators", not as a tool for absolute ordinal rankings.

These evaluations are by no means intended to be the last word on the subject It is our expectation that the weights and evaluations are subject to some change as concepts are further refined or as new technologies become available. It is for precisely that reason that the spreadsheet formalism has been chosen; it provides a simple way to perform various sensitivity analyses. For instance, if the Federal Highway Administration chooses a different weighting scheme of importance factors for the evaluation criteria, or if new requirements are inserted, the comparisons could change dramatically. Various scenarios can be evaluated easily with this approach.

2. OVERVIEW OF MANEUVER TAXONOMY AND REQUIREMENTS

Based upon a careful review of a wide variety of representative system configurations (RSCs), a set of AHS maneuvers was defined that covers the majority of RSCs analyzed. In some instances, a maneuver may be required by an RSC that is not defined in this set or a maneuver is defined in this set that *is* not required by an RSC$_1$ but for the most part the maneuvers listed here form a representative set for a large majority of RSCs. Though many maneuvers were nominated, only those directly affecting lateral/longitudinal control issues were incorporated. After the maneuver set was defined, a taxonomy for the set was developed based upon a subsumption architecture, depicted in figure 2.

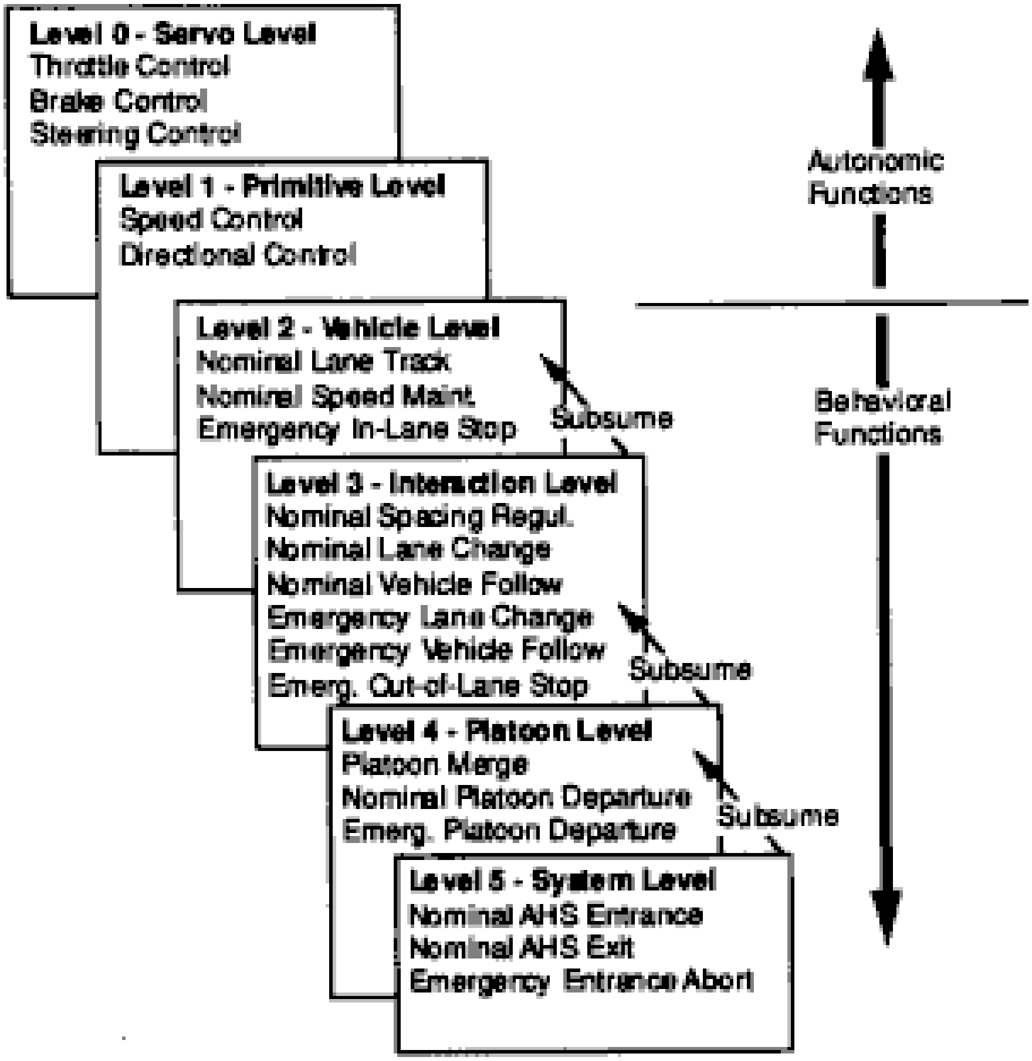

Figure 2. Maneuver Hierarchy

Recent research in the development of system architectures for autonomous and/or automatic vehicles has demonstrated successful autonomous operations using subsumed behavior levels to define and implement varying levels of control complexity. The taxonomic categories for the maneuver set were defined based upon the level of complexity of the maneuver wherein each maneuver was viewed as a vehicle behavior. Low level vehicle control functions (e.g. servo control) that would not normally be considered as behaviors were included in the maneuver set for completeness and to define the end-to-end flow from high level maneuver goals to solenoid voltages.

Level 0 (Servo) maneuvers and Level 1 (Primitive) maneuvers represent the equivalent of autonomic functions for the vehicle. They run at all times and are not subsumed by higher level maneuvers. Speed control and directional control in Level 1 may also be thought of as longitudinal control and lateral control behaviors. Level 2 (Vehicle) maneuvers are the lowest level behaviors that can be subsumed. They represent vehicle maneuvers that can be performed without the need to coordinate or interact with other vehicles. Level 3 (Interaction) maneuvers are so named because they involve potential interaction with other vehicles. Level 4 (Platoon) maneuvers require not only interaction with other vehicles but may also require coordination with other vehicles. Lastly, Level 5 (System) maneuvers are the most complex in that they require not only interaction and coordination with other vehicles, but also must handle the difficult task of changing from non-automated operation to automated operation and back again.

In addition to providing an intuitive structuring of control authority for the various maneuvers, the subsumption architecture also provides a logical path for evolutionary implementation of the system architecture. In general, with each step up in maneuver level, the requirements on processing, sensing, communications and coordination also increase. If the AHS system is to be implemented in an evolutionary fashion, then the system vehicle control architecture must be able to accommodate evolutionary increases in performance requirements.

Figure 2 also illustrates the grouping of maneuvers by behavior level. The control of each maneuver over the vehicle may at anytime be subsumed by a higher level maneuver if the situation warrants. When the subsuming maneuver is completed it will return control authority to the lower level maneuver. In as much as higher level maneuvers embody greater complexity and hence greater risk of control decision errors, it is the goal of the system architecture to operate under the lowest level of maneuver control possible. Multiple behaviors may operate simultaneously, especially at the lower levels.

The maneuvers in each level are not all-inclusive. We defined only those maneuvers that directly impacted our study of lateral/longitudinal control issues. As other studies present their conclusions, we trust that additional required maneuvers will be defined and can be added to this taxonomy. The important point is that, at this stage of development, having a structure to clearly capture requirements *incrementally* is a major benefit.

2.1. Level 0: Servo Level Maneuvers

This level provides the most basic control actions capable by the vehicle's control system. While we defined this level of detail and developed requirements that led to the identification of significant issues, the requirements for these maneuvers were so basic that all concepts had to meet them and we elected to omit them from the evaluation matrices. Maneuvers in this level include:

Throttle Control - Servo control of the throttle actuator based on throttle command from speed control.

Brake Control - Servo control of the brake actuator based upon brake commands from speed control.

Steering Control - Servo control of the steering actuator based upon steering commands from steering control.

2.2. Level 1: Primitive Level Maneuvers

This level is the level at which basic vehicle states are controlled, including all six degrees of freedom. Controls will have to be highly reliable for safety and stability reasons, but it is likely that this level can be decoupled from the levels above it in terms of update rate and levels of redundancy. Maneuvers in this level include:

Speed (Longitudinal) Control - generate throttle and brake commands in response to speed commands from higher level maneuvers. Compensate as necessary for wheel lock. Maintain safety interlocks between steering and acceleration/deceleration.

Directional (Lateral) Control - generate steering commands in response to direction commands from higher level maneuvers within constraints of current operating states such as vehicle speed and allowable lateral acceleration levels. May be required to account for outside information on roadway conditions.

2.3. Level 2: Vehicle Level Maneuvers

This is the level at which behaviors begin to emerge. The states in this level are more complex and not always directly measurable but may be inferred from combinations of other states (such as vehicle position relative to lane center). Maneuvers are divided into "nominal" and "emergency". "Nominal" refers to those maneuvers performed while the highway is operating as designed (though not necessarily at full speed or full capacity) and in the absence of failures or accidents. "Emergency" refers to all other operating conditions. This is the lowest level at which the evaluation matrices include requirements, since it was the most primitive level at which we could distinguish the representative system concepts. Maneuvers in this level include:

Nominal Lane Tracking - Generate direction commands to maintain vehicle to within :1: ±TBD (nominally 10) cm of lane center. This maneuver allows the vehicle to laterally control its position to remain on the highway in the absence of other vehicles or other obstacles to its path.

Nominal Speed Maintenance - Generate speed commands to maintain commanded vehicle speed to within ±0.5 m/sec. May include rapid deceleration under non-emergency conditions.

Emergency In-lane Stop - Safely stop vehicle at maximum braking capacity, which must be at least 5.9 meters/sec^2 (.6 g's) for all vehicle types, while maintaining vehicle within ± 10 cm of lane center-line (using a $3\ \sigma$ criterion). This maneuver (or its derivatives) specifies a minimum level of deceleration performance for operation on the AHS.

2A. Level 3: interaction Level Maneuvers

At this level, vehicles are no longer considered to be isolated entities on the highway. Rather, vehicles operate in the context of other vehicles nearby and must take their presence into account. Maneuvers are divided into "nominal" and "emergency". "Nominal" refers to those maneuvers performed while the highway is operating as designed (though not necessarily at full speed or full capacity) and in the absence of failures or accidents. "Emergency" refers to all other operating conditions. Maneuvers in this level include:

Nominal Spacing Regulation - Generate speed commands to maintain the desired separation distance with the preceding vehicle.

Nominal Lane Change - Change position laterally to an adjacent lane within 5 seconds Nominal Vehicle Following - Track lateral motion of the preceding vehicle to within ± 15 cm. This maneuver allows the capability for entire platoons to perform lane changes to avoid an obstacle or avoid congestion ahead.

Emergency Lane Change - Generate direction and speed commands to transition vehicle to an adjacent lane within 2 seconds. Allows vehicles to perform controlled changes under emergency conditions to avoid collision with other vehicles or objects on the highway.

Emergency Vehicle Follow - Track lateral motion of the preceding vehicle to within ±15 cm. The difference between this maneuver and the "nominal vehicle follow" will be in the underlying performance specifications, such as response time and magnitude.

Emergency Out-of-Lane Stop - Generate direction and speed commands to transition vehicle to an adjacent lane within 2 seconds and stop at a maximum deceleration of 5.9 m/sec^2 or the maximum capabillty of the vehicle, whichever is greater. In some cases less damage will occur if stopping in a nearby lane is feasible as opposed to merely stopping as quickly as possible in the current lane of travel.

2.5. Level 4: Platoon Level Maneuvers

While level 3 begins to describe the interactions between vehicles, those interactions are not necessarily deliberately coordinated among them. In this level, coordination is achieved for platooning operations, and possibly other forms of coordinated activity. Maneuvers in this level include:

Nominal Platoon Merge - Assume a trailing position behind the last vehicle of a platoon. Platoons form like queues; each new member attaches at the rear.

Nominal Platoon Departure - Depart platoon for the purpose of exiting AHS lane or other mode and state change not consistent with continuation in the platoon. Departure may be from the front, rear, or interior of the platoon.

Emergency Platoon Departure - Depart platoon for reasons of an emergency. This maneuver would be invoked, for instance, when a tire blowout occurs while in a platoon.

2.6. Level 5: System Level Maneuvers

This is the highest, most abstract level of maneuver definition, involving the interactions between individual or groups of vehicles and the AHS infrastructure. There are a number of other such interactions possible, but we have limited our analysis to just those that affect lateral/longitudinal control. Maneuvers in this level include:

Nominal AHS Entrance - Transition vehicle from non-automated to automated operation on AHS lanes

Nominal AHS Exit - Transition vehicle from automated operation on AHS lane(s) to non-automated operation

Emergency Abort - Generate speed and direction commands at a minimum or the appropriate interaction level maneuvers if possible to safely abort AHS Entrance maneuver

2.7. Notes On Maneuver-Based Requirements Definition

For each of the maneuvers described above, the MDFRD defines a preliminary set of requirements. The requirements themselves were not intended to be all-inclusive. Rather, they were defined to sufficient breadth and depth to uncover what the authors believed to be the significant system issues that must be addressed as the system concepts are developed and evaluated by the AHS Consortium. Our expectation is that this set will form the beginning of a detailed set of requirements for the Consortium's more detailed trade studies, and that the structure we have built into this document will provide the means for capturing that more detailed set

Requirements should be written such that they are implementation-independent; we have tried to do this. In some cases, it was difficult at this stage of high-level concept definition and evaluation to separate out implementation details from requirements. For instance, a key question is whether platooning (vehicles following one another in small clusters) is a requirement or an approach to meeting a more abstract requirement. Is the requirement to simply provide a means for increasing the density on the highway, or is it a given that platooning is the best way to achieve that increase and that any candidate concept must include it as a mandatory function? We have taken the latter approach in defining system requirements, though it is possible to remove this requirement without violating the structure of the document or the method of organizing the set of requirements.

Requirements should also be written to be quantitative and testable wherever possible. In developing the list of requirements herein, we often found that we could state what we thought was the best measure of system performance or effectiveness, but it was not possible to determine with confidence the threshold value. In such cases, we inserted a "TBD" followed by a suggested value in parentheses. For some of these TBDs, other researchers may have already found satisfactory values. For other TBDs, the work of the Consortium in the next phase of the program will uncover the right value through analyses or simulation. At this point, we would caution the reader to examine first *whether the metric in the requirement is the right metric by* *which to measure system performance or effectiveness,* and judge later whether the value is the right threshold level. Too often it is easier to argue the size of the threshold than to ask the difficult questions of what is the right approach to specifying performance. In most cases, we considered the threshold value included to be a rational stating point based on nothing more than engineering judgment.

3. OVERVIEW OF SYSTEM CONCEPT DEFINITIONS

This section provides a highly abbreviated description of each of the six concepts evaluated in this study. A more detailed description is provided in the *AHS System Concept Definition Document* Each concept was chosen and elaborated because we had an *a priori* notion of the classes of issues we believed were important to explore. These six were also chosen because they represented distinctly different philosophies from one another. They do not belong to any sort of logical grouping. For such grouping, the reader is referred to the RSC taxonomy developed by Calspan under their Precursor Systems Analyses (unpublished as of this writing). Instead, we deliberately chose concepts that "pushed the comers of the box" that bounds the set of all possible implementations, with one exception: use of pallets was excluded by direction from FHWA. Finally, the concepts used in this study do not necessarily compete on a "level playing field." For instance, the first concept contains obstacle avoidance as part of its overall approach, while the second concept ignores obstacle avoidance.

3.1. Autonomous Vision-Guided Concept

This concept places the burden for the maximum amount of AHS functionality on the vehicle. Sensing and control of lateral position, longitudinal position, presence of and range to vehicles, obstacle detection, and prevailing traffic conditions is the responsibility of the vehicle. The highway provides no support, active or passive, for any sensing functions. Speed control is completely asynchronous within limitations dictated by internally maintained knowledge-based determination of what is allowed for that particular highway segment and autonomously sensed environmental conditions.

Evaluation is based on experience out of existing research and development from the field of mobile robotics. The motivator behind this concept is to include in the evaluation a minimal infrastructural impact model, under the presumption that the major difficulty in the initial implementation of an AHS will be the amount of infrastructral improvement required before the first vehicle can traverse the first segment of AHS highway. The supporting belief is that to the extent that the concept requires little to no improvement to existing highways, the system startup will be completely dependent on the individual's ability and desire to pay for the required capability.

3.2. Magnetic Reference *I* Infrared Cooperating Active Targets Concept

This concept is based on an augmentation of the idea upon which research at the PATH program is based. Specifically, lateral control is achieved via a magnetic reference placed in the highway. Longitudinal control is achieved via infrared sensing with active, cooperating targets. This system provides no obstacle detection. The infrastructure is responsible for determining the desired operating parameters (speed range, platoon length, etc.) and communicating those desired operating parameters via broadcast medium. Speed and longitudinal position control is distributed and asynchronous.

3.3. MillImeter Wave Radar-Guided Concept

This concept is based on using millimeter wave radar as the primary sensor for information external to the vehicle. In this concept, the system senses lane position, existence and proximity of in-lane obstacles, and closure rate based on millimeter wave radar transceivers on the vehicle. It also senses proximity of other vehicles in adjacent lanes by using rearward pointing transceivers. Sensing is in the active mode with little or no assistance from other vehicles. The infrastructure (median barriers) may contain corner reflectors to augment the signal return for sensing lateral position. This concept is mostly autonomous in that lateral position and longitudinal position sensing are performed by sensors on board the vehicle. It adds the capability for sensing and avoiding obstacles not present in the concept.

In this concept, the AHS lanes are separated from the non-AHS lanes by physical barriers. The presence of barriers is assumed for two reasons. The first is that some studies by the PATH program indicate that physical separation is needed to assure safe operation, since statistical studies show that a significant risk of accident is due to lane intrusion. Their analysis shows that, without separation barriers, the introduction of AHS technology and the concomitant increase in density would lead to approximately a doubling of accident and fatality statistics from present-day operations. With separation, the numbers will reduce by approximately a factor between six and twelve. The second reason is that the barriers are used for "feeling" the vehicle's position relative the lane which presumes that the barrier would be accurately placed a fixed distance from the lane center.

3.4. RF-Beacon "Socialist" Concept

This concept. distinguishes itself from the others in this report in that it employs a centralized control of individual vehicle behaviors. Lateral control is individually performed using triangulation of low-power, semi-directional RF beacons placed some TBD (nominally 100 meter) intervals along the highway. The beacons' energy is modulated with timing data for more accurate positioning of the vehicle. The potential exists for also providing dynamic and static highway information via this medium.

Longitudinal control is provided by controlling synchronous "time slots" within which the vehicle must remain, providing both speed and headway control which processing elements in the infrastructure regulate. One fall-operational-fail-safe processing element will control each TBD segment of highway (nominally 1 kilometer). These processing elements are connected to one another in daisy-chain fashion along a fiber-optic bus that is connected to a regional traffic control center.

3.5. Inductive Drive for Lat and FMCW Radar for Long

This concept is based on the notion of using linear inductive drive for powering the vehicle and concurrently using the ability to sense the fields generated by the linear drive for primary lateral control sensing. To provide the necessary capability for longitudinal control, we have added Frequency-Modulated Continuous Wave radar in the microwave region to detect other vehicles and obstacles in the lane of travel and adjacent lanes also. A limited field of view is presumed (nominally around j45^{0}from the body centerline) with a range of no less than 200 meters. Speed is assumed to be synchronous with the field rate of the linear motor, but may be reduced from that Speed condition under exceptional conditions by individual vehicles' sensing and control functions. This concept incorporates the notion of short range, low-bandwidth UHF communication among vehicles and between the vehicles and the infrastructure for limited coordination purposes.

The purpose of incorporating this concept is that it has been under consideration in other areas for a number of years and has recently surfaced as an AHS candidate. It represents one of the more extreme cases from an infrastructural cost and complexity standpoint and we felt that it merited serious consideration vis-a-vis some of the more popular ideas that are currently extant in the community.

3.6. Direct Pickup, Shared Transit

This concept is for direct-drive electric motors on each vehicle operating on a dedicated set of infrastructure. Private and commercial vehicles and share the same infrastructure with public transit vehicles. Private and commercial vehicles are assumed to be hybrid vehicles capable of operating on normal highways using internal combustion power, and then moving onto the AHS by coupling into a direct pickup electrical power source. Longitudinal control is performed by mechanical means through the power pickup mechanism. Longitudinal control is performed by operating at set speeds on the highway, with internally-maintained radar for headway sensing. Information on current highway conditions and operating modes and states is obtained from the infrastructure via low-bandwidth RF broadcast Speed management would be autonomous and distributed within infrastructure determined parameters.

4. OVERVIEW OF EVALUATION RESULTS AND CONCLUSIONS

4.1. Requirements Satisfaction Evaluation

Table 1 below summarizes all the individual requirements satisfaction evaluations contained in the SCED. Each row is summed at the right for an overall score. The highest score possible on any one entry is 3.0, and the highest overall sum for a given concept is 45 (given the current maneuver set; specifying additional maneuvers changes the number of columns). Since there are many assumptions about how configurations did or did not meet requirements, the overall score is at best a very coarse goodness indicator. The authors anticipate that these results are merely the first of several iterations for several reasons. Each of the concepts rated could be redefined to meet additional requirements and bring up their respective scores. Each of the requirements must be assessed for its true applicability and whether it is a firm or "soft" requirement.

Table 1. Concept Requirements Evaluation Summary

		Maneuver Number (Reference from MDFRD)															
Concept	**Mnemonic**	**4.1**	**4.2**	**4.3**	**5.1**	**5.2**	**5.3**	**5.4**	**5.5**	**5.6**	**6.1**	**6.2**	**6.3**	**7.1**	**7.2**	**7.3**	**Overall Rating**
1	Autonomous Vision-Guided Concept	2.3	0.0	1.6	2A	1.8	2.6	0.0	1.6	0.0	0.0	0.0	0.0	2.7	1.8	2.0	18.7
2	Magnetic Ref/Infared Active Target	3.0	0.0	1.6	2.8	2.2	2.8	0.0	2.3	1.9	2.6	2.5	2.7	2.7	1.8	2.0	30.8
3	Millimeter Wave Radar Concept	2.7	0.0	2.3	3.0	2.5	2.8	2.1	2.3	2.2	2.9	2.5	2.7	2.7	1.8	2.0	34.5
4	RF-Beacon Concept	2.8	0.0	1.7	21	1.9	2.0	1.3	1.6	1.5	2.9	2.5	2.7	2.8	1.8	2.0	29.8
5	Inductive Cable/FMCW Radar	2.7	0.0	2.3	2.8	2.5	2.8	2.0	2.3	2.1	2.9	2.5	2.7	2.7	1.8	2.0	34.0
6	Direct Pickup Shared Infrastructure	2.6	0.0	2.1	2.4	3.0	2.0	0.0	2.3	0.0	2.6	2.5	2.7	2.7	1.8	2.0	28.7

What intermediate conclusions may be drawn from this evaluation? The first is that in terms of the likelihood of satisfying requirements, there appear to be four logical groupings. The highest band contains concepts three and five. The second band contains concepts two, four. The third band contains concept six, and the lowest contains concept one. As stated above, the numerical values are of low precision, and differences of tenths of a point are meaningless. Second, concept ratings are highly dependent on the definition of the concept A simple addition of intervehicle communication to the first concept would have substantially increased its rating in terms of requirements satisfaction. At this point in the study, we found no single attribute other than communication coming to the fore in terms of overall influence on concept "goodness".

4.2. Figure of Merit Evaluation

The final step in the evaluation is to apply the criteria to each of the concepts and score them according to the weights defined in the previous segment. This has been done and the results are presented in Table 2 on the next page.

It is important to note that the evaluation is purely from a lateral-longitudinal control perspective. Those more concerned with environmental impact, legal and societal issues, human factors, or other perspectives would likely choose other criteria and other weight sets. Even within the limited domain of lateral-longitudinal control, it is also important to note that this is a judgment-driven process. There is no completely objective way to perform such an evaluation. One may argue with the selection of criteria, the scales along which the criteria are evaluated, the weight factors, the particular scores assigned to each concept for each criterion, and even the combining process. There is plenty of room for results to vary widely. The table above is our first cut at such an evaluation, and we have tried here to justify the results. We fully acknowledge that others may derive different but equally or perhaps even more valid results.

Table 2. Figure of Merit Evaluation Summary

		System Evaluation Criteria											
	Weights:	8	6	7	9	6	8	7	5	6	5	7	74
Concept	Mnemonic	3.1.1.1.1	3.1.1.1.2	3.1.1.2.1	3.1.2.1	3.1.2.2	3.1.3.1	3.1.3.2	3.1.3.3	3.1.3.4	3.1.4	3.1.5	Wt. Avg.
1	Vision-Guided Autonomous	0	2	9	2	2	1	3	9	5	3	3	3.3
2	Magnetic Ref/IR Stereo	4	5	7	3	4	5	9	7	7	9	7	5.9
3	MMW-Guided Lat & Long	3	4	6	3	3	7	9	5	5	7	7	5.3
4	RF-Beacon Socialist	7	5	5	2	2	9	9	5	1	7	3	5.0
5	Inductive Pickup/FMCW	2	6	2	5	5	7	9	5	1	3	3	4.4
6	Direct Pickup/Shared Transit	5	6	3	5	5	9	9	9	1	3	3	5.3

However, given all those caveats, it is clear that concept #2 comes to the fore as a leading candidate. There are a variety of reasons for this that are summarized in section 5.1 and treated in depth in the SCED. In short, the low cost of required infrastructural improvements, high degree of robustness, and relative insensitivity to common failure modes make it a strong contender. The second leading candidate is concept #3.

4.3. Simulation Results

As stated in section 1.2, part of our approach was to validate some of our analyses through the use of simulation. During the course of definition of maneuver requirements and system concepts, we identified some concerns about the influence of sensor and control sample rate, sensor quantization intervals, and vehicle control bandwidth that lent themselves well to a limited simulation effort Sensing for all vehicle states was assumed to be the ideal case. Since the test cases involving multiple vehicles, the models were extended by adding five vehicles in series coupled by headway sensors and a simple control feedback scheme to control throttle based on speed and sensed headway. In addition, a feedback from each vehicle to the vehicle following was provided to emulate a communications link to demonstrate the benefits of communicated speed information during platooning.

Once again, the reader should note that the scope of this study was to determine longitudinal/lateral control issues. Toward that end, we developed a longitudinal and lateral vehicle model in the MatLab simulation environment based on vehicle model data developed at USC by Petros Iannou and his associates. MatLab was selected because it is a widely available tool and it provides an environment in which such models can be very quickly and accurately implemented. Those models will be provided to the FHWA in as-is condition at the close of the study, and it is our hope that others will be able to use these models and extend and adapt them to their own work. For that purpose, AHS researchers may acquire the models by contacting FHWA.

Twenty-five test runs, summarized in table 28 of the SCED, were performed on the longitudinal model. The parameters for these test runs were selected to emphasize performance variations as a result of changes in sensor sample rate, control update rate,
sensor quantization interval, vehicle performance bandwidth, and presence or absence of communication. lower train response was defined in terms of slow, medium, and fast responses to throttle changes. Bandwidth values of 0.07 Hz, 0.15Hz, and 0.20Hz respectively were chosen as representative values for passenger automobiles and smaller heavy vehicles. For the purposes of this simulation, only homogeneous platoons were modeled; later simulation work will have to include platoons of mixed vehicle types.

Control update rates were varied between two values; fast refers to 50 Hz update and medium refers to 20 Hz. Sensor update rates were varied between three values: slow = 10 Hz, medium =20 Hz, and fast =50 Hz. Sensor quantization was defined in terms of a virtual "headway sensor" that sensed headway distance between the vehicle carrying the sensor and the vehicle immediately to the front, such as radar or passive stereo. Quantization intervals were defined as coarse =0.02 meters (1%) and fine =0.002 meters (0.1%). The last variable determined whether vehicles had communicated velocity data for the lead vehicle in the platoon.

For ease of comparison, the twenty-five runs were organized into eight different comparison groups. Analyses of the output plots for each member of a group yielded some insights that later system designers will have to consider, such as:

- Plant performance - particularly responsiveness of the drive train - was the major influence on whether platoons could be safely engaged, even with communication of velocity of the lead vehicle to provide "lead".

- Without the "lead" provided by communication of velocity or acceleration state of the lead vehicle, it will not be possible to operate safely at headways of around 2 meters.

- The rate of sensor sampling and rate of control implementation was not as critical as we first expected, given the relatively low bandwidth of the typical power train.

- Ride quality performance appears sensitive to the range resolution and that coarser sensors will place a greater burden on the control system to compensate, which increases complexity and, hence, cost.

- As anticipated (and validated by similar studies undertaken at the path program), lead vehicle information is vital to achieving safe close following performance.

- Even with lead vehicle communication, it is not possible to maintain two meter headways if the power train is too sluggish in its response to throttle commands.

The simulation effort raised an interesting point for the systems definition process and particularly for the development of quantitative requirements: what is the set of conditions that define minimum (or maximum) metrics under each of the various operating conditions? Careful consideration will have to be given to each individual requirement to define the conditions of testing compliance. Merely stating the metric itself leaves compliance evaluation wide open. In the comparison of cases 23 and 25, we find it is possible for either system to meet the requirement for maintaining a 50% safety margin, one only needs to specify the size of the maximum allowable disturbance and assume a suitably large headway value. This, of course, leaves open the question of how large a disturbance must be allowed for. Other related unanswered questions surrounding this testability question might include the following:

- What performance limitations (control bandwidth, deceleration performance with and without brakes, acceleration performance, etc.) will be placed on all vehicles operating on the AHS?
- How does the selection of operating speed affect these calculations?
- Within what headway constraints will the systems be forced to perform?
- What are the reasonable best-case and worst-case disturbances that will have to be handled by the system?
- How do ride quality requirements couple into these considerations? We conclude that a

significant simulation effort may be required before definitive
requirements can be finalized.

5. MAJOR STUDY CONCLUSIONS

5.1. Concept Evaluation Results

If one were to attempt to summarize the results of the entire study, they may be found from several places. First, the evaluation is summarized in tables 1 and 2. Second, strengths and weaknesses of each of the representative system configurations are summarized in section 3.4 of the SCED. These are too lengthy to repeat here, and the reader is referred to that section directly. Third, each of the documents in the series (MDFRD, SCDD, and SCED) contains various sections in which significant issues have been identified. During the course of the study, a total of 87 issues were captured in the section of documentation with which they were most closely associated. For easy reference, the summary statements for each has been tabulated in appendix C of the SCED.

Though many issues were identified, none of these were determined to be a "show-stopper. " Some have more far-reaching ramifications than others, but none of them indicated that the goal of building an AHS is infeasible. However, significant questions remain about which concepts are the most viable, and how each of them could be implemented within the constraints of safety, public acceptance, environmental concerns, legal and societal issues, and the like.

To determine the most likely winning concept from this evaluation, we refer again to tables 1 and 2. The second table is actually the primary means for determining a winner. The former table, since it is based on requirements, merely serves to "quality" a concept for consideration. The latter table provides the relative figure of merit for surviving concepts. In table 1, the first concept receives a very low rating, and we previously noted that this rating was strongly influenced by the lack of communication and was easily corrected. However, that lack has relatively little influence in the results tabulated on table 2, and still the concept rates low compared to the others. The combination of low rating on both tables makes it a likely loser.

On the other hand, the second concept rates very highly on table 2, and is in the top three in table 36. That combination, and the assessment of its strengths and weaknesses, make it a likely winner, in our assessment. Using the same logic, the second most highly ranked concept overall is concept #3.

The common elements among the leading candidates includes the following:

- They require relatively simple equipment, both on the vehicle and in the infrastructure for both primary and backup (redundant) functions.
- They have an easily-defined path for evolutionary deployment.
- They distribute control functionality among vehicles as much as possible and thereby reduce the impact of systemic failures.
- They limit the public liability for failure-related incidents.

5.2 Key Points for the Final Results Conference

One of the directed tasks under the study is to present the key points or issues for the final results workshop. That workshop will have a broad audience of participants, many of whom may have little background in the AHS. These points are an attempt to encapsulate the most important messages we would pass on to the consortium and to the broad community of stakeholders as a result of this study. The points we identified and submitted in preparation for the workshop include the following:

The breadth and complexity of system trades will require *a well-defined* evaluation methodology agreed to before concept evaluations start. The diverse, distributed nature of the consortium staff coupled with the need to generate public support and support of stakeholders not directly participating in the consortium efforts makes it mandatory that the process be well established and faithfully adhered to before the results can be meaningful and generally accepted. The community must achieve a priori consensus on:

- system requirements, including satisfaction threshold values
- evaluation metrics
- relative importance (weighting) factors for those metrics
- specific configurations to be evaluated
- capturing, cataloging, and resolving system design and implementation issues

- The importance of phased, evolutionary implementation cannot be underestimated for the winning concept
  - Compared mass transit options, the benefits of AHS options are difficult for public to conceptualize; justifying expenditures of public money is made more difficult by this problem
  - Public experience with tile performance and benefits achievable (the public trust in the system) for a given cost needs to be developed; this requires time and familiarity with the enabling technologies. That familiarity is best achieved through gradual development and fielding of new capabilities.
  - Infrastructural improvements will not be justified unless there are enough vehicles to make use of them, and vehicles will not appear on the market in any significant numbers until enough miles of roadway have the required improvements. We refer to this as the "market penetration chicken-and-egg syndrome." Concepts that avoid this syndrome by allowing market forces to determine what capabilities are fielded at a given point in time are more likely to succeed.

Of the six approaches we evaluated, magnetic nails for lateral control with either stereo IR correlation or radar for longitudinal sensing appears to be the leading concept because of the following factors:

- a very robust implementation
- a combination of relatively simple vehicle equipment complement and simple infrastructure complement - results in the lowest overall cost profile
- it is very well-suited for phased implementation - market-driven forces will dominate how the system evolves
- it provides the best combination of near-term implementation and far-term growth potential for gradual building of public confidence in system's capability

- Vision-guided approaches appear to be weak candidates at this time
    - There are significant problems of robustness with respect to night and weather given the current state of the art
    - The expense of in-vehicle equipment may be prohibitive, particularly for redundant "fail-safe" designs.
    - Some of the difficulties of reducing various latencies in the system for improved performance greatly exacerbate the expense problem.

- Centrally-powered vehicles appear to be weak candidates at this time
    - They suffer from the chicken-and-egg syndrome referred to above.
    - Safety and public liability for the aftermath of a power failure will be serious concerns.
    - The wide dynamic range on power demand could lead to over-designed, expensive power distribution systems.

- Low-latency, low-bandwidth communication of state information among vehicles will be essential if close vehicle following is a requirement
    - simulation results show unbounded errors if platoon length is not limited
    - even for sluggishly-responding vehicle types, communication bounds the worst case error and allows bounded performance specifications
    - barring a breakthrough in communications technology, interference among communicating entities will likely result in a limiting constraint of low-bandwidth communication; systems designs will have to work within that constraint.

5.3. Summary of Significant Issues

Throughout the MDFRD, SCDD, and SCED we captured issues in the sections most closely associated with that issue. A summary table is provided in appendix C of the SCED listing all 87 issues documented. We have selected the twelve most significant issues and reproduced them here to provide a general idea of the kinds of issues contained in the detailed documentation.

MDFRD §2A.3.1: Decoupling Steering from Human Control

Should the steering be physically decoupled from the steering wheel during automated operation?

From a human factors and safety standpoint, this is a serious issue to be resolved with respect to steering control. There are various arguments on both sides of the issue:

- Individual operator safety arguments may dictate that the operator must be able to take over at any point with very little special action other than grabbing the steering wheel. If a situation develops that is clearly outside the operating envelope of the automated system, the system cannot prohibit immediate, reflexive action on the part of the operator.

- System level safety concerns are centered around the fact that nearly 90% of all accidents involve operator error as a significant contributing (if not the primary) cause. With automated operation in high traffic density environments, the ability to override the system may cause more frequent and more severe accidents. This argument suggests the desirability of completely decoupling the steering so that manual preemption is not possible without deliberate, cognitive acts on the part of the driver.

- Depending on bandwidth and control torque available to the automatic system, it may be possible to hurt the operator. If the operator were to hang his/her wrist in the spokes of the steering wheel and a sudden, high-torque input were commanded by the system, a wrist, hand, or finger could be injured, depending on the design of the equipment on the steering column (such as levers ,switches, actuation components).

- Back-drivable actuation increases steering chain inertia. Increased inertia makes it harder for the human driver to perform quick control actions. This argument suggests the desirability of decoupling electro-mechanical actuation during manual control, if such is used. If hydraulic actuation *is* used, the issue is reduced or eliminated, since designs that place no additional inertia on the steering chain *are* possible.

- If the mechanism of sensing the user's desire to usurp control is sensed by torque applied to the steering wheel, then careful attention must be paid to the problem of how to sense the presence of *intentional* user input. Suppose, for instance, that the input were to be sensed by torque applied to the steering wheel. If the steering wheel is not decoupled, then the inertial reaction of the steering wheel to a sudden movement by the control system would be indistinguishable from user input at the torque sensor. Also, distinguishing intentional input from unintentional input is a problem requiring careful human factors engineering.

MDFRD §2A.4.1: Operator Intervention While In AHS Lanes And Modes

Under unusual or emergency conditions, the tendency will be for the operator to attempt to wrest control from the system. Because of the high density of traffic and short reaction times in some operating modes, the consequences of inappropriate action might be not only to endanger the driver avid occupants of a given vehicle, but to endanger nearby vehicles as well.

Once under automatic control, the operator is expected to sit back and "enjoy the ride." However, should an unusual situation occur, the operator's attention will be brought back to the highway situation in an abrupt manner. Assuming the vehicle is traveling in dense traffic at highway speeds, short reaction times would be required to perform any required corrective action. In such circumstances, the operator might find his attention awakened in one of three circumstances:

- Something's wrong, and he does not take the right action.
- Something's wrong, and he fails to take control when he should.
- Everything is under control and he attempts to usurp control when he shouldn't Each of these situations is potentially very dangerous, not only to the individual, but potentially to those around him as well. Assuring under sudden circumstances that the correct action (or inaction) always occurs will be a significant and important human factors design issue.

MDFRD *§2A.4.2:* Redundancy Cost/Performance Tradeoffs

Automatic control under high performance, safety-critical conditions requires fault tolerance to *a level not expected in manual systems. A large body of knowledge in redundancy management exists, but solutions are frequently expensive, requiring additional equipment for sensing, processing, and activation.*

Fault tolerance of the system will likely be at the heart of many control-related safety concerns in the AHS system. The level of redundancy required to assure the proper level of safety in each element of the system. Fail-safe designs, those preventing a dangerous situation from developing after a failure, will be mandatory.

However, safety is only the first level of concern. The second level of concern is what happens to the continued operation of the system when one of the vehicles fails. A major goal of the AHS is to provide high throughput in high density situations. Failure modes with the potential to obstruct a highway segment may require fail-operational-fail-safe design. On the other hand, the cost of redundant designs are likely to cost more than may be acceptable to the end users.

MDFRD §3.3.6: Control Authority Limits - Adverse Conditions

Specification of lateral acceleration limits for other than dry pavement conditions complicates the issue because of the wide variety of environmental conditions. Sensing traction-reducing conditions in all but very coarse ways is beyond current state of the art.

The degree of lateral acceleration authority that can be allocated to an automatic controller is not only a function of human factors (primarily ride comfort) considerations.
Attainable lateral acceleration performance can also be affected by vehicle design, state of tire wear, vehicle load, road condition, surface conditions (icy, wet, gravel), and other factors beyond the control of designers. We conclude that programmable lateral acceleration authority limits will be required.

To determine the appropriate lateral acceleration limits needed for safety, two significant questions remain:

- How does one determine the values for these limits under adverse conditions? Significant testing to develop an empirical data set seems to be needed.

- How does one sense reliably the environmental conditions that reduce traction? Accurately sensing water, ice, sand, gravel, and other traction-reducing conditions remain a technology gap at present.

MDFRD *§4.4.4:* Sensing/Communication/Activation Latency and Headway

Headway requirements are dominated by latency under emergency stop maneuvers. Latencies will have to be very low to avoid impact during maximum deceleration maneuvers.

A number of concepts have been advanced postulating operating at very small headways. While controllers can be designed for safe operation under nominal operating conditions assuming reasonable disturbances, the minimum headway is limited by the stopping performance under the worst case conditions. Under ideal conditions, the headway required to assure no-impact stopping is dominated by the initial velocity and the latency between successive stop command onsets. Analysis suggests that very low-latency sensing or communication and very low latency control processing will be required to achieve small headways safely. The authors would caution that the assumption of fast (10ms or better) communications does not obviate this concern because it fails to take into consideration all the factors that influence system latency, much less performance differentials

MDFRD §5.7.1.1: Variable Vehicle Performance Implications

Variations in vehicle performance may make it imperative that the performance of vehicles behind are considered in executing control actions. Failure to do so may create dangerous situations. such as braking too hard with a heavy truck immediately behind.

The control needed to optimize dynamics of a platoon is a non-linear problem that is highly dependent on the performance of the vehicles involved. The smaller the spacing, the higher the bandwidth required and the more sensitive the whole system is to individual performance differences. To date, most of the work in longitudinal coordinated control has not allowed for significant variations in acceleration/deceleration capability. If the vehicle behind has less control authority, one's own actions must not exceed his capability to respond.

Gross maneuvers such as hard braking are not the only maneuvers affected by this issue. If there are significant disparities in the plant model for the vehicles involved (e.g., poorly tuned engine or loss of power due to use of air conditioning), energy usage optimization could in some cases yield considerably worse performance in terms of emissions and fuel efficiency than would otherwise be experienced because the model on which the control designs were based are not longer true. If the vehicle behind is significantly less capable in terms of acceleration and deceleration, then one's own vehicle may need to allow more room in front to act as a "cushion" for eliminating disturbances.

Can and should spacing regulation performance be specified as a function of relative performance of the vehicles both in front of and behind the vehicle in question?

MDFRD §5.7.2.2: How does the system avoid 'lemming-like" behaviors?

Vehicle following without independent verification can cause a following vehicle to inappropriately follow a failing lead vehicle. This may give rise to a new class of tort litigation - the "you led me astray" case.

When in nominal vehicle-following mode, if each vehicle does not independently sense lane-relative position, one vehicle may follow another that is wandering out of its lane due to failure. Positive means must be established for determining the health of the control system of the vehicle in front or for independently validating its behavior. Without such independent verification, it is impossible to guarantee the safety of vehicles behind. On the other hand, if the means of detecting lane position is through a look-ahead sensor (such as a forward-looking camera), then vehicles in front are likely to obstruct such sensors' field of view.

MDFRD §5.7.3.1: Static Obstacle Detection Capability Is Presently Sensor Limited

Generalized obstacle avoidance is currently limited by obstacle detection sensor performance. AHS concepts will likely have to work within the constraint of an inability to detect and avoid flotsam or holes on the highway until sensor capability improves within a reasonable cost profile.

There may be no combination of sensors and processing available in the near term to do obstacle detection at a cost that is remotely affordable unless the problem is carefully constrained. Obstacles come in a variety of sizes, shapes, and materials that defies current technology if all-inclusive sensing of any obstacle that can damage the car is required. An object as small as 0.1 meter can be enough to damage a passenger automobile, yet it must be identified 100 meters or more in front of the car to be able to react in time at highway speeds

Even more challenging is the problem of reliably detecting holes in the pavement. Detecting and avoiding potholes is not likely to be an affordable capability within the next 20 years, baring an unforeseen technological breakthrough. By comparison, the human eye not only has better pixel resolution than most cameras and other imaging sensors, but contextual cues (lighting, shading, color, presence of debris, actions of preceding vehicles) provide information that an automatic system will not be able to detect with present technology. This is not a "show-stopper" issue; AHS concepts can be formulated on the assumption of well-maintained roads. Especially in the context of our interstate system and urban freeways, such occurrences are relatively rare.

On the other hand, if the sensing requirement is limited to detecting vehicles with a threatening relative speed profile in current or immediate neighbor lanes only, techniques such as FMCW radar and even computer vision may prove effective.

MDFRD §6.4.3.2: Standard Protocols For Emergency Conditions

Extensive analysis will be required to determine the kinds of emergency (off-nominal) conditions the AHS must be capable of responding to and the right protocols for response to those conditions. This analysis will have to documented as standards that form the basis for limiting product liability.

Our recommendation is that, once the possible configurations have been narrowed to a few candidates, an effort must be undertaken to perform failure modes and effects analysis with an emphasis on defining standard response protocols for various emergency conditions, and that legislation should be considered that will limit liability if those protocols are observed.

SCDD §4.5.1: Lane limitations on lateral sensing concepts

Lateral position sensing using out-of-lane infrastructural elements may limit AHS implementation to no more than two adjacent lanes.

A number of concepts have been proposed using some form of sensing of infrastructural elements to the side of the lane for lateral position data. Examples of this type of sensing include triangulation of RF beacons placed at a fixed interval, radar comer reflectors at fixed intervals, visual tracking of reflectors, visual tracking of barriers, and the concept in this section of using radar reflection from the barriers. All of these implementations have a common limitation. In almost all of these concepts, if the line of sight is obstructed, the ability to sense lateral position is degraded or eliminated.

Under dense traffic conditions where vehicles are traveling in close spacing, the middle lanes of a three or more lane configuration will be obscured most of the time. Assuming that the AHS does not eliminate dense traffic, but merely makes the system efficiently handle high traffic volumes, the likelihood of obstruction is very high during the times that the capability is most needed. Allowing for platoons in adjacent lanes will exacerbate the problem because the close spacing may make lateral sensing impossible anywhere along the platoon length. Therefore, one may conclude that any concept using side-looking sensors and infrastructural references outside the lane will limit AHS implementation to no more than two adjacent lanes. Vertical elevation of the infrastructural element is not necessarily a good solution; the local horizon of a passenger automobile while traveling next to a tractor-trailer combination is quite high (60~7O~), and the infrastructural elements would have to be too high to be effective in that case.

This is particularly a problem for urban freeway situations, where the number of total lanes in the highway can be up to six lanes. For rural intestate highways, the number of total lanes is usually no more than three in each direction, and the number of AHS lanes that would be assigned would likely be less than three. However, the winning AHS concept *must* be capable of working in urban as well as rural freeway conditions.

If each lane has barriers on each side, then the issue is moot, but at substantially increased infrastructural cost. Unless there other reasons (e.g., safety) for completely cordoning off each lane, the cost impacts of installing barriers for the purposes of sensing are likely to be too high relative to the anticipated benefit and compared to other concepts.

SCDD §7.5.2: Fines for Poor Maintenance

A disincentive for poor maintenance needs to be included in the system definition for AHS users under this concept to minimize the impact of failures on the general public.

The fundamental goal of this concept is improved people-moving capacity. Failures of private vehicles on the shared infrastructure have a potential impact on the good of the public at large. Ensuring that private operators perform the appropriate preventive maintenance could become a problem once private use becomes widespread.

A disincentive for poor upkeep would be to *fine* private users whose vehicle failures create congestion in the system. This is a radical concept in some regards, but the notion is that use of the AHS is a privilege, accepting the consequences of failure are an integral part of the user's agreement. Certain failures blowout due to cut tires, failures induced by the infrastructure) would be excluded.

Why is this required when there is no such provision in today's operating environment? After all, a failure is not necessarily the individuals fault, right? Public transit systems operate in one of two modes: they either operate on dedicated rights of way that the general public may not enter, or they operate on existing highways where they can generally circumvent problems created by private users. In the latter case simple vehicle failures are treated by pulling the failed vehicle onto the shoulder and the resulting traffic transients are usually short-lived. In an AHS system where there are a limited number of exit points and a single vehicle can bring an entire highway to a dead stop, there is potential for one individual to affect tens of thousands of commuters as well as the revenues of a public transit system. The consequences of failed vehicle causing a "system outage" *must* be directly felt by the individual responsible for the problem.

SCDD §7.5.4: System-Wide Power Requirements May Be Prohibitive

The magnitude of power required for an entire urban area avid the infrastructures it implies in power generation and distribution is quite substantial for centrally-powered concepts.

The question is, how much energy would be required to power traffic for each kilometer of travel? In the SCDD we examine two cases. Under these scenarios, one could reasonably expect to have a requirement for almost 10 MW per kilometer of highway. This calculation is based on roughly 3100 vehicles/lane/hr. However, it should be noted that AHS researchers are planning toward densities of 4000-6000 vehicles per lane per hour, causing the power draw to scale proportionately. We also presume that lost energy due to acceleration/deceleration sequences for normal headway rnaintenance functions are included in' the efficiency factors. We presume for the sake of argument that a worst-case (high density) flow is under consideration, since those conditions would dictate the infrastructural requirements.

Suppose an average urban center were assumed to require (conservatively estimating) an average of 3 megawatts for each kilometer under high-density conditions. If there were 250 miles of urban freeways and arterials in a service district, a power generation plant of 750 megawatts' capacity would be required. While these are very approximate estimates, they point out that a substantial power generation and distribution capacity would be required if all the car and truck traffic currently on the highway were to be powered centrally. Obviously, not all vehicles will be transformed to use infrastructural power all at once; initially the power requirement would be a small fraction of what is calculated above, but system architects must contemplate the final cost of the fully-implemented system.

5A. Recommendations to the AHS Consortium

The overarching intent of this study was to provide a structure for evaluation of concepts and to uncover, in a first pass evaluation, those issues that should be investigated in further detail during the system definition phase of the AHS program. We believe that the structure of this study, as reflected in the chain of three documents produced under this effort, is the right methodology for the consortium to follow.

We have also attempted to perform our specific analyses within that structure as a means of demonstrating how the structure can be used. However, we also recognize that there are some areas for additional study arising from this effort that could be addressed by the Consortium should they choose to follow this approach. These include:

Additional maneuver definition - The maneuvers set the stage for the definition of functional requirements that in turn drive the system design at both the conceptual and detailed levels. Having defined the taxonomy of maneuvers and proceeded with the evaluation, we soon realized that there were probably some sub-categories of maneuvers that may have been omitted. However, we believe that the structure of the taxonomy provides the basis for filling in the "holes". Some effort should be expended in filling out the list of required maneuvers so that all required activities are defined.

In-depth requirements definition - Developing a consistent and all-inclusive set of requirements generally requires multiple iterations for which there was insufficient time under this limited scope study. We attempted to define a set of requirements on a first-pass basis, and performed one iteration of review and refinement. However, we recognize that this set has many points of incompleteness that will require broader expertise than our limited team could provide. Nonetheless, we believe that the requirements provided should be a good starter set to generate discussions from which the full set of requirements will emerge. That discussion should be on a national basis and should involve participation by all categories of stakeholders. Failure to do so will induce the risk of rejection of whatever solution the Consortium settles on. If you don't support the requirements set, you can't possibly endorse the solution that arose from that requirements set.

Detailed system concept definition - Not only because of the limited time and resources but also because of incomplete requirements at the time of concept selection, there was demonstrably less detail in the concept definitions than needed to fully evaluate them in a completely meaningful way. As we stated several times in the preceding sections, we determined from the outset to define some concepts and then hold those definitions constant. This approach was necessary to avoid an open ended process of modify-reevaluate-modify-reevaluate ad *nauseam.* Our recommendation, however, is to avoid detailed concept definition before there is general agreement on a complete set of requirements. The system definition phase of the program should allocate sufficient time allocated for iterating on both requirements and concept definition *and to maintain broad involvement on all intermediate steps.* Failure to do so will be costly in terms of dead end pursuits and unfocused, unproductive debate in the community at large.

Of course, the core activity of the Consortium is to develop the system definition. Our evaluations and recommendations are not so much intended to skew the Consortium toward or away from particular concepts, but to highlight the major issues we could see and to demonstrate what we believe is a rational, traceable approach to defining the final concept. Without a reasonably rigorous methodology that is *agreed to from the outset of the system definition phase,* the effort to define a workable AHS concept will be mired by the diverse and distributed nature of the consortium. It is our hope that the product of this effort will provide the basis to avoid that pitfall.

Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Task D: Lateral-Longitudinal Control Analysis

Volume II: AHS Maneuver Definition and Functional Requirements Document

U.S. Department of Transportation
Federal Highway Administration
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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research and Development

NOTICE

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List of Acronyms and Abbreviations

AHS	Automated Highway System
FUR	Forward Looking Infared
LIDAR	Laser Imaging Detection and Ranging
LLCS	Lateral/Longitudinal Control Study
MDFRD	Maneuver Definition and Functional Requirements Document
MMWR	Millimeter Wave Radar
mps	meters per second
mph	miles per hour
PSA	Precursor Systems Analysis
RSC	Representative System Configuration
SCDD	System Concepts Definition Document
SCED	System Concept Evaluation Document
TBD	To Be Determined

AHS Maneuver Definition and Functional Requirements Document

1. INTRODUCTION

1.1. Purpose of the Document

This document is one of three documents produced under the Precursor System Analyses for the Automated Highway System (AHS). It provides a detailed description of the maneuver taxonomy to be used in the study of Lateral/Longitudinal Control issues. The purpose for developing the taxonomy is to derive the requirements upon which system concepts for automated highways are to be evaluated. The other two documents are the *AHS System Concepts Evaluation Document* (SCDD) that presents the concepts under evaluation, and the AHS *System Concept Evaluation Document* (SCED) that provides the evaluation itself.

The structure of the evaluation is a series of spreadsheets - one for each maneuver -wherein the rows form the alternative system concepts defined in the SCDD and the columns represent the requirements for each maneuver. The final form of this document, together with the SCDD, provides detailed descriptions needed to understand the trade space in this study. The SCED contains the evaluation data according to the methodology outlined in the previous two documents.

The content of this document defines the structure for the evaluation task of this study. Each concept will be evaluated in three steps The first step is to determine if it is impossible, possible, likely, or definite that the concept meets all the absolute requirements. The second step is to determine how well the concept can be projected to meet the optimization criteria contained herein. The third step is to uncover any issues relevant to the implementation of an AHS.

1.2. Organization of the Document

The main body of this document is divided into six major sections (§2 though §7) that outline the maneuvers for a level in the taxonomy of maneuvers. These sections use the following structure:

- Outline Level 1 (e.g. 2.): Levels of the Maneuver Taxonomy -- The classes of maneuvers are organized into a hierarchy such that each level subsumes all the levels below.

- Outline Level 2 (e.g. 2.1.): Generic AHS Maneuvers -- Within each level, the significant maneuvers required to perform all AHS operations at that level are described.

- Outline Level 3 (e.g. 2.1.1.): Each maneuver is specified in the following manner:

    - Description --- a textual description distinguishing it from all other maneuvers.

    - Assumptions --- a set of assumptions upon which the definition and distinguishing characteristics are based.

- Requirements-- the performance and design requirements on the maneuver at that level of the taxonomy against which concepts can be measured in a binary "can-meet I can't-meet" evaluation. Wherever possible, these requirements are expressed as quantified thresholds which a given concept can be evaluated against. The reader should note that there are two levels on which the expressed requirements should be evaluated (in priority order): 1) does the requirement invoke the correct metric, regardless of whatever threshold values are picked, and 2) given that the correct metric is used, has the correct threshold value been specified. A preliminary division between absolute (applicable under all circumstances) and conditional (applicable under certain conditions) has been included.

- Issues --- significant design or implementation issues uncovered as a result of analyzing requirements.

1.3. Maneuver Taxonomy Overview

Based upon a careful review of a wide variety of representative system configurations (RSCs), a set of AHS maneuvers was defined that covers the majority of RSCs analyzed. In some instances, a maneuver may be required by an RSC that is not defined in this set or a maneuver is defined in this set that is not required by an RSC, but for the most part the maneuvers listed here form a representative set for a large majority of RSCs.

After the maneuver set was defined, a taxonomy for the set was developed based upon a subsumption architecture. Recent research in the development of system architectures for autonomous and/or automatic vehicles has demonstrated successful autonomous operations using subsumed behavior levels to define and implement varying levels of control complexity. The taxonomic categories for the maneuver set were defined based upon the level of complexity of the maneuver wherein each maneuver was viewed as a vehicle behavior. Low level vehicle control functions (e.g. servo control) that would not normally be considered as behaviors were included in the maneuver set for completeness and to define the end-to-end flow from high level maneuver goals to solenoid voltages.

Level 0 (Servo) maneuvers and Level 1 (Primitive) maneuvers represent the equivalent of autonomic functions for the vehicle. They run at all times and are not subsumed by higher level maneuvers. Speed control and directional control in Level 1 may also be thought of as longitudinal control and lateral control behaviors. Level 2 (Vehicle) maneuvers are the lowest level behaviors that can be subsumed. They represent vehicle maneuvers that can be performed without the need to coordinate or interact with other vehicles. Level 3 (Interaction) maneuvers are so named because they involve potential interaction with other vehicles. Level 4 platoon) maneuvers require not only interaction with other vehicles but may also require coordination with other vehicles. Lastly, Level 5 (System) maneuvers are the most complex in that they require not only interaction and coordination with other vehicles, but also must handle the difficult task of changing from non-automated operation to automated operation and back again.

In addition to providing an intuitive structuring of control authority for the various maneuvers, the subsumption architecture also provides a logical path for evolutionary implementation of the system architecture. In general, with each step up in maneuver level, the requirements on processing, sensing, communications and coordination also increase. If the AHS system is to be implemented in an evolutionary fashion, then the system vehicle control architecture must be able to accomodate evolutionary increases in performance requirements.

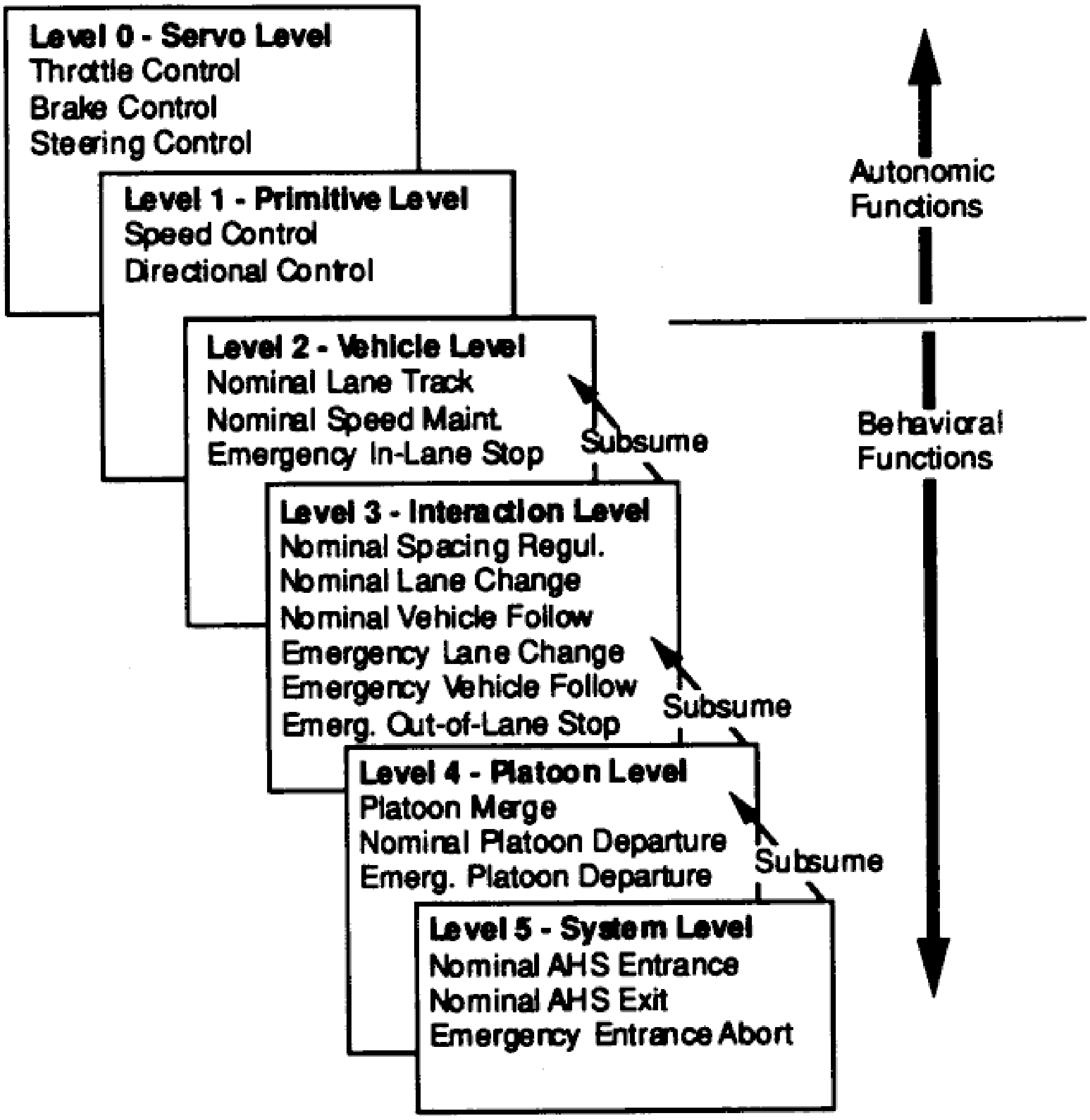


Figure 1. Maneuver Hierarchy

Figure 1 illustrates the grouping of maneuvers by behavior level. The control of each maneuver over the vehicle may at anytime be subsumed by a higher level maneuver if the situation warrants. When the subsuming maneuver is completed it will return control authority to the lower level maneuver. In as much as higher level maneuvers embody greater complexity and hence greater risk of control decision errors, it is the goal of the system architecture to operate under the lowest level of maneuver control possible. Multiple behaviors may operate simultaneously, especially at the lower levels.

1.5. System Requirements

This document defines only a preliminary set of requirements. We undertook definition of requirements to provide a basis for evaluating the various concepts. The requirements themselves were not intended to be all-inclusive. Rather, they were defined to sufficient breadth and depth to uncover what the authors believed to be the significant system issues that must be addressed as the system concepts are developed and evaluated by the AHS

Consortium. Our' expectation is that this set will form the beginning of a detailed set of requirements for the Consortium's more detailed trade studies, and that the structure we have built into this document will provide the means for capturing that more detailed set

Requirements should be written such that they are implementation-independent; we have tried to do this. In some cases, it was difficult at this stage of high-level concept definition and evaluation to separate out implementation details from requirements. For instance, a key question is whether platooning (vehicles following one another in small clusters) is a requirement or an approach to meeting a more abstract requirement Is the requirement to simply provide a means for increasing the density on the highway, or is it a given that platooning is the best way to achieve that increase and that any candidate concept must include it as a mandatory function? We have taken the latter approach in defining system requirements, though it is possible to remove this requirement without violating the structure of the document or the method of organizing the set of requirements.

Requirements should also be written to be quantitative and testable wherever possible. In developing the list of requirements herein, we often found that we could state what we thought was the best measure of system performance or effectiveness, but it was not possible to determine with confidence the threshold value. In such cases, we inserted a "TBD" followed by a suggested value in parentheses. For some of these TBD, other researchers may have already found satisfactory values. For other TBDs, the work of the Consortium in the next phase of the program will uncover the right value through analyses or simulation. At this point, we would caution the reader to examine first *whether the metric in the requirement* is the right *metric* by *which* to *measure system performance or effectiveness, and* judge later whether the value is the right threshold level. Too often it is easier to argue the size of the threshold than to ask the difficult questions of what is the right approach to specifying performance. In most cases, we considered the threshold value included to be a rational starting point based on nothing more than engineering judgment

In summary, this requirements definition was undertaken with a very limited team of engineers operating from the very limited perspective of lateral-longitudinal control only. The contents of this document by no means is a definitive set of requirements, and we expect that a lively discussion will ensue on the "real" requirements for an AHS. In the meantime, the set contained in this document served as a basis for the evaluation that was the subject of this study.

2. AHS SERVO LEVEL MANEUVERS (LEVEL 0)

Maneuvers at this level are physical hardware interface maneuvers. These maneuvers are to be considered as a common set of maneuvers to all higher level maneuvers and to all representative system concepts. These maneuvers are provided primarily for completeness of definition; however issues pertaining to these maneuvers will be found at the end of this section.

2.1. Throttle Control

2.1.1. Maneuver Description

2.1.1.1. Function:

Servo control of the throttle actuator based on throttle command from speed control

2.1.1.2. Subsumed Maneuvers:

~ none

2.1.1.3. Inputs:

Throttle command Throttle excursion and rate limits Throttle position

2.1.1 4. Outputs:

Throttle solenoid voltage
Throttle out of limit status

2.1.2. Operational Scenario Assumptions

Limits on throttle actuation and coordination with braking and steering will be established at higher maneuver' levels within permanent safety limits established and maintained at the lowest level of control and established by vehicle designers.

Throttle control is intended for nominal operating modes only. Use of acceleration as a means of mitigating an emergency condition is not anticipated because of the wide variations in vehicle performance levels, as well as the low bandwidth available to most power trains. Throttle and brake commands are presumed to be coordinated such that throttle is to be immediately set to the minimum commendable level any time brakes are applied.

Braking commands in all cases take precedence over throttle commands. The reader' should note that section 2.1.3 only specifies accelerations due to throttle commands, section 2.2.3 provides brake control acceleration requirements.

2.1.3. Absolute Requirements

2.1.3.1. Vehicle Acceleration Limits

Under nominal operating conditions, accelerations shall not exceed 0.98 meters/sec^{2} (0.lg). This requirement is intended to place an upper bound on acceleration performance. Vehicles will be capable of a minimum of 0.098 meters/sec^{2} (0.0lg) before engaging the AHS capability.

Applied jerk shall not be greater than TBD *meters/sec*^{3}

Throttle controller shall not cause loss of tire traction due to applied torque.

Rationale: While vehicles of different designs will have different capacities for acceleration, designers of the AHS will need bounds on acceleration/deceleration performance to limit the design choices.

2.1.3.2. Vehicle Deceleration Limits

In emergency conditions, the throttle controller shall not cause the vehicle to decelerate faster than 1.% meters/sec^{2} (0.2g).

Applied jerk shall not be greater than 1% meters/sec^{3} (0.2 g/sec) to maintain operator comfort under nominal operating conditions.

Throttle controller shall not cause loss of tire traction due to applied torque.

Rationale: Throttle-only deceleration is a function of nominal operations. Higher levels of deceleration are implemented via braking response, particularly under emergency operating conditions.

2.1.3.3. Fault Tolerance

The controller shall provide a fault-tolerant implementation such that any one fault will result in the system reverting to a safe state. "Safe," as referred to here, precludes uncontrollably increasing or locked throttle conditions.

2.1.3.4. Operator Fault Notification

Once a fault has occurred, the operator shall be notified of the fault condition, and the vehicle shall be required to leave disengage the automatic control capability in a controlled, safe manner at the next available opportunity. if manual control action is required, an annunciator shall make this need apparent to the operator.

2.1.3.5. Operator Override

The controller shall preclude operator intervention, except in an emergency condition as designated by TBD. Example emergency conditions could be internal, such as a runaway actuator condition, or external, such as a suddenly developing accident situation outside the ability of the sensor system to detect

2.1.3.6. Operator Safety

The controller shall preclude injury to the operator via actuation of the vehicle throttle, by design, actuation force limits, or any other means deemed suitable by TBD governing authority.

2.1.4.1. Throttle Deceleration Limits

The throttle controller shall be designed to avoid invoking braking actuation under nominal conditions whenever possible. Use of brakes 10 control spacing or accelerations is energy consumptive and should not be a primary means of control. This requirement is subject to limitations of minimum spacing and speed limitation requirements.

2.1.4.2. Throttle Controller Bandwidth Limitations

The controller shall preclude rapid application and removal of the engine throttle in excess of TBD Hz and TBD percent of throttle travel. Personal ride comfort limitations on longitudinal acceleration shall be within ISO standards defined in ISO-DIS-2631.

2.1.4.3. Control bandwidth

The closed-loop actuation shall exhibit a position bandwidth of no less than 3 Hz., to a
-3-dB criteria.

2.1.4.4. Delay Time

The actuation delay time shall not exceed 0.05 seconds, measured from command initiation to 5% of unit step response.

2.1.4.5. Overshoot

The time response overshoot shall not exceed 5 percent, under all operating conditions.

2.2. Brake Control

2.2.1. Maneuver Description

2.2.1.1. Function:

- Servo control of the brake actuator based upon brake commands from speed control

2.2.1.2. Subsumed Maneuvers:

- none

2.2.1.3. Inputs:

- Brakeconanand
- Brake excursion and rate limits
- Brake position

2.2.1.4. Outputs:

- Brake solenoid voltage
- Brake out of limit status

2.2.2. Operational Scenario Assumptions

Limits on brake actuation and coordination with throttle and steering will be accomplished at higher maneuver levels.

2.2.3 Absolute Requirements

2.2.3.1. Operator Fault Notification

Once a fault has occurred, the operator shall be notified of the fault condition, and the vehicle shall be required disengage the automatic control capability in a controlled, safe manner at the next available opportunity. If manual control action is required, an annunciator shall make this need apparent to the operator.

2.2.3.2. Operator Override

The controller shall preclude operator intervention, except in an emergency condition as designated by TBD.

The Brake actuation implementation shall allow for manual brake operation in the event of TBD system failures, as a minimum.

2.2.3.3. Operator Safety

The controller shall preclude injury to the operator via actuation of the vehicle brake, by design, actuation force limits, or any other means deemed suitable by TBD governing authority.

2.2.3.4. Delay Time

The actuation delay time shall not exceed 0.05 seconds, measured from command initiation to 5% of unit step response.

2.2.3.5. Fault Tolerance

The controller shall provide a fault/tolerant implementation such that any one fault will result in a safe state. "Safe," as defined here, precludes uncontrollably increasing or locked state.

2.2.3.6. Vehicle Deceleration Limits

The brake controller shall not cause the vehicle to decelerate faster than 6.44 ft/sec/sec.

2.2.3.7. Overshoot

The time response overshoot shall not exceed 5 percent, under all operating conditions.

2.3. Steering Control

2.3.1. Maneuver Description

2.3.1.1. Function:
Servo control of the steering actuator based upon steering commands from steering control

2.3.1.2. Subsumed maneuvers:
~ none

2.3.1.3. Inputs:
~ Steering command
~ Steering position

2.3.1.4. Outputs:
~ Steering Actuator Voltage

2.3.2. Operation Scenario Assumptions

Steering is the highest bandwidth component of the system Steering commands will be generated at higher levels in response to such activities as lateral lane tracking, obstacle avoidance, and entry/exit (if such is performed automatically). Limits on steering actuation and coordination with throttle be calculated at higher levels and passed to the steering controller as an authority limit message, but absolute minimum on steering position and rate authority must be implemented in firmware or hardware independent of such commands. Under no circumstances are these upper limits on the position and rate limits to be violated.

2.3.3. Absolute Requirements

2.3.3.1. Vehicle Cornering Limits

The absolute vehicle steering travel limits and absolute vehicle steering rate limits shall be defined as a function of the vehicle speed independent of higher level commands or imposed, programmable safety limits. Such limits shall be in force even after loss of steering command or steering position feedback signals. These limits shall be defined so as not to exceed an absolute, i.e. emergency, lateral acceleration limit.

2.3.3.2. Fault Tolerance

The controller shall provide a fault-tolerant implementation such that any one fault will allow the system to continue operating. Once a fault has occurred, the operator shall be notified of the single fault condition, and the vehicle shall leave the AHS capability at the next available opportunity.

2.3.3.3. Operator Fault Notification

Once a fault has occurred, the operator shall be notified of the fault condition, and the vehicle shall be required disengage the automatic control capability in a controlled, safe manner at the next available opportunity.

2.3.3.4. Operator Override

The controller shall preclude operator intervention, except in an emergency condition as designated by TBD.

2.3.3.5'. Steering Rate Limits

In emergency conditions, the controller shall limit steering angle changes to no more than 15 percent of travel per second. In case of conflict between this requirement and the requirements of Paragraph 2.3.3.1, Paragraph 2.3.3.1 shall take precedence.

2.3.3.6. Steering Travel Limits

In emergency conditions, the controller shall limit steering angle commands to no more than ± 10 percent of travel, referenced about straight ahead. In case of conflict between this requirement and the requirements of Paragraph 2.3.3.1, Paragraph 2.3.3.1 shall take precedence.

2.3.3.7. Operator Safety

The controller shall preclude injury to the operator via actuation of the vehicle steering, by design, actuation force limits, or any other means deemed suitable by TBD governing authority.

2.3.3.8. Delay Time

The actuation delay time shall not exceed 0.05 seconds, measured from command initiation to 5% of unit step response.

2.3.4. Conditional Requirements

2.3.4.1. Relaxation of Vehicle Cornering Units

In the presence of automatic skid compensation, steering limits imposed by requirement 2.3.3.1 may be overridden.

2.4 Servo-Level Issues

2.4.1. Throttle Control Issues

2.4.1.1. Longitudinal Performance Analysis Needed

Throttle actuation bandwidth and latency requirements need some quantitative backup that doesn't exist.

To date, there is little direct design experience to guide evolution and development of new products in this area Significant simulation modeling may be required to determine bounds on bandwidth and latency. Control requirements are also highly dependent on system configuration. For instance, a system concept with forward-looking sensors will be able to sense changes in the environment sooner than a concept using a look-down sensor such as for one detecting an electric field from a buried cable. The forward-looking concept will be able to achieve stable response with a significantly lower' actuation bandwidth or a longer processing latency time. In general, ability to anticipate required control action permits a slower response time.

Standards for control performance need to be developed and published to provide guidance for developers and limit product liability.

2.4.1.2. Design for Optimizing Energy Use

Throttle excursions need to be an important measure in control system design for energy efficiency.

In the literature we have reviewed to date, there have been relatively few references to control schemes aimed at optimizing energy consumption by minimizing throttle variations. For most internal combustion engines, changes in manifold pressure move the engine into regions of sub optimal performance. Even with modern electronic ignition and fuel control equipment, transients reduce engine efficiency, increase the rate of carbon deposition inside the engine, and increase emissions and fuel consumption.

This is particularly problematic when controlling a vehicle to maintain close separation with another vehicle in a line of such vehicles. If controller designs allow even small amplification of transients down the chain of vehicles, the last vehicle in the line could experience significant throttle deviations which, even though not felt by the operator, reduce efficiency and increase engine wear.

2.4.2. Brake Control Issues

2.4.2.1. Failure Mode Response For Braking

When it comes to assuring 5 responses to failure conditions, what is appropriate under what conditions? Standards may need to be created for basic vehicle control (independent of vehicle performance specifics) similar to those that exist for aircraft flight control.*

For instance, in the event of system failure for longitudinal control, should brakes be applied to slow the vehicle as quickly as safety permits? If braking is being applied and a system failure occurs$_1$ is it more appropriate for braking force to be maintained, or released? Generation of such standards will be an important factor for controlling product liability litigation; being able to demonstrate compliance with accepted standards is often an important element of defense in liability suits.

2.4.3. Steering Control Issues

2.4.3.1. Decoupling Steering from Human Control

Should the steering be physically decoupled from the steering wheel during automated operation?

From a human factors and safety standpoint, this is a serious issue to be resolved with respect to steering control. There art various arguments on both sides of the issue:

Individual operator safety arguments may dictate that the operator must be able to take over at any point with very little special action other than grabbing the steering wheel. if a situation develops that is clearly outside the operating envelope of the automated system, the system cannot prohibit immediate, reflexive action on the part of the operator.

- System level safety concerns are centered around the fact that nearly 90% of all accidents involve operator error as a significant contributing (if not the primary) cause. With automated operation in high traffic density environments, the ability to override the system may cause more frequent and more severe accidents. This argument suggests the desirability of completely decoupling the steering so that manual preemption is not possible without deliberate, cognitive acts on the part of the driver.

- Depending on bandwidth and control torque available to the automatic system, it may be possible to hurt the operator. If the operator were to hang his/her wrist in the spokes of the steering wheel and a sudden, high-torque input were commanded by the system, a wrist, hand, or finger could be injured, depending on the design of the equipment on the steering column (such as lever's , switches, actuation components).

- Back~drivable actuation increases steering chain inertia. Increased inertia makes it harder for the human driver to perform quick control actions. This argument suggests the desirability of decoupling electromechanical actuation during manual control, if such is used. if hydraulic actuation is used, the issue is reduced or eliminated, since designs that place no additional inertia on the steering chain are possible.

- If the mechanism of sensing the user's desire to usurp control is sensed by torque applied to the steering wheel, then careful attention must be paid to the problem of how to sense the presence of *intentional* user input Suppose, for instance, that the input were to be sensed by torque applied to the steering wheel. if the steering wheel is not decoupled, then the inertial reaction of the steering wheel to a sudden movement by the control system would be indistinguishable from user input at the torque sensor'. Also, distinguishing intentional input from unintentional input is a problem requiring careful human factors engineering.

2.4.3.2. Stability and Control Standards and Requirements

Standards should to be established defining stability, control, and failure mode requirements and limitations before designs move to the system deployment phase.

A variety of failure mode responses are possible, depending on the circumstances. Upon system failure, should the steering be locked in the last generated steering angle until control is resumed by the driver? Should it be returned to neutral position while the vehicle is slowed? if lateral control is by sensing distance from a roadside barrier, how should a sudden sensor signal dropout be handled by the control system? Generation of such standards will be an important factor for controlling product liability litigation; being able to demonstrate compliance with accepted standards is often an important element of defense in liability suits.

This issue is closely related to that of section 2.4.1.1. 2A.3.3. Steering Position and Steering Rate

Safety Limits

A tension exists between safety limits and performance. Safety limits are imposed to prevent inducing loss of control, but the more stringent the limits, the less control authority is available.

Steering control 1 the highway is a highly complex, non-linear problem that can change dramatically with weather, road condition, surface material, vehicle tire wear, current applied braking force, vehicle load, vehicle center of gravity, and presence of vehicle articulation. Such limits must be programmable, but must also have an inviolable range determined by vehicle designers. Even so, conditions will arise which designer's could not account for, and the implications of loss of control because of inappropriate limits for the prevailing conditions on product liability could be significant

There is also coupling between steering limits and braking limits. When the vehicle is under lateral acceleration, limitations on applied braking force must also be asserted. Tire break-away force (the amount of longitudinal force required to transition from rolling contact to sliding contact) reduces as the side load on the tire increases. Therefore, braking force limits must be reduced when experiencing lateral load on the

According to sources in the automotive industry, skid compensation is not being contemplated for future. However, it may become a requirement for Systems implementing automatic obstacle avoidance because of the possibility of abrupt maneuvering. if so, it will require careful relaxation *of steering limits imposed for safety reasons.*

A requirement exists to ensure that the steering angle never exceeds lateral acceleration limits. The question of how much steering authority is available to the system under what conditions is the primary concern here. Automated steering deflection limits should be based on vehicle speed and tire traction limitations to assure that the system never causes a skid condition.

However, even the most robust design may experience a skid if abrupt maneuvering occurs under adverse traction conditional. The advent of automated steering gives rise to the possibility of sensing and automatically correcting for skid conditions. However, skids are a highly non-linear condition affected by factors which may be difficult or even impossible to detect such as changes in the roadway/tire coefficient of friction. If this capability is developed, it will require a significant relaxation of the steering angle limitations mentioned above because under skid conditions larger excursions will be required to take corrective action.

2.4.4. General Control Issues

2.4.4.1. Operator Intervention While In AHS Lanes And Modes

Under unusual or emergency conditions, the tendency will be for the operator to attempt to wrest control from the System. Because of the high density of traffic and short reaction times in some operating modes, the consequences of inappropriate action might be not only to endanger the driver and occupants of a given vehicle, but to endanger nearby vehicles as well.

Once under automatic control, the operator is expected to sit back and "enjoy the ride." However, should an unusual situation occur, the operator's attention will be brought back to the highway situation in an abrupt manner. Assuming the vehicle is traveling in dense traffic at highway speeds, short reaction times would be required to perform any required corrective action. In such circumstances, the operator might find his attention awakened in one of three circumstances:

- Something's wrong, and he does not take the right action.
- Something's wrong, and he fails to take control when he should.
- Everything is under control and he attempts to usurp control when he shouldn't

Each of these situations is potentially very dangerous, not only to the individual, but potentially to those around him as well. Assuring under sudden circumstances that the correct action (or inaction) always occurs will be a significant and important human factors design issue.

2.4.4.2. Redundancy Cost/Performance Tradeoffs

Automatic control under high performance, safety-critical conditions requires fault tolerance to a level not expected in manual Systems. A large body of knowledge in redundancy management exists, but solutions are frequently expensive, requiring traditional equipment for sensing, *processing, and actuation.*

Fault tolerance of the system will likely be at the heart of many control-related safety concerns in the AHS system. The level of redundancy required to assure the proper level of safety in each element of the system. Fail-safe designs, those preventing a dangerous situation from developing after a failure, will be mandatory.

However, safety is only the first level of concern. The second level of concern is what happens to the continued operation of the system when one of the vehicles fails. A major goal of the AHS is to provide high throughput in high density situations. Failure modes with the potential to obstruct a highway segment may require fail-operational/fail-safe design. On the other hand, the cost of redundant designs are likely to cost more than may be acceptable to the end users.

3. AHS PRIMITIVE LEVEL MANEUVERS (LEVEL 1)

3.1. Speed (longitudinal) Control

3.1.1. Maneuver Description

3.1.1.1. Function:

- generate throttle and brake commands in response to speed commands from higher level maneuvers.

3.1.1.2. Inputs:

- speed command
- vehicle speed
- wheel speed
- surface condition
- turn rate
- nominal / emergency condition

3.1.1.3. Outputs:

- throttle command
- brakecommand

3.1.2. Operational Scenario Assumptions

Throttle and brake commands will be generated based upon speed commands and rate of change of speed commands. Speed commands that are produced by higher level maneuvers will reflect expected changes in operating conditions such as anticipated grade changes and lane curvature.

3.1.3. Absolute Requirements

3.1.3.1. Traction Control

Speed commands shall be moderated to maintain traction control under all surface conditions.

At no point shall the controller command acceleration or deceleration levels which cause the vehicle to exceed its traction capability.

3.1.3.2. Stability Control

Speed commands shall be moderated to insure vehicle stability at all times.

3.1.3.3. Control Channel Priorities

The vehicle shall implement a heading preemptive control algorithm. "Heading preemptive" means that steering channel is the priority channel when conflict requirements arise. The vehicle shall monitor, in real-time, the vehicle lateral stability profile. Velocity commands shall be evaluated to assure the vehicle remains laterally stable. If necessary, the speed commands shall be modified to maintain stability.

3.1.3.4. Fail Safe Operation

Speed commands shall be generated via a fail safe sensing, processing and control system. "Fail safe," in this context, means that failures will absolutely not be the cause of accelerations leading to collision with other vehicles.

3.1.3.5. Operator Override

The operator shall, at his discretion, be capable of immediate override of the brake control without action beyond stepping on the brake pedal The pedal must be fully back-drivable and require not more than 10* additional force above that required for non-actuated vehicles of similar' design to achieve comparable deceleration.

Operator override on the throttle for purposes of commanded acceleration is not required.

3.1.4. Conditional Requirements

3.1.4.1. Operator Comfort

Operator comfort as defined by IOC-DIS-2631 shall be maintained while operating under nominal conditions.

Operator comfort is not considered a constraint while operating under emergency conditions.

3.1.4.2. Vehicle Efficiency

In the absence of emergency conditions, optimum vehicle efficiency will be maintained for the given operating conditions; whereever possible, designers should seek to minimize throttle excursions.

3.1.4.2.1. Emissions

The vehicle throttle commands shall be optimized to minimize RMS throttle travel over a TBD time interval. Throttle commands shall also be rate limited to optimize vehicle power requirements. These limits are subject to the characteristics of each vehicle type and shall be independently determined for each vehicle.

3.1.4.2~ Fuel Economy

The vehicle shall never be commanded to exceed TBD (nominally 75) mph steady-state in order to optimize vehicle fuel mileage. Brief commands, in order to regulate vehicle headway, up to *85* mph may be permitted under suitable ambient conditions.

3.2. Directional (Lateral) Control

3.2.1. Maneuver Description

3.2.1.1. Function:

~ generate steering commands in response to direction commands from higher level maneuvers

3.2.1.2. Subsumed Maneuvers:

* none

3.2.1.3. Inputs:

- direction command
- surface condition
- vehicle velocity
- vehicle acceleration turn rate
- nominal *I* emergency condition

3.2.1A. Outputs:

steering command

3.2.2. Operational Scenario Assumptions

Directional commands that are generated by higher level maneuvers will reflect projected changes in the operating environment. The directional control maneuver will provide additional checks to insure coordination with speed control to maintain vehicle stability. Steering limits as a function of speed are to be set to limit lateral accelerations to within safe levels.

3.2.3. Absolute Requirements

3.2.3.1. Traction Control

Steering commands shall be moderated to maintain traction control under all surface conditions.

3.2.3.2. Stability Control

Steering commands shall be monitored to insure vehicle lateral stability. Steering commands shall take precedence over speed commands.

Steering commands shall be limited in position and rate as a function of actual vehicle speed to maintain lateral stability at all times.

3.2.3.3. Redundancy

Steering commands shall be generated via a fail operational/fail safe sensing, processing and control system.

3.2.4. Conditional Requirements

3.2.4.1. Operator Comfort

Operator comfort as defined by ISO-DIS-2631 is maintained while operating under nominal conditions.

Steering commands shall not induce lateral accelerations higher than 0.98 $meters/sec^2$ (0.1 g) under normal operating conditions.

Steering commands shall not induce lateral jerk higher than 0.005 meters/sec^3 under normal operating conditions.

Operator comfort is not considered a constraint while operating under emergency conditions.

3.3.1. Mixing Manual With Automated Control Modes

Does certification for AHS operation require the presence of automatic transmissions?

If speed is falling off on a steep grade, such as 1-70 west of Denver, and the operator elects to downshift, how does that impact other vehicles in close proximity behind?
Disengaging the clutch of a standard transmission on an incline will cause an abrupt speed transient that will shortly be recovered, but that can be a very non-linear control problem for following vehicles. Since the magnitude and duration is completely
unpredictable due to wide variations in human performance, we recommend that manual shifting be precluded while under automated AHS operation.

3.3.2. Assumption Of Steering Control By The Operator

How and under what conditions does the System permit user takeover of steering control?

If the user perceives a need to take over control on an emergency basis but the system correctly senses nominal operating conditions, may system prohibit usurpation by the user to prevent dangerous or inappropriate involvement? Can an inattentive operator be trusted to take the appropriate action under emergency conditions? We believe that human factor design considerations and/or liability considerations will require the operator to be fully responsible for any control activity, implying a requirement for instantaneous usurpation by the operator. See § 2.4.4.1 for further discussion.

3.3.3. Design For Energy Efficiency And Emissions Control

By what strategies will the AHS most effectively manage vehicle emissions?

How is this management affected by issues such as climate or terrain? On uneven terrain, is it more important to reduce speed on uphill sections to optimize emissions and fuel economy, or is it more important maintain a homogeneous vehicle/highway speed? Performance differences among vehicles, and performance changes on a given vehicle (while using of air conditioning, for instance) can make this a complex problem

Current cruise control mechanisms merely react to speed changes. On an incline, this may cause downshifting in cases where proactive energy management would have resulted in no shifting action, lower engine RPM, and lower emissions profiles. Must AHS cars be designed to maintain homogeneous highway speed regardless of energy cost, or should terrain variations be handled with controlled speed changes? Simulation may be in order to quantitatively answer these issues. To date, only limited work has been done involving changing performance due to incline/decline situations and variable performance disturbances.

3.3.4. Steering Control Failure Modes

What is the proper fail-safe protocol for steering actuation?

Should the system be designed to maintain the last valid command upon failure? Should the steering position be allowed to relax to neutral as dictated by the force on the wheel due to caster angle?

3.3.5 Latency of Operator Notification of Failure

No requirements exist for maximum acceptable latency between occurrence of a failure and operator notification.

Because of the higher response bandwidths and reaction times, steering failures are critical to safety, much moreso than throttle failure, for instance. From a human factor standpoint, what *is* the maximum allowable elapsed time between failure mode and operator notification? Considerable human factors testing will have to be performed because of the criticality of steering failures in particular.

3.3.6 Control Authority Limits - Adverse Conditions

Specification of lateral acceleration limits for other than dry pavement conditions complicates the issue because of the wide variety of environmental conditions. Sensing traction-reducing conditions in all but very coarse ways is beyond current state of the art.

The degree of lateral acceleration authority that can be allocated to an automatic controller is not only a function of human factors primarily ride comfort) considerations. Attainable lateral acceleration performance can also be affected by vehicle design, state of tire wear, vehicle load, road condition, surface conditions (icy, wet, gravel), and other factors beyond the control of designers. We conclude that programmable lateral acceleration authority limits will be required.

To determine the appropriate lateral acceleration limits needed for safety, two significant questions remain:

- How does one determine the values for these limits under adverse conditions? Significant testing 10 develop an empirical data set seems lobe needed.

- How does one sense reliably the environmental conditions that reduce traction? Accurately sensing water, ice, sand, gravel, and other traction-reducing conditions remain a technology gap at present

3.3.7. Control Authority Limits - Steering Angle Precision

Derived steering angle limits may generate a requirement for relatively high precision on steering position feedback signals.

Safety and reliability considerations drive designers to impose such limits as close to the physical variables as possible. Using this logic, it would be preferable to impose safety steering limits based on wheel angle rather than derived quantities such as lateral acceleration or heading rate. However, doing so may require fairly high precision sensing on steering angle. The following derivation illustrates the relationship between lateral acceleration and steering angle limits:

For a flat roadway (no superelevation), lateral acceleration is a function of speed and turn radius:

$$a_y = V^2/r$$

For a two-axle vehicle, steering angle ~ is related to the turn radius (r) and wheelbase (WB) by the approximate relationship:

$$\tan \xi = WB/r$$

Combining these equations and applying the desired acceleration limits, we can determine the limits on steering as a function of maximum lateral acceleration and velocity through the following relationship:

$$\xi_{\lim} = \tan^{-1}\left(\frac{a_{y_{lim}} \bullet WB}{V^2}\right)$$

The steering angles resulting are the actual tire angle with respect to the body centerline, not the angular deflection of the steering column.

Using this relationship, we have derived some sample data for the case of a vehicle with a 12-foot wheelbase. These limits should be applied as safety limits on innermost control loops. Figure 2 shows limits for the cases of lateral acceleration limits of 0.05g, 0.1 g, and 0.2g at a range of speeds from 30 to 70 mph.

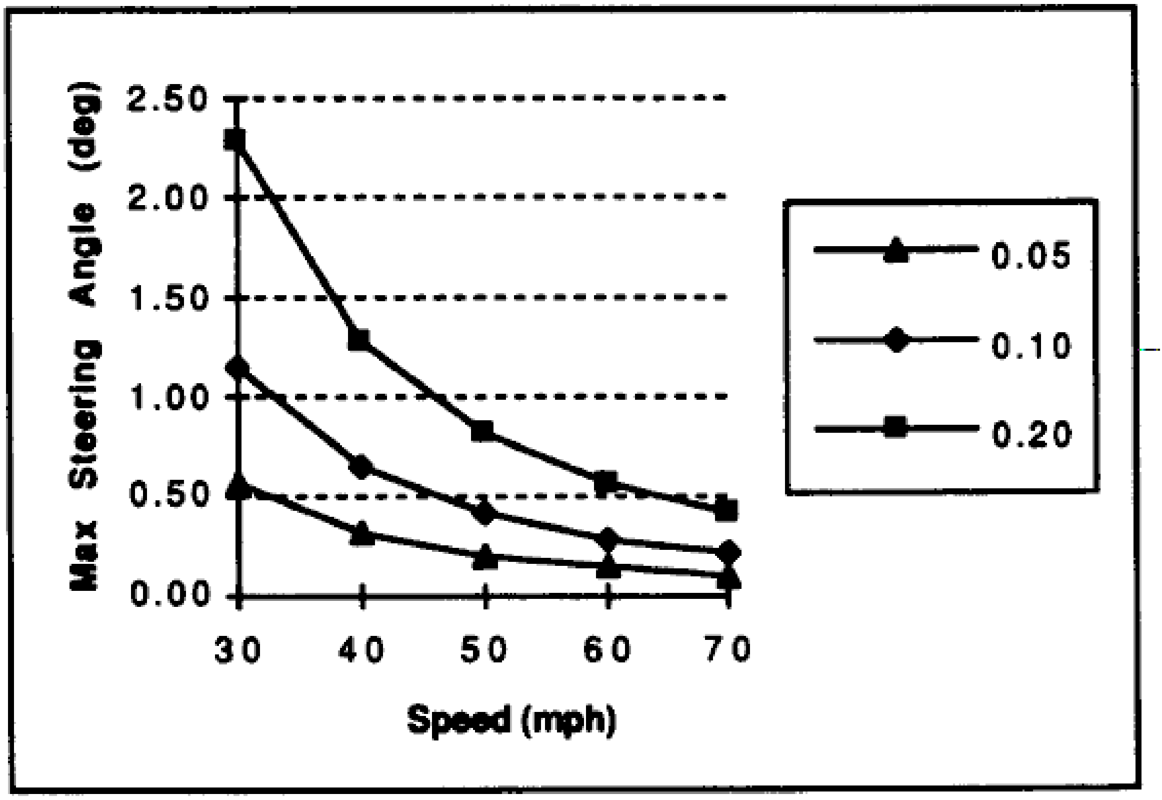


Figure 2. Sample Steering Limits for Wheelbase=12 ft.

The acceleration limits used in this figure are conservative to assure no loss of control under a wide variety of traction conditions and assure operator comfort. However, the maximum steering angles displayed show how restrictive this requirement can be. Using the 0.1 g limits at highway speeds, the steering angle dynamic range under automatic control is ±0.21°, or a total of 0.42°. From unmanned ground vehicle experience, smooth automatic steering using steering angle as a feedback requires at least 50 quantization levels or "hunting" behaviors (limit cycling) tend to develop. This means that the minimum steering angle measurement precision is 0.42/50=0.0084. In addition, the operating range of steering for most passenger cars is between 20° and 30°. The sensor must be able to unambiguously determine current position anywhere in the mechanical range of the steering system. A dynamic range ±30° with a minimum precision of 0.0084° means that a minimum precision of 7143 quantization levels is required for steering feedback. The result is that encoders with at least *13 bits* of precision are needed to assure unamibigous steering angle sensing; inexpensive components, such as 8-bit encoders will not be suitable for this application.

The precision requirement of 0.0084° may be difficult to meet because of unknowable levels of hysteresis in the mechanical linkages. Poor maintenance or events that *cause* misalignment (such *as* hitting a pothole) can dramatically affect this property. Unless individual sensing of wheel angle at the pivot point is used, it may be impossible to determine steering angle with that degree of precision. We conclude that control mechanizations based on wheel angle sensing are going to be problematic.

This is a design issue, not a system configuration issue of discriminating value in selecting AHS configurations.

4. AHS VEHICLE LEVEL MANEUVERS (LEVEL 2)

4.1. Nominal Lane Tracking

4.1.1. Maneuver Description

4.1.1.1 Function:

- Generate direction commands to maintain vehicle to within ± TBD (nominally 10) cm of lane center. A TBD (3 σ criterion shall apply.

4.1.1.2. Subsumed Maneuvers:

- None

4.1.1.3. Inputs:

- Vehicle position relative to lane
- Lateral vehicle velocity
- Lateral lane clearance
- Lane curvature

4.1.1.4. Outputs:

~ Directional command

4.1.2. Operational Scenario Assumptions

Projected lane curvature changes are used to provide lead and optimize lane tracking performance. Normal lane widths of 12 feet are presumed.

4.1.3. Absolute Requirements

4.1.3.1. Lateral Acceleration

Incremental heading command *changes* shall not induce *sufficient* lateral acceleration to violate the vehicle's traction *capability*. Under nominal operating conditions, lateral accelerations shall not *exceed* ISO-DIS-2631 for ride quality standards. Under emergency conditions, lateral accelerations shall not exceed 0.2 g.

4.1.3.2. Heading Rate Command Limit

The incremental heading command change shall not *exceed a* heading rate of 10 degrees *per* second under nominal maneuvers.

4.1.3.3. Stability-- Steering Angle Deflection

Any limit cycles present in the heading control shall be provably stable and shall have a magnitude less than 0.05^0 of steering angle deflection at highway speeds to prevent annoying ride quality behaviors.

4.1.3.4. Reliability

The *lane* tracking system shall fail safe. is not a requirement. Fail-safe *is* defined *as* guaranteeing no lane boundary violations under any circumstances for at least two seconds after the failure event to permit operator intervention alter sounding a warning.

4.1.3.5. Operator Comfort-- Lateral Acceleration

Lateral acceleration induced by nominal lane tracking steering commands shall not exceed 0.05 g to prevent operator and passenger discomfort from sustained or transient sideforce loading, particularly under conditions where the operator/passengers might not be anticipating lateral maneuvers.

4.1.3.6. Operator Comfort -- Lateral Jerk

Lateral acceleration rate induced by nominal lane tracking steering commands shall not exceed 0.2 g/sec to prevent appearance of loss of control and provide smooth ride quality.

4.1.3.7. Operator Comfort -- closed-loop Stability

The heading controller design shall preclude limit cycle frequencies in excess of 0.1 Hz.

4.1.3.8. System Efficiency

In order to optimize vehicle efficiency, the controller shall provide road curvature commands which track the road curvature to within a curvature radius of 0.1%.

4.1.4. Conditional Requirements

4.1.4.1. Barrier Avoidance

Where applicable, physical barriers shall be placed no closer than TBD (nominally *1.5)* meters from the edge of the lane to allow vehicles the fully lane width for operating under normal circumstances.

4.1.4.2. Multiple Lane Capability

For system configurations requiring the ability to freely change lanes, forms of lateral and longitudinal control must be capable of operating on two or more adjacent lanes without interruption.

4.2. Nominal Speed Maintenance

4.2.1. Maneuver Description

4.2.1.1. Function:

- generate speed commands to maintain commanded vehicle speed to within ± .5m/sec

4.2.1.2. Subsumed Maneuvers:

- none

4.2.1.3. Inputs:

- target speed
- grade change projection
- lane curvature projection

4.2.1.4. Outputs:

- speed command

4.2.2. Operational Scenario Assumptions

Speed commands will be moderated based upon projected lane changes such as grade and curvature. Commands will be coordinated with steering to insure vehicle stability. Steering commands do not limit speed commands, though planned heading changes, if known, may affect speed commands.

4.2.3. Absolute Requirements

4.2.3.1. Traction Control

The requirements of Section 3.1.3.1 shall apply.

4.2.3.2. Stability Control

The requirements of Section 3.1.3.2 shall apply. In case of conflict between vehicle speed and vehicle heading requirements, vehicle heading requirements shall take precedence.

4.2.4. Conditional Requirements

4.2.4.1. Operator Comfort

The speed maintenance controller shall provide a gradual velocity profile such that the rate of change of commanded velocity does not exceed 0.27 rn/sec^2 (-1 kph/sec).

The controller design shall preclude the insertion of limit cycles with amplitudes in excess of *0.25* m/sec.

4.2.4.2. Throttle Excursion Minimization

The speed maintenance controller shall be designed to minimize throttle motion.

4.2.4.3. Braking Minimization

The speed maintenance controller shall preclude brake utilization for nominal speed maintenance.

4.3. Emergency In-lane Stop

4.3.1. Maneuver Description

4.3.1.1. Function:

- safely stop vehicle at a maximum deceleration of 5.9 meters/sec^2 (.6 g's) or at the limit of the vehicle's braking capacity, whichever is greater, while maintaining vehicle within ± 10 cm (3 σ) of lane center-line.

4.3.1.2. Subsumed Maneuvers:

- speed maintenance

4.3.1.3. Inputs:

- emergency stop command
- range to obstacle
- required stopping distance

4.3.1.4. Outputs:

- speed command
- emergency status

4.3.2. Assumptions

4.3.2.1. Antilock Braking System

To achieve the desired maximum deceleration levels it is assumed that the RSC is equipped with an AHS system. The maximum deceleration level will not always be required for all emergency stops. Deceleration levels will be driven by range to obstacles and/or external emergency halt commands. Surface conditions will also moderate deceleration commands

4.3.3. Absolute Requirements

4.3.3.1. Braking Authority Limits

The controller shall have full authority up to the traction limits of the car.

4.3.3.2. Non-Moving Obstacle Detection

Any article altering the roadway elevation in excess of TBD (nominally 2) inches shall be recognized as a potential obstacle at a distance necessary to successfully invoke an emergency in-lane stop. Any obstacle in excess of 4 inches shall induce this maneuver.

4.3.3.3. Observation to Action Latency

The time from positive obstacle lock to command issuance shall not exceed 10 msec.

4.3.3.4. Limitation of Deceleration Requirement

For cases where platooning is allowed, system configurations shall support sense/act latency periods and following distances such that vehicles are not required to decelerate at levels greater than 90% of maximum deceleration capacity and still avoid collisions.

4.3.3.5. Reliability-- False Alarm Rate

Since this maneuver is likely to be very undesirable and disturbing to the operator, this maneuver shall have a false alarm probability of no more than 0.01 percent for obstacles that represent a serious threat of damage.

4.3.3.6. Reliability -- Missed Detection Rate

This maneuver shall have a missed detection probability of no more than 0.0001 percent for obstacles that represent a serious threat of damage.

4.3.4. Conditional Requirements

4.3.4.1. Moving Obstacle Detection

The vehicle shall react to a moving obstacle which is impinging upon the present lane as if it were an actual obstacle at the same range as the moving obstacle.

Any article altering the roadway elevation in excess of 2 inches shall be recognized as an obstacle. Any obstacle in excess of 4 inches shall induce this maneuver.

The vehicle shall detect and predict motion of obstacles in adjacent lanes.

4.3.4.2. Non-Moving Obstacle Detection

In the presence of a higher-level capability to safely execute lane change maneuvers, requirement

4.3.3.2 shall be relaxed to distances necessary to permit a successful lane change.

4.4. Vehicle-Level Issues

4.4.1. Control Coupling Performance Standards Must Be Developed

Safety standards need to be developed covering coordination and coupling of controls. How does the AHS designer formalize the coupled stability and control relationship for steering, heading, and speed control (where speed control includes control of throttle and brake)? This question goes beyond simple stability and control models and methods to include logical behaviors. A vehicle, needing to make a turn should first slow down and then turn. Application of brakes in the middle of a turn can actually aggravate a bad situation. The trick is to apply available braking based upon the available traction for a given steering angle. What happens when the available traction for steering is not sufficient to produce the required heading change in the vehicle? What standards could be written such that, if properly applied by developers, would adequately defend developers against claims of negligence or improper and unsafe design?

4.4.2. Communication of Deceleration Performance Within Platoons

Deceleration performance limits of each vehicle in a platoon must be communicated to all vehicles forward of that vehicle when closely-spaced following is engaged.

Vehicles in front a given vehicle could conceivably have more stopping capability than ones to their rear. In that case, maximum performance stopping will cause rear-end collisions depending on sensing or communications latency, braking deceleration, and actuation latencies. To prevent this, it is necessarily for each vehicle to limit its stopping performance to that of the vehicles following, or assume the risk of causing a rear-end collision.

4.4.3. Deceleration Limitations and Assignment of Liability

Relative deceleration performance capability and imputed limits create complex liability assignment issues in closely-spaced platooning.

Seemingly simple on the surface, the previous issue is made more complex by liability concerns. Under present practice, each driver is obligated to maintain a space sufficient to assure he does not strike the vehicle in front under any condition. if the normal operating mode for the AHS is to employ minimally-spaced (say, two meter') platoons, then the driver following is *required to maintain smaller spacing* than his vehicle might possibly be unknowingly capable of dealing with. This places the burden on the vehicle in front for limiting deceleration to safe levels or risk *causing* the rear-end collision. If it does not, does liability rest with the leader? Conversely, the requirement to use reduced decelerations may cause the lead vehicle to avoidably strike a vehicle or object in front of it. Does this situation transfer liability to the following vehicles?

Under these circumstances, where does the liability lie? Trailing vehicles, not leading vehicles, have the ability to control headway but are required by the AHS to minimize headway. The trailing vehicle could alleviate the situation but is constrained from doing so to improve highway throughput. On the other hand, lead vehicles are in control of decelerations under emergency conditions, but must limit their use of braking authority (possibly) below the level required to avoid impact

4.4.4 Sensing/Communication/Actuation Latency and Headway

Headway requirements are dominated by latency under emergency stop maneuvers.
Latencies will hove to be very low to avoid impact doing maximum deceleration maneuvers.

A number of concepts have been advanced postulating operating at very small headways. While controllers can be designed for safe operation under nominal operating conditions assuming reasonable disturbances, the minimum headway is limited by the stopping performance under the worst case conditions. Under ideal conditions, the headway required to assure no-impact stopping is dominated by the initial velocity and the latency between successive stop command onsets.

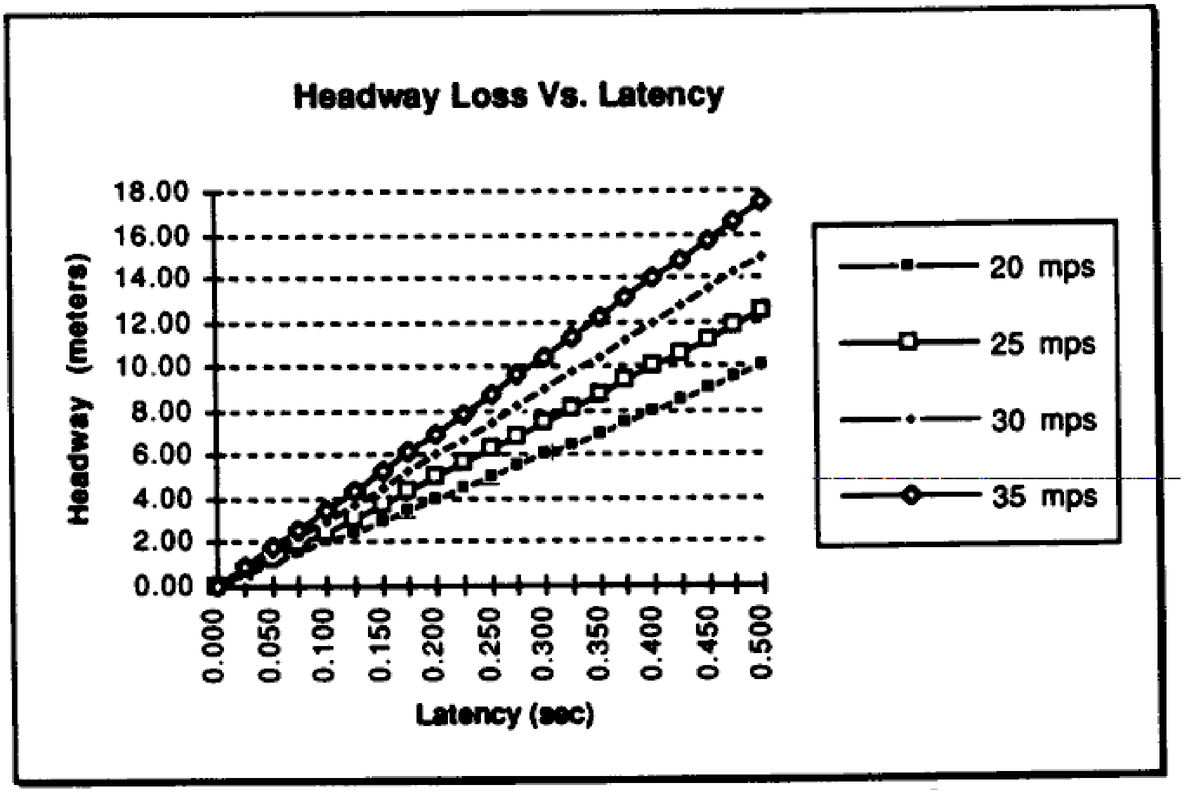


Figure 3. Headway Loss Due to Sensing/Communication Latency

Figure 3 shows the case for vehicles initially traveling at 20,25,30, and 35 meterslsec *(45,56,67,78* mph). The graph depicts the amount of headway lost by the time both vehicles come to rest. This can be taken to be an absolute minimum headway for the latency given and does not include any safety margin. The following assumptions are included in this simplified analysis:

- all vehicles are traveling at the same initial speed,
- all are capable of precisely the same deceleration and come to rest in the same stopping time maximum deceleration is instantaneously achieved

- each vehicle exhibits the same latency from stop command executed by the vehicle in front until stop command is executed by that vehicle

Latency, in this case, is limited to the time differential between command onset of one vehicle and that of the next. This includes either sensing or communication delay, and processing delay to initiate commands, and delay in taking up actuation slack (hysteresis). For this idealized case, the result is true for the n-vehicle platoon case. However, non-instantaneous onset of deceleration, differences in actuation performance, sensing delay (including data acquisition), sensor data processing (including averaging, filtering, and time differencing for rate), sensor sample time offset, differences in coefficient of friction, differences in braking force available, and differences in processing time have been neglected. All of these factors plus safety margins will increase the amount of headway required to avoid impact on sudden emergency stop conditions.

This analysis suggests that very low-latency sensing or communication and very low latency control processing will be required to achieve small headways safely. The authors would caution that the assumption of fast (10ms or better) communications does not obviate this concern because it fails to take into consideration all the factors that influence system latency, much less performance differentials.

One way to reduce the headway requirement is to permit vehicles further back to operate at successively higher decelerations. This will have the effect of placing severe deceleration limits on the lead vehicle, or the length of the platoon, or both. Suppose a smaller headway required each vehicle to stop at 0.02g more deceleration than the one in front of it. Suppose further that the last vehicle in line has a maximum braking performance of *0.55g* and there are eight vehicle in line. Under this operating assumption, the first vehicle can decelerate no faster than 0.41g or the last vehicle will not be able to apply enough braking force to meet the requirement. This does not seem to be a wise approach.

Another way to reduce headway safely is to require communication among vehicles to eliminate the puretime delay associated with communication, but this approach does not eliminate the other potentially significant differences contributing to latency mentioned above. For example, electromechanically actuated vehicles may use push/pull cables that exhibit varying degrees of stretch, or a given vehicle may have more take-up in applying the brakes due to worn pads. Either of these conditions would potentially requiremore actuator motion and hence more time to bring the break pads in contact with the rotors. Experience with these types of actuation schemes show that end-to-end latencies of 0.4-*0.5* seconds are not unreasonable to expect.

Designing system for lower latencies can be done, but at higher system cost. Our conclusion is that aggressive headway requirements, while feasible under nominal operating conditions, may be infeasible due to the requirements for safe design under extrodinary (emergency) conditions. To mitigate this, it may be necessary to specify required safety in terms of maximum relative velocity at collision instead of no collisions at all.

4.4.5 Avoiding Moving Obstacles

Ability to detect and avoid moving obstacles is beyond the current state of the art and should not be a requirement.

The reaction to a moving obstacle should be to execute a trajectory to avoid the obstacle given its position and velocity. The problem with this approach is animals, people, and other moving obstacles, don't always continue on a constant path. if you detect a moving obstacle in your path, you may err by stopping for an obstacle that is gone by the time you get there, or you may err by assuming an erroneous obstacle trajectory and collide anyway. Another problem is the detection of objects which may be moving into your path, and knowing which will become th'ats and which will not. For instance, if a vehicle appears to be moving into your' lane some distance ahead, is it actually doing so, or is it merely following a bend in the road you cannot yet perceive?

Sensing moving obstacles along with other obstacles and reacting to their presence should be part of the system's responses to its environment, but auempdng to predict movement and formulate the right response is a very complex problem. It would seem imprudent to design for lane changes to avoid the obstacle, as the trajectories of moving obstacles are not generally predictable.

4.4.6. Obstacle Detection and Sensor Requirements

Sensor resolution and update rates for vision-based obstacle detection remain the most demanding technology deficits today. Solulions are achievable, but the cost renmuns prohibitive.

The issue of obstacle detection and avoidance has been pursued by researchers in the mobile robotics domain for a number' of years. One of the more technologically challenging programs in this ar'ea is the ARPA-sponsored Unmanned Ground Vehicle Demo II program, which has experimented with both active and passive sensing of terrain and ground obstacles. A report titled "Stopping Distance Analysis of Ladar and Stereo" prepar'ed for the Demo II program analyzes the ability of various ladar and stereo correlation configurations to detect objects of various sizes at sufficient ranges to safely stop before impact In particular, the report details the methodology for estimating sensor resolution's impact on detection ranges and subsequent stopping distance. Figures 4 and 5 below highlight the results of that study. Figure 4 presents the detection distance for the various state-of-the-art sensing configurations as a flinction of object size. For the purposes of 'his study, object size was deteimined by vertical extent only, not cross-sectional area or volume, since height represented the danger dimension for vehicle damage. The steeper the curve, the roore advantageous for safe operation. Figure 5 presents maximum safe speed that allows stopping short of detected objects of various sizes, given the results of figure 4 and other constraints on the vehicle (in this case a HMM'WV) and sensor configuration under study.

The generalized conclusion one may draw ftDm these results is that vision-based techniques do not at present have the ability to detect any but the largest objects at highway speeds. For instance, a muffler lying on the highway presents a vertical aspect of approxumaely four incheL Detection ranges for objects of this size were so short that only a slow crawl permitted the vehicle to sense and react in time, and even then only with the most advanced sensor (the Odetics ladar in this study was under development at the time and is currently still unavailable). These results are not applicable to radar-based approaches.

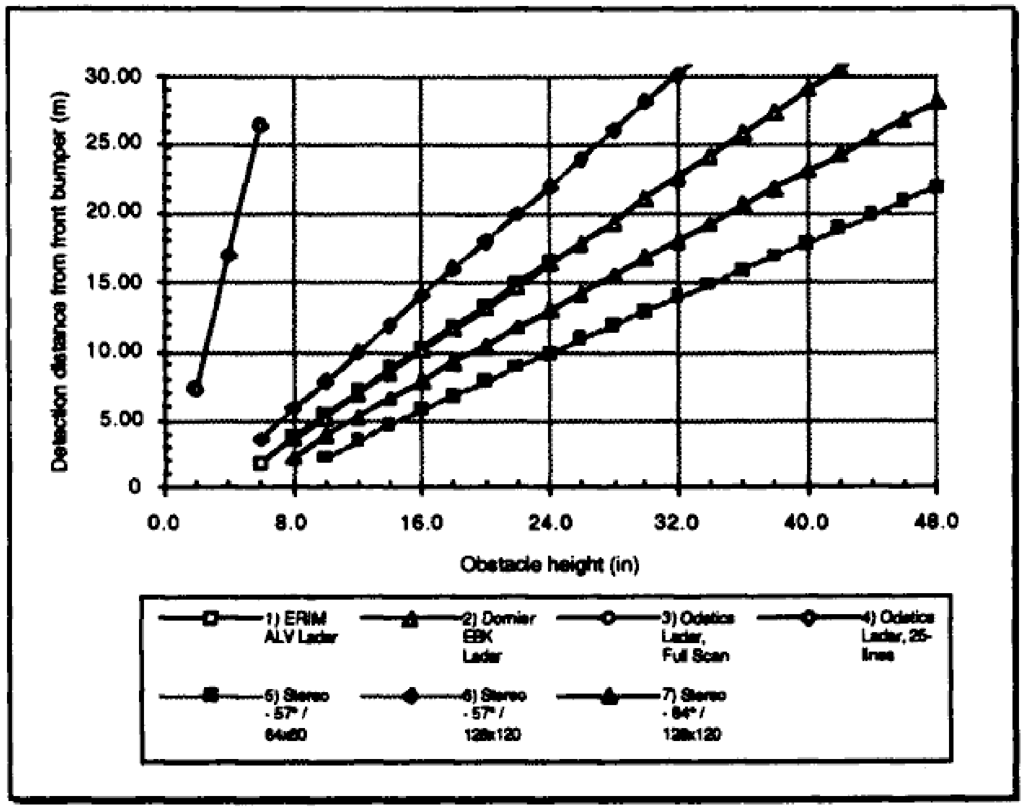


Figure 4. Detection Distance vs. Obstacle Size

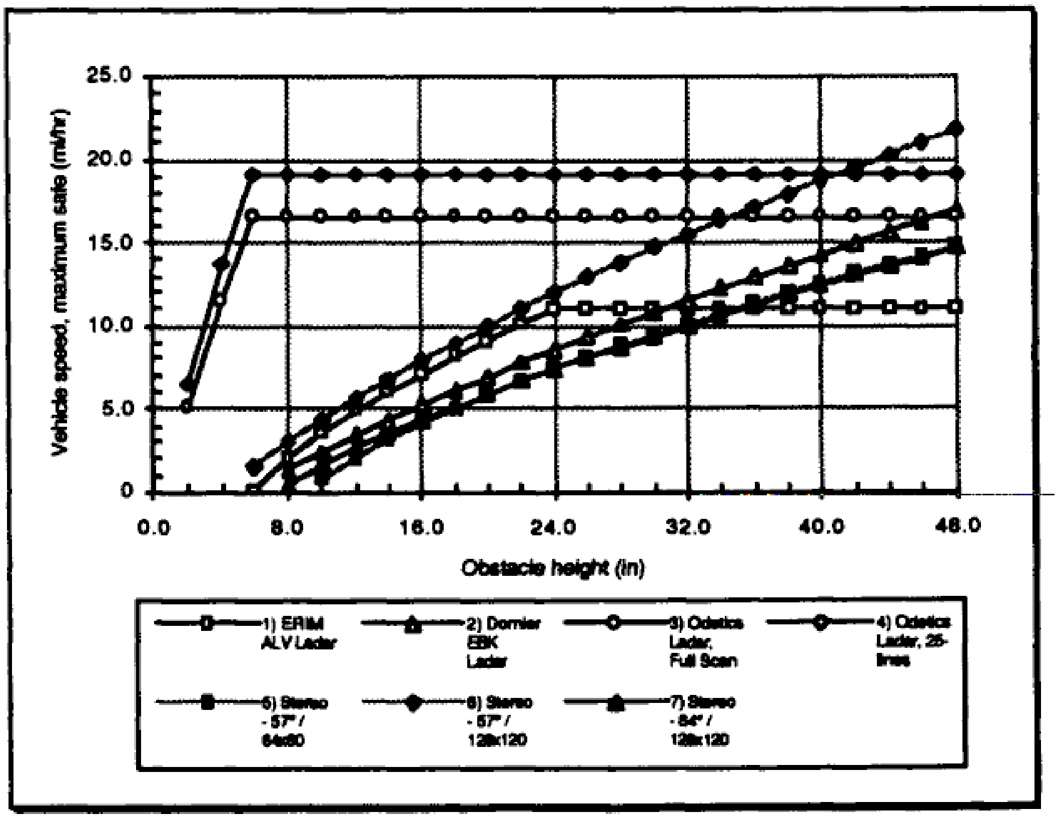


Figure 5. Maximum~Safe Speed for In~Lane Stop vs. Obstacle Size

5. AHS INTERACTION LEVEL MANEUVERS (LEVEL 3)

5.1. Nominal Spacing Regulation

5.1.1. Maneuver Description

5.1.1.1. Function:

- Generate speed commands to maintain the desired separation distance with the preceding vehicle.

5.1.1.2. Subsumed Maneuvers:

Speed Maintenance

5.1.1.3. Inputs:

Vehicle separation distance
Vehicle separation rate of change
Vehicle speed
Grade change projection
laane curvature projection

5.1.1.4. Outputs:

- Speed commands

5.1.2. Operational Scenario Assumptions

Spacing of vehicles will be dependent upon surface conditions, mode of operation (platoon, independent, etc.), speed of vehicles and types of vehicles.

5.1.3. Absolute Requirements

5.1.3.1. Headway Distance

The headway controller shall preclude vehicle headway from dropping below one half of the desired headway. If this condition is violated an emergency situation shall be declared.

The headway controller shall preclude headway control from being activated in the event that either the lead vehicle headway is in excess of 100 meters or if the lead vehicle velocity is more than 3 mps greater that the present vehicle velocity.

The headway controller shall generate a time-out and abort to (TBD) in the event that headway lock has not occurred within 1 minute of maneuver initiation.

5.1.3.2. Headway Rate

The headway controller shall provide vehicle speed bias commands which does not exceed a 8 mph closing rate.

5.1.3.3. Collision Avoidance - Other Vehicles

The headway controller shall take whatever action necessary to avoid collision with other vehicles on the highway. Primary responsibility will be for avoiding collision with vehicles to the front and immediately to the side. Whereever possible, the headway controller shall avoid executing maneuvers that compromise the state of vehicles to the rear.

5.1.3.4. Headway Response Characteristics

The vehicle headway controller shall assure the headway error never exceeds ~50% of the desired interval, under all conditions.

The vehicle headway controller shall provide an over damped response, in the absence of external disturbance signals.

5.1A. Conditional Requirements

5.1.4.1. Operator Comfort

The incremental velocity command change shall not exceed an acceleration of 0.49 meters/sec^2 (0.05 g) under normal operating conditions.

The headway controller design shall preclude limit cycles with magnitudes in excess of 1 percent of desired headway, and shall not induce velocity command limit cycles in excess of 0.5 mps

The heading controller design shall preclude limit cycle frequencies in excess of 0.1 Hz. The headway controller shall provide vehicle headway regulation to within 5 percent of the desired headway reference distance. This requirement applies in the absence of external disturbances.

The headway controller shall provide vehicle headway regulation to within 15 percent of the desired headway reference distance, under all operating conditions.

5.2. Nominal Lane Change

5.2.1. Maneuver Description

5.2.1.1. Function:

transition vehicle to adjacent lane within 5 seconds

Editor's Note: There are some arguments against the specification of time in this case. Perhaps the lane change should be a function of speed and road curvature.

5.2.1.2. Subsumed Maneuvers:

~ lane track

5.2.1.3. Inputs:

- vehicle position relative to initial lane
- vehicle position relative to final lane
- lane path
- lateral vehicle velocity

5.2.1.4. Outputs:

direction command

5.2.2. Operational Scenario Assumptions

For this maneuver it is assumed that both the initial and destination lanes are automated lanes. This maneuver will not initiate the lane change if adequate clearance in the destination lane is not available.

5.2.3. Absolute Requirements

5.2.3.1. Collision-Free Lane Change Maneuvers

The automatic lane change function shall assure collision-free lane changes in the absence of failures.

5.2.3.2. Minimum Safe Clearance Distances

Lane change shall be inhibited if the adjacent corridor contains a vehicle less than 10 meters in front of the vehicle or 15 meters behind the vehicle prior to performing a lane change.

5.2.3.3. Safe Rates of Closure Ahead

Lane change shall be inhibited if there are any vehicles within 100 meters to the front of the vehicle that are closing at a rate leading to impact in under 10 seconds.

5.2.3.4. Safe Rates of Closure Behind

Lane change shall be inhibited if there are any vehicles within 200 meters behind the vehicle that are closing at a rate leading to impact in under 10 seconds.

5.2.3.5. Lateral Acceleration

The lane change trajectories shall not induce lateral acceleration in excess of 0.05g (0.49 meters/sec^2).

5.2.4. Conditional Requirements

5.2.4.1. Angular Rate Limitations

Subject to the outcome of human factors evaluations, the lane change trajectories shall not induce vehicle body-frame angular velocities greater than 2 degree per seconds.

5.2.4.2. Operator Awareness

Prior to and during execution of the maneuver, the vehicle shall alert the operator to the expected lane change. The operator shall be alerted via a combination of audio and visual cues.

5.3. Nominal Vehicle Following

5.3.1. Maneuver Description

5.3.1.1. Function:

Track lateral motion of the preceding vehicle to within ± 15 cm.

5.3.1.2. Subsumed Maneuvers:

- Lane track

5.3.1.3. Inputs:

- Vehicle position relative to preceding vehicle
- Vehicle position relative to lane barriers
- Lane path projection
- Lateral vehicle velocity Preceding vehicle steering commands
- Adjacent lane clearance
- Preceding vehicle departure status

5.3.1.4. Outputs:

- Direction command

5.3.2. Operational Scenario Assumptions

Direction commands will be generated to track the lateral motion of the preceding vehicle as long as the preceding vehicle has not communicated its intention to exit the AHS lane and as long as the tracked lateral motion of the preceding vehicle will not cause a collision with lane barriers, obstacles or vehicles in adjacent lanes.

5.3.3. Absolute Requirements

5.3.3.1. Headway Distance

The requirement(s) of Section *5.1.3.1* shall apply.

5.3.3.2. Headway Rate Excursions The requirement(s) of Section 5.1.3.2 shall apply.

5.3.3.3. Collision Avoidance

The requirement(s) of Section *5.1.3.3* shall apply.

5.3.3A. Lateral Trajectory Tracking

The vehicle shall track the lateral trajectory of the leading vehicle to within an average lateral tracking error of 5 cm, relative to the leading vehicle track. The peak excursions for vehicle tracking error shall not exceed 10 cm, relative to the leading vehicle track.

The vehicle shall track the lateral trajectory of the leading vehicle to within an average lateral tracking error, relative to the leading vehicle track, of:

[0.5*MAX_ALLOWABLE_ERROR/NUMBER_OF_VEHICLES] cm.

The peak excursions for vehicle tracking error, relative to the leading vehicle track, shall not exceed:

[MAX~ALLOWABLE_ERROR/NUMBER_OF_VEHICLES] cm.

5.3.4.1. Operator Comfort

The acceleration profiles, resulting from this maneuver, shall not exceed TBD g's below TBD Hz.

5A. Emergency Lane Change

5.4.1. Maneuver Description

5.4.1.1. Function:

- Generate direction and speed commands to transition vehicle to an adjacent lane within 2 seconds

5.4.1.2. Subsumed Maneuvers:

- Lane Track
- Speed Maintenance

5.4.1.3. Inputs:

- Vehicle position relative to initial lane

- Vehicle position relative to final lane
- Lane path
- Lateral vehicle velocity
- Distance to obstacle
- Adjacent lane clearance

5.4.1.4. Outputs:

- Direction commands
- Speed commands
- Emergency status

5.4.2. Operational Scenario Assumptions

Direction and speed commands will be generated to transition the vehicle from its current lane to an adjacent lane as quickly as possible while maintaining vehicle stability. Operator comfort constraints can be violated during this maneuver. The vehicle will not necessarily slow down or stop during this maneuver. Adjacent lane clearance is verified prior to starting this maneuver.

5.4.3. Absolute Requirements

5.4.3.1. Collision Free Execution

The system shall assure collision-free lane changes in the absence of malfunctions.

5.4.3.2. Minimum Lane Clearance to the Front

The lane change controller shall assure that a clear space of 2 meters in front of the vehicle prior to initiating a lane change.

5.4.3.3. Minimum Lane Clearance to the Rear

The lane change controller shall assure that an adjacent corridor of 5 meters behind the vehicle prior to initiating a lane change.

5.4.3.4. Minimum Time Separation to the Front

The lane change shall be inhibited if the velocity differential with respect to vehicles immediately in front and in the destination lane is such that collision would occur in less than two seconds.

5.4.3.5. Minimum Time Separation to the Rear

The lane change shall be inhibited if the velocity differential with respect to vehicles immediately in front and in the destination lane is such that collision would occur in less than three seconds.

5.4.4. Conditional Requirements

5.4.4.1. Operator Safety

All vehicle trajectory commands shall be limited such that minimal injury to vehicle occupants will result, assuming occupants properly use standard vehicle restraint and safety devices such as lap and shoulder belt systems.

5.4.4.2. Operator Warning

All applicable warning measures shall be utilized to advise the vehicle occupants of the existence of an emergency condition.

5.5. Emergency Vehicle Follow

5.5.1. Maneuver Description

5.5.1.1. Function:

* Track lateral motion of the preceding vehicle to within ± 15 cm.

5.5.1.2. Subsumed Maneuvers:

- Lanetrack

5.5.1.3. Inputs:

- Vehicle position relative to preceding vehicle
- Vehicle position relative to lane barriers
- Lane path projection
- Lateral vehicle velocity
- Preceding vehicle steering commands
- Adjacent lane clearance
- Preceding vehicle departure status

5.5.1.4. Outputs:

- Direction command
- Emergency Status

Unless the preceding vehicle has communicated that it is going to execute a nominal lane change or platoon departure, then it is assumed that the preceding vehicle is changing lanes for emergency reasons and should be followed out of the current lane. This maneuver is activated even if the nominal vehicle following maneuver is not currently active. This maneuver assumes that the lead vehicle has the best view of potential obstacles and that the forward view of trailing vehicles is severely constrained. Therefore the emergency actions of the lead vehicle should be followed reflexively.

5.5.3. Absolute Requirements

5.5.3.1. State Change Detection

The vehicle shall be capable of determining in a period of time no longer than 0.1 seconds that this maneuver is required, based upon the actions of the leading of the vehicle - or other TBD information.

5.5.3.2. Collision Avoidance

The maneuver shall assure that collisions with the leading vehicle do not result, to the extent possible within the limits of lower level emergency maneuvers.

For cases where collisions are unavoidable, the maneuver shall optimize the vehicle velocity reduction and the vehicle attitude to minimize severity of impact

5.5.4. Conditional Requirements

5.5.4.1. Operator Safety

The requirements of section 5.4.4.1 shall apply.

5.6. Emergency Out-of-Lane Stop

5.6.1. Maneuver Description

5.6.1.1. Function:

- Generate direction and speed commands to transition vehicle to an adjacent lane within 2 seconds and stop at a maximum deceleration of 5.9 m/sec2.

5.6.1.2. Subsumed Maneuvers:

- Lane Track
- Speed Maintenance

5.6.1.3. Inputs:

- Vehicle position relative to initial lane
- Vehicle position relative to final lane Lane path
- Lateral vehicle velocity
- Distance to obstacle

5.6.1.4. Outputs:

Direction commands
Speed commands

Emergency status

5.6.2. Operational Scenario Assumptions

This maneuver is invoked if a failure or obstacle requires that the vehicle remove itself from the current AHS lane as quickly as possible and stop. The stopping deceleration level will be dictated by the nature of the failure or location of the obstacle. In as much as this is an emergency maneuver, operator comfort constraints may be violated.

5.6.3. Absolute Requirements

5.6.3.1. Collision Free Execution

The system shall assure collision-free lane changes in the absence of malfunctions.

5.6.3.2. Minimum lane Clearance to the Front

The lane change controller shall assure that a clear space of 2 meters in front of the vehicle prior to initiating a lane change.

5.6.3.3. Minimum lane Clearance to the Rear

The lane change controller shall assure that an adjacent corridor of 5 meters behind the vehicle prior to initiating a lane change.

5.6.3A. Minimum Time Separation to the Front

The lane change shall be inhibited if the velocity differential with respect to vehicles immediately in front and in the destination lane is such that collision would occur in less than two seconds.

5.6.3.5. Minimum Time Separation to the Rear

The lane change shall be inhibited if the velocity differential with respect to vehicles immediately in front and in the destination lane is such that collision would occur in less than three seconds.

5.6.3.6. Skid Control *I* Avoidance

At no time shall this maneuver command vehicle motion or state changes which cause the vehicle to violate it's traction capability.

5.6.4.. Conditional Requirements

5.6.4.1. Operator Safety

All vehicle trajectory commands shall be limited such that minimal injury to vehicle occupants will result, assuming occupants properly use standard vehicle restraint and safety devices such as lap and shoulder belt systems.

5.6.4.2. Operator Warning

All applicable warning measures shall be Utilized to advise the vehicle occupants of the existence of an emergency condition.

5.7. Interaction-Level Issues

5.7.1. Nominal Spacing Regulation Issues

5.7.1.1. Variable Vehicle Performance Implications

Variations in vehicle performance 'Flay make it imperative that the performance of vehicles behind are considered in executing control actions. Failure to do so 'Flay create dangerous situations. such as braking too hard with a heavy truck immediately behind.

The control needed to optimize dynamics of a platoon is a non-linear problem that is highly dependent on the performance of the vehicles involved. The smaller the spacing, the higher the bandwidth required and the more sensitive the whole system is to individual performance differences. To date, most of the work in longitudinal coordinated control has not allowed for significant variations in acceleration/deceleration capability. if the vehicle behind has less control authority, one's own actions must not exceed his capability to respond.

Gross maneuvers such as hard braking are not the only maneuvers affected by this issue. If there are significant disparities in the plant model for the vehicles involved (e.g., poorly tuned engine or loss of power due to use of air conditioning), energy usage optimization could in some cases yield considerably worse performance in terms of emissions and fuel efficiency than would otherwise be experienced because the model on which the control designs were based are not longer true. If the vehicle behind is significantly less capable in terms of acceleration and deceleration, then one's own vehicle may need to allow more room in front to act as a "cushion" for eliminating disturbances.

Can and should spacing regulation performance be specified as a function of relative performance of the vehicles both in front of and behind the vehicle in question?

5.7.1.2. Air Quality For Occupants In Close Following

Will long strings of vehicles in platoons exacerbate the problems of ingesting the fumes of vehicles to the front?

In most highway situations, spacing between cars provides time for normal turbulence to disperse enough of the exhaust from vehicles in front for adequate ventilation. How serious are occupant air quality issues in close spacing? Will close following a diesel Mercedes be objectionable or even dangerous to the first, second, or third car following? What is the impact on exhaust design and cabin air intake design if close following is to be accommodated? Should standards for placement of air intake and exhaust be adopted to minimize the effects of ingested fumes?

5.7.1.3. Air Flow and Engine Cooling

Close following 'Flay reduce airflow through engine contents, aggravating heat rejection problems, particularly for air-conditioned vehicles.

Today's engine compartments are designed for free air flow from the front to force cooling air into the engine compartment. One of the benefits claimed for platooning is reduced drag. However, reduced drag is due to lower dynamic pressure at the forward face of the vehicle, which may translate to reduced air flow through the engine compartment.

What are the impacts of engine cooling and air flow problems in close following? Are there sequences of vehicle shapes that could increase engine wear or cause failure due to inadequate cooling?

5.7.1.4. Collisions and Incompatible Bumper Configurations

The risk of injury or damage to property is greatly increased if bumpers are at incompatible heights in close following situations.

If a Porsche is following a tractor-trailer combination and a rear-end collision occurs, the risk to the occupants of the Porsche is much greater due to their car passing underneath the trailer. What is the total impact of bumper incompatibility when in close following formations?

Should there be a requirement for multiple platoon types, one for each allowable type of bumper/bumper combination? Such a requirement would limit risk in close following situations, but also complicates system design.

5.7.2. Nominal Vehicle Following Issues

5.7.2.1. Incremental Errors As A Function of Platoon Length

In the presence of tracking errors, vehicle following alone may cause growing offset errors as each vehicle going around the turn exhibits successively greater offset from the lane center.

In tracking curves, the likelihood is that steady-state tracking errors may be biased toward either the inside or outside of the curve, depending on particular implementation. For instance, if there is a significant lag in the sensing/processing(actuation loop, subsequent vehicles are likely to track to the outside of the vehicle in front. Consider platoon following where each vehicle is off by 10 cm to the outside of the turn relative to the vehicle immediately in front. For long platoon lengths, the error accumulation may be intolerable. If you consider a platoon of arbitrary length, N. then the total error at the last vehicle is N* 10 cm. For anything in excess of 4 to 5 vehicles, the accumulation is most likely not acceptable. In general, concept testing must include modeling accumulation of errors as a function of platoon length where platooning is postulated.

5.7.2.2. How does the system avoid "lemming-like" behaviors?

Vehicle following without independent verification can cause a following vehicle to inappropriately follow a failing lead vehicle. This may give rise to a new class of tort litigation - the "You led me astray" case.

When in nominal vehicle-following mode, if each vehicle does not independently sense lane-relative position, one vehicle may follow another that is wandering out of its lane due to failure. Positive means must be established for determining the health of the control system of the vehicle in front or for independently validating its behavior. Without such independent verification, it is impossible to guarantee the safety of vehicles behind. On the other hand, if the means of detecting lane position is through a look-ahead sensor (such *as a* forward-looking camera), then vehicles in front are likely to obstruct such sensors' field of view.

5.7.2.3. Sensor Obstruction While Close Following

Concepts dependent on forward-looking sensors for determining lane position are incompatible with close vehicle following. Lane acquisition when changing modes may be hindered by obstruction by preceding vehicles.

Compatibility across modes and continuity through mode changes will be important design properties, particularly for systems with forward-looking sensors. For instance, if a vehicle is equipped for lane following using cameras, the cameras are looking some distance ahead of the vehicle. If the vehicle is disengaging vehicle following mode and reengaging lane tracking mode, the system must not be thrown into a temporary state of being in neither mode because of insufficient lane clearance ahead to determine lane position.

5.7.3. Emergency Lane Change Issues

5.7.3.1. Static Obstacle Detection Capability Is Presently Sensor Limited

Generalized obstacle avoidance is currently limited by obstacle detection sensor performance. AHS concepts will likely have to work within the constraint of an inability to detect and avoid flotsam or holes on the highway until sensor capability improves within a reasonable cost profile.

There may be no combination of sensors and processing available in the near term to do obstacle detection at a cost that is remotely affordable unless the problem is carefully constrained. Obstacles come in a variety of sizes, shapes, and materials that defies current technology if all-inclusive sensing of any obstacle that can damage the car is required. An object as small as 0.1 meter can be enough to damage a passenger automobile, yet it must be identified 100 meters or more in front of the car to be able to react in time at highway speeds

Even more challenging is the problem of reliably detecting holes in the pavement. Detecting and avoiding potholes is not likely to be an affordable capability within the next 20 years, barring an unforeseen technological breakthrough. By comparison, the human eye not only has better pixel resolution than most cameras and other imaging sensors, but contextual cues ('lighting, shading, color, presence of debris, actions of preceding vehicles) provide information that an automatic system will not be able to detect with present technology. This is not a "show-stopper" issue; AHS concepts can be formulated on the assumption of well-maintained roads. Especially in the context of our interstate system and urban freeways, such occurrences are relatively rare.

On the other hand, if the sensing requirement is limited to detecting vehicles with a threatening relative speed profile in current or immediate neighbor lanes only, techniques such as FMCW radar and even computer vision may prove effective.

5.7.3.2. Automatic Lane Changing May Require Traction Sensing

L*ateral acceleration profiles permissible for emergency maneuvering will have to take worst-case traction conditions into account, or a highly reliable means of detecting traction conditions will have to be present in the System concept.*

Without an absolute guarantee of preventing skids, sudden lane changes to avoid obstacles may in fact induce a more dangerous situation than the one invoking the reactive maneuver. It would be better to hit the vehicle in front of you that just went into a skid than to lose control and hit a stationary object such as a bridge abutment. Lateral acceleration capability on dry pavement is considerably greater than that for wet, icy, or sandy, or gravel-covered roads. To limit the capability under all conditions to the accelerations achievable under the worst conditions is excessively limiting. Yet, without the ability to sense traction conditions, an upper bound must be the worst case definition for reasons of guaranteeing safety.

One near-term partial solution for the problem of ice or snow is to set a table of limits. Infrastructural sensing should be able to determine the presence of precipitation and temperature, and notify vehicles of the prevailing environmental conditions. The on-board controller would then set the response limits according to a pre-specified table that takes vehicle design parameters into account. Table I below provides a sample set of limits.

Table 1. Sample Emergency Lateral Acceleration Units

Condition	Description	Lat Accel Limit (g's)
0	Temperature $\geq 35^{0}$F, Precipitation has not occurred in the last 6 hours.	0.2
1	Temperature <35°F, Precipitation has not occurred in the last 24 hours.	0.15
2	Temperature $\geq 35^{0}F$, Precipitation has occurred in the last 6 hours. (Residual water may be present)	0.1
3	Temperature $<35^{0}$F, Precipitation has occurred in the last 24 hours. (Ice/snow may be present)	0.05

The logic behind this table is that if no precipitation has occurred within a reasonable time before, the likelihood is that the pavement is dry and traction conditions are better. If the temperature is lower, the chances of there being ice or snow, either current or residual, is higher over a longer period, and therefore lateral accelerations should be less aggressive.

This scheme obviously cannot account for the presence of other traction-reducing agents such as sand, oil, or gravel on the road, though if a highway advisory capability included reporting of such conditions, they could be similarly treated.

5.7.3.3. Relationship Between Lateral Authority and Look-Ahead Distance

The authority of the vehicle to execute obstacle avoidance needs 10 be kept low to avoid the possibility of loss of control, but doing so increases the look-ahead requirement.

Assuming that the vehicle must detect the obstacle and execute a lane change to avoid it, what are the approximate required look-ahead distances? Suppose the required maneuver is an S-turn at the acceleration limit with instantaneous accelerations (zero steering angle rise time) from the center of one lane to the center of the next. Suppose further that there is a time delay involved in sensing and processing. The required look-ahead distance would be:

$$look\_ahead = velocity * latency + maneuver\_length$$

where:

$$maneuver\_length = 2 * \sqrt{(2 * turn\_radius * half\_width) - half\_width^2}$$

$$turn\_radius = {velocity^2}/{lat\_accel_{max}}$$

$$half\_width = lane\_width / 2$$

Presuming the latency is 0.5 seconds (a relatively conservative guess), figure 6 below depicts the look-ahead distance required for the sensor to be able to discriminate an obstacle.

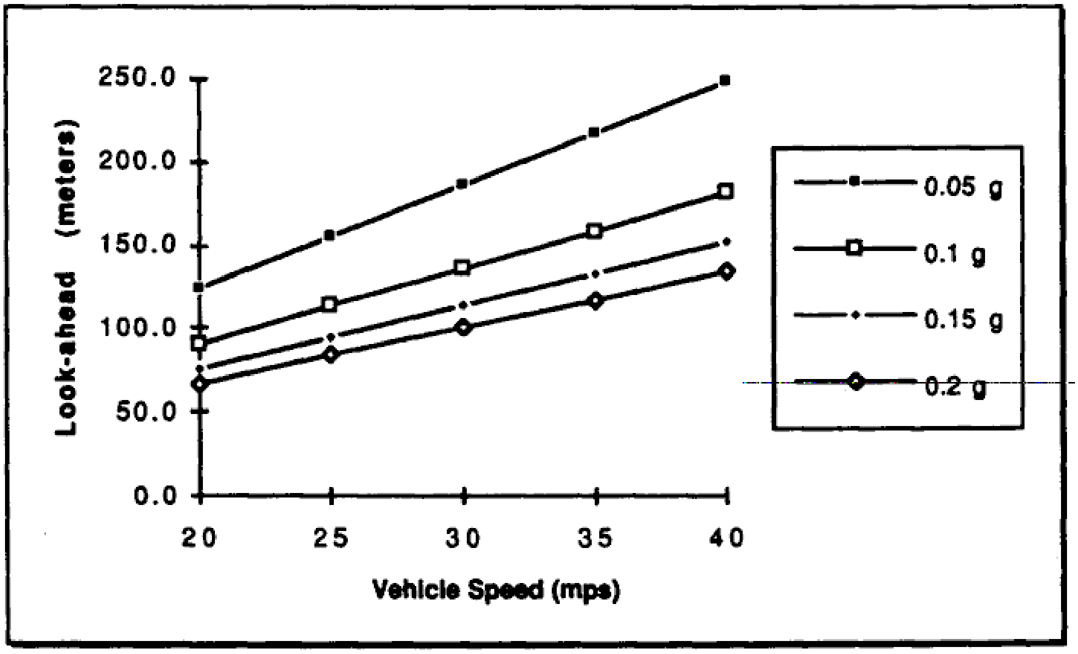


Figure 6. Obstacle Detection Look-ahead vs. Speed and Lateral Acceleration

For comparison, 25 mps corresponds to *56* mph. This analysis presumes a straight road segment and the necessity of executing a complete lane change maneuver when a less aggressive maneuver might suffice. On the other hand, it also assumes a step change in steering angle, and in fact a significant time will elapse while the steering slews from one position to the next, suggesting that reaction times may have to be greater. Hence, we believe it is a conservative estimate. However, it illustrates a significant point: lookahead distances are quite long for obstacle avoidance using lane change maneuvers, especially under reduced lateral acceleration limits. At these distances, the system must be able to both detect the existence of the obstacle and verify that a high relative velocity exists. Three question areas remain open issues in this context:

- Can obstacle detection sensors detect vehicle-sized stationary objects and determine they are non-moving at sufficient ranges to meet this requirement? Active sensors (radar and ladar) will probably have little difficulty meeting this requirement on a straight roadway. Passive techniques (machine vision, stereo correlation) will likely be unable to determine relative speed at these distances, even if they are able to detect their presence.

- If the view is blocked by the presence of other vehicles (such as trucks on the inside lane of a curve), there may not be sufficient look-ahead for the prevailing conditions, particularly if lateral acceleration limits are reduced for poor traction.

- Can obstacle detection sensors detect small objects (such as a muffler lying on the pavement) at these ranges? Testing would be required for radar sensors, but current technology will permit neither ladar nor vision techniques nor stereo correlation to successfully detect smaller objects much less measure their relative speed.

5.7.3.4. Inappropriate User Interference

Sudden lane changes are likely to alarm the operator and may induce him to try to intervene. How to notify him under duress that the System is functioning properly is a difficult human factors issue.

If automation of emergency response is permitted, a significant issue is how to ensure that the driver does not interfere with emergency mode operation thinking it is a system failure? A sudden, unannounced lateral acceleration may cause the operator to conclude that a system failure has occurred when in fact the system is responding as designed. Unannounced," as used here, includes annunciation with less than two seconds to the action, such that the operator hasn't the time to become fully aware of what is happening before it occurs. This will need to be the subject of intense human factors engineering and failure mode analysis on any specific design.

6. AHS PLATOON LEVEL MANEUVERS (LEVEL 4)

6.1. Platoon Merge

6.1.1. Maneuver Description

6.1.1.1. Function:

~Assume a trailing position behind the last vehicle of a platoon.

6.1.1.2. Subsumed Maneuvers:

Nominal Spacing Regulation Speed Maintenance

6.1.1.3. Inputs:

Vehicle position relative to preceding vehicle
Vehicle separation rate of change Vehicle position relative to lane barriers Lane path projection
Lane grade projection Vehicle speed

6.1.1.4. Outputs:

Speed command

6.1.2. Operational Scenario Assumptions

This maneuver assumes that entrance to a platoon will always be done from the rear and that merging into the middle of a platoon from the side will not be allowed. For the purposes of maintaining maximum system efficiency and throughput, the vehicle will be allowed to travel slightly above the nominal lane speed in order to consolidate several small platoons into a single large platoon. In some cases it may be necessary to limit the size of a platoon in order to provide sufficient opportunity for entrance onto the AHS by vehicles queued up at AHS interchanges.

6.1.3. Absolute Requirements

6.1.3.1. Initial Separation

This maneuver shall be inhibited if at any time the vehicle headway exceeds 200 meters.

6.1.3.2. Initial Rate of Closure

This maneuver shall be inhibited if at any time the vehicle headway closure rate falls below -5 mps (vehicle ahead is pulling away).

6.1.3.3.' Aborted Maneuver Initiation

Upon an aborted platoon merge, the vehicle shall resume it's originally commanded headway and speed, as per the appropriate maneuvers.

6.1.3.4. Required Vehicle-Vehicle Communications

If applicable, the vehicle shall receive information defining the platoon state via a dedicated communications link. Failure of the communications link shall constitute a failure to merge with the platoon.

6.1.3.5. Required Vehicle-Infrastructure Communications The vehicle shall coordinate the platoon merge though the vehicle to infrastructure communication link. Once data transmission is initiated directly from the platoon, transmission to the infrastructure shall cease. Reception may continue, at the discretion of the architect

6.1.3.6. Capture Interval

The vehicle controller shall provide a trajectory which assures platoon capture within 2 minutes. Failure to capture the platoon inside this two minute period shall constitute a failure to capture and result in an aborted platoon merge.

6.1.4. Conditional Requirements

6.1.4.1. Operator Comfort

The requirement(s) of Section *5.1.4.1* shall apply.

6.1.4.2. Stability of Closure

This maneuver shall be aborted if more than two sign changes in acceleration occur.

6.2. Nominal Platoon Departure.

6.2.1. Maneuver Description

6.2.1.1. Function:
Depart platoon for the purpose of exiting AHS lane.

6.2.1.2. Subsumed Maneuvers:
Lane track or Vehicle Follow

6.2.1.3. Inputs:

- *V dc position relative to preceding vehicle
- *Vehicle position relative to lane barriers
- *Lane path projection
- *Lateral vehicle velocity
- *Adjacent lane clearance

6.2.1.4. Outputs S:

- *Direction command Speed command
- *Departure status

6.2.2. Operational Scenario Assumptions

An example of when a nominal platoon departure maneuver would be invoked is when the vehicle is changing from one AHS highway to another or departing the AHS system completely. Depending upon the nominal intervehicle spacing being used by the platoon, it may be necessary to slightly increase the separation distance with the preceding vehicle to insure a safe departure. Prior to the departure maneuver, the vehicle win receive an acknowledgment that the intended AHS exit zone is able to accommodate an exiting vehicle. In addition, a notice of intended platoon departure will be communicated to the platoon to preclude invoking unwarranted vehicle following maneuvers by trailing vehicles. Departure is assumed to be executed by a lane change, or by breaking off to the rear if the vehicle in question is the last in the platoon.

6.2.3. Absolute Requirements

6.2.3.1. Rearward Lane Clearance

Lane change shall be inhibited if the adjacent corridor contains a vehicle less than 10 meters in front of the vehicle or 15 meters behind the vehicle prior to performing a lane change.

6.2.3.2. Separation on Disengage Maneuver Initiation

Upon approval to Disengage, the vehicle shall reduce velocity, on a smooth profile, to no more than 2 mps less than the velocity of the platoon, until safe clearances are achieved.

6.2.3.3. Required Vehicle-Vehicle Communications

The vehicle shall coordinate the disengage through the dedicated vehicle communications link. Once disengage is completed, communications through the dedicated link shall cease.

6.2.3A. Required Vehicle-Infrastructure Communications

The platoon shall coordinate the vehicle disengage though the vehicle to infrastructure communication link. Once data transmission is terminated directly from the platoon, bi-directional communication with the infrastructure shall be initiated.

6.2.3.5. Rate of Departure

The vehicle controller shall provide vehicle speed bias commands which does not exceed a 2 mps departure rate.

6.2.4. Conditional Requirements

6.2.4.1. Operator Safety

All vehicle trajectory commands shall be limited such that minimal injury to vehicle occupants will result, assuming occupants properly use standard vehicle restraint and safety devices such as lap and shoulder belt systems.

6.2.4.2. Operator Awareness

All applicable warning measures shall be used to advise the vehicle occupants of the pending platoon departure.

6.3. Emergency Platoon Departure

6.2.1.1. Function:

- *Depart platoon for reasons of an emergency.

6.2.1.2. Subsumed Maneuvers:

- *Lane track or Vehicle Follow

6.2.1.3. Inputs:

Vehicle position relative to preceding vehicle Vehicle position relative to lane barriers Lane path projection

- *Lateral vehicle Velocity
- *Adjacent lane clearance

6.2.1.4. Outputs:

- *Direction command
- * Speed command
- *Departure status
- *Emergency status

6.3.2. Operational Scenario Assumptions

This maneuver is invoked when due to an emergency, it is necessary to depart the platoon as quickly as possible. An emergency platoon departure will not necessarily occur at an AHS exit zone. As in other emergency maneuvers, the operator comfort constraint may be violated in order to maximize safety. The communicated emergency status to the platoon will depend upon the nature and urgency of the emergency. In some cases, such as an hazard falling off of a preceding vehicle, it may be desirable for all trailing vehicles to depart the platoon, i.e. perform an emergency lane change or emergency in-lane-stop. In the majority of cases, an emergency platoon departure involves a lane change or lateral departure as opposed to an in-lane longitudinal departure.

6.3.3. Absolute Requirements

6.3.3.1. Collision Avoidance *I* Lane Clearance

The system shall assure collision-free lane changes in the absence of malfunctions.

6.3.3.2. Separation on Disengage Maneuver Initiation

Upon initiation of this maneuver, the vehicle shall reduce velocity, on a smooth profile, to no less than 2 mps less than the velocity of the platoon.

6.3.3.3. Skid Control I Avoidance

At no time shall this maneuver command vehicle motion or state changes which cause the vehicle to violate it' 5 traction capability.

6.3.3.4. Required Vehicle-Vehicle Communications

The vehicle shall advise the platoon of the disengage through the dedicated vehicle communications link. Upon initiation of this maneuver, reception of data from the platoon shall be inhibited.

The vehicle shall coordinate the vehicle disengage though the vehicle to infrastructure communication link.

6.3.4. Conditional Requirements

6.3.4.1. Operator Safety

The requirements of Section 6.2.4.1 shall apply.

6.3.4.2. Operator Awareness The requirements of Section 6.2.4.2 shall apply.

6.3.4.3. Operator Override Conditions

If the action requires human intervention, the operator shall be alerted by an unambiguous audible and visual alert no less than two seconds before such action must be initiated.

6.4. Platoon-Level Issues

6.4.1. Platoon Entry and Merging Issues

6.4.1.1. Infrastructure-Limited Platoon Length

In order to be able to assure entry for vehicles queued up for entry at a given point, it will likely be necessary to limit platoon length to assure sufficient opportunities for entry under high density conditions.

Under normal conditions, it is conceivable that platoon length could be unlimited as long as the platoon dynamics were controllable [Shladover:91]. Assuming that the AHS will operate at high densities much of the time, the opportunity to merge into traffic could become a rare event. If platooning is being done to increase efficiency, then it may become necessary for the infrastructure to regulate platoon length to guarantee existence of holes to merge into. If platoons are allowed to grow to lengths of twenty or more with minimal separation between, there may not be sufficient flow rate from the entry ramp onto the highway to meet demand, causing congestion at the entry point.

This will be particularly true of interchanges between two AHS segments, where the flow of traffic from one highway to another demands frequent insertion of enqued vehicles to prevent spillback congestion onto the highway from which vehicles are exiting.

6.4.1.2. Intervehicle Communications for Tail-on Platoon Merging

Assuming that platoon length is limited as in §6.4.1.1, intervehicle communication or platoon coordination will be mandatory to assure vehicles do not form platoons of arbitrary length.

If platoon length is to be regulated, there must be communication between vehicles (either directly or via the infrastructure) to permit a request/acknowiedge sequence to occur. If this is not the case, then the infrastructure will be required to monitor platoon length and orchestrate insertions to and departures from platoons. This latter option will complicate infrastructure design considerably. Vehicles must also be capable of accepting instruction from the infrastructure on allowable platoon length to know what the current limit is.

6.4.1.3. Regulating Inter-Platoon Spacing

In addition to regulating platoon length, the infrastructure may need to regulate interplatoon *spacing to permit safe entry.*

In addition to the problem of assuring existence of holes, it may become necessary to regulate the spacing between the platoons to permit safe entry of vehicles of differing performance and length. For instance, should the spacing be fixed so that the largest, slowest-accelerating vehicles can get in, even when there are no such vehicles enqucued? How much spacing is adequate to allow for performance uncertainties and to achieve desired safety margins?

This regulation, if indeed a genuine requirement, would probably have to be done in the infrastructure. The amount of lead required to make sure that the "hole" in traffic was of sufficient size at the merge point would probably require starting the maneuver 0.5 to 1 km prior to the merge point This suggests that the control and coordination function cannot be done vehicle4o-vehicle.

6.4.1.4. Operator Comfort and Close Following

Operator comfort testing has exclusively focused on the vehicles ahead and not on the presence of vehicles behind.

There have been tests and considerable analysis associated with determining the comfort level operators will have with operating in close proximity to the vehicles in front, but there has been little to no activity on the issue of comfort levels with close following vehicles behind. Some human factors testing and analysis with close following behind conditions is required.

6.4.2. Nominal Platoon Departure Issues

6.4.2.1. Speed Change Required Before Exit?

Can a vehicle safely depart the highway from within a platoon without change in speed or separation distance?

Our first impression is that the answer is a conditional yes, depending on the configuration of the exit ramp and the control performance of the vehicles involved. However, there are some subtleties to this problem warranting investigation. If the answer is no, then issues *6.4.2.2-6.4.2.4* apply, otherwise issue 6.4.2.5 applies.

6A.2.2. Is Extra Space Required In Front and/or Behind During Exit? If so, how much?

6.4.2.3. Additional Platoon Exit Dynamics Analysis Required

Modeling needs to be done to determine traffic flow impact of opening space for disengagement *from platoons*

If entry/exit ramps occur every two kilometers, and vehicles are entering and leaving a platoon with some regularity, the need to slow to get out of a platoon *at an* exit may cause *a* compression wave of slowing behind the vehicle, particularly *if* the exit is a popular one. Some modeling of high density *traffic* situations is needed to measure the effects of such actions on overall flow and help specify the requirements on the system. How much spacing is required? What are the effects

6.4.2.4. Communication Required to Disengage from Platoons

If a vehicle is exiting from the middle of the platoon, all vehicles in that platoon need to be advised of the condition. The transients and required maneuvers will most likely require some anticipation to coordinate properly.

6.4.2.5. Is Automatic Control Required for Exit

If vehicles are to exit platoons at speed with no increase in spacing, does that mean that manual exit from platoons or from the AHS while in a platoon are prohibited?

This issue couples with the other user-usurpation issues (see) under exceptional or emergency conditions, but also applies under nominal operating conditions as well. Suppose the user suddenly decides based on traffic advisories that the upcoming exit is the exit of choice instead of the planned exit. By what mechanization will he be able to interact with the system, and how does the design preclude accidental input?

6.4.3. Emergency Platoon Departure

6.4.3.1. Discriminating Failure vs. Intentional Emergency Exit

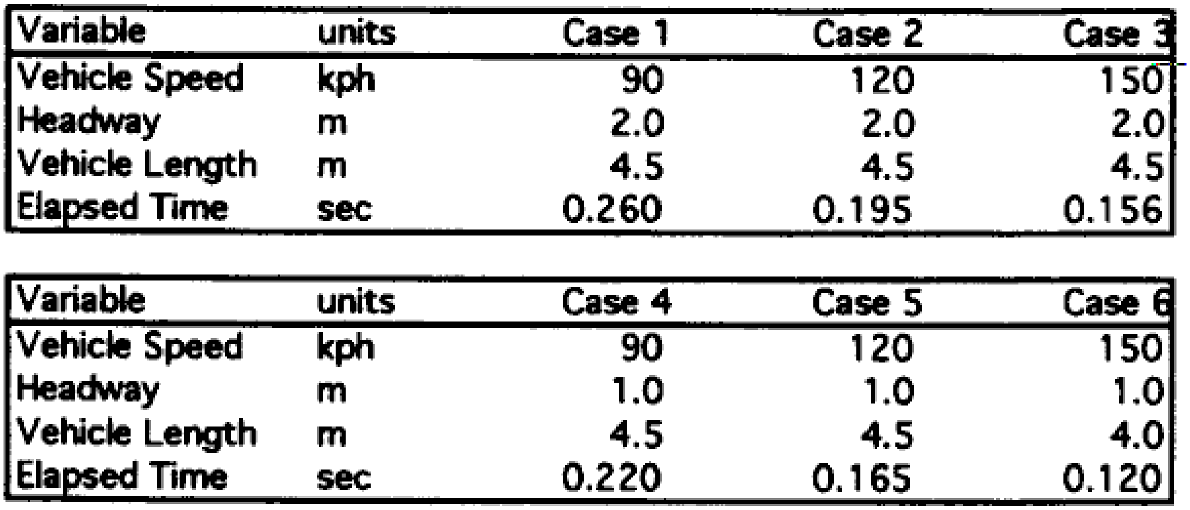
Under small headway conditions, each vehicle must be capable of distinguishing between failure and intentional emergency exit by the vehicle in front of it within a very short time interval.

Nominally, one might expect that communication of intent will occur when a vehicle plans to depart from the interior of a platoon. However, when a vehicle in front departs its lane suddenly, there are two possibilities: 1) a failure has occurred to the vehicle in front, or 2) an emergency condition has been detected warranting immediate evasive action. It is imperative to know which of these two conditions exists. if the vehicle behind has no information on the conditions ahead, and if its ability to sense conditions ahead is obstructed until the vehicle in front moves out of the way, it may be too late to respond once the vehicle in front has moved aside. On the other hand, following a failed vehicle out of the lane compounds the problem and may be the worst possible choice. It will also lead to interesting tort liability problems.

The time available for response is very short indeed. Suppose that a vehicle is following closely behind another. Suppose further that the lead vehicle senses an obstacle at the last possible instant and begins maneuvering to avoid the obstacle. Since both vehicles are presumably traveling at the same speed, the second vehicle has only the amount of time *it* takes to reach the same point in space where the first vehicle began maneuvering to initiate its maneuver.

Table 2 illustrates how little time exists for vehicles of nominal length and speed with one and two meter headways. In this table, three speeds are considered corresponding to approximately *55*,*75*, and *95* mph. Vehicle length is assumed to be about 4.5 meters, and headway is 2 meters. Times are in the vicinity of 0.2 seconds. Within this short time, the following vehicle must detect, analyze, and react to the condition. Sensor latency, sensor data conditioning and processing time, control processing, and actuation latency must all be included in this interval. For most conceivable configurations involving autonomous sensing and reaction (e.g. non-communicated), these times could be considered aggressive design constraints. We conclude that constant, low-latency communications between successive vehicles in close proximity (whether platooning or not) is required to meet this functional need.

Table 2. Time Interval For Successive Vehicles to Cross the Same Point



Variable	units	Case 1	Case 2	Case 3
Vehicle Speed	kph	90	120	150
Headway	m	2.0	2.0	2.0
Vehicle Length	m	4.5	4.5	4.5
Elapsed Time	sec	0.260	0.195	0.156

Variable	units	Case 4	Case 5	Case 6
Vehicle Speed	kph	90	120	150
Headway	m	1.0	1.0	1.0
Vehicle Length	m	4.5	4.5	4.0
Elapsed Time	sec	0.220	0.165	0.120

An alternative way to to view the issue is that intervehicle spacing must be no closer than the product of the vehicle speed and the worst-case latency from one vehicle's failure to the following vehicle's control response.

6.4.3.2. Standard Protocols For Emergency Conditions

Extensive analysis will be required to determine the kinds of emergency (off-nominal) conditions the AHS mast be capable of responding to and the right protocols for response to those conditions. This analysis will *have to documented as standards that form the basis for limiting product liability.*

Our recommendation is that, once the possible configurations have been narrowed to a few candidates, an effort must be undertaken to perform failure modes and effects analysis with an emphasis on defining standard response protocols for various emergency conditions, and that legislation should be considered that will limit liability if those protocols are observed.

7. AHS SYSTEM LEVEL MANEUVERS (LEVEL 5)

7.1. Nominal AHS Entrance

7.1.1. Maneuver Description

7.1.1.1. Function:

*Transition vehicle from non-automated to automated operation on AHS lanes

7.1.1.2. Subsumed Maneuvers:

*All

7.1.1.3. Inputs:

Vehicle status
Operator status
Vehicle speed
AHS lane clearance
Vehicle position relative to AHS lane

7.1.1.4. Outputs:

Speed/commands
Direction commands

7.1.2. Operational Scenario Assumptions

This maneuver is dependent upon the Representative System Configuration. RSC's that allow automated vehicles to enter an automated lane at any point (i.e. the automated lane is separated from non-automated lanes by white stripes only) will require a significantly different AHS Entrance maneuver than RSCs that allow entrance to automated lanes at designated interchanges (i.e. the automated lane may be separated from non-automated lanes by physical barriers). For the purposes of this document, it is assumed that the AHS lane(s) is physically separated from non-AHS lanes and AHS entrance is controlled AHS interchanges. The AHS interchange will consist of an entrance and deceleration zone, a certification zone, a queuing zone and an acceleration and merge zone. Automatic control of the car will be assumed at the queuing zone.

7.1.3. Absolute Requirements

7.1.3.1. Vehicle Certification

Prior to acceptance into the AHS, all applicable vehicle communications and functions shall be verified to be operating properly.

If the certification is carried out while the vehicle is in motion, the certification shall be unobtrusive to the nominal operation of the vehicle.

Under all conditions, the certification shall not cause harm to the vehicle.

7.1.3.2. Operator Certification

At TBD intervals, the operator certification and/or capability shall be verified.
Prior to entrance into the AHS, all operator safety devices shall be verified as being operational and engaged.

7.1.3.3. Platoon Spacing Regulation

The entrance operation shall not violate platoon spacing regulations in place on the AHS section, if applicable.

7.1.3.4. AHS Operations Perturbation

The entrance operation shall be performed in such a manner that the merge does not perturb traffic flow in the AHS section, in other words the entrance operation shall be transparent to the other AHS users.

7.1.4. Conditional Requirements

7.1.4.1. Operator Safety

The entrance operation shall be performed in such a manner as to maintain operator safety at all times.

The entrance operation shall not subject the operator to unsafe acceleration profiles, either longitudinally or laterally.

7.1.4.2. Operator Awareness

The operator shall be provided TBD audible and/or visual status indicators apprising the operator of the vehicle operation status.

7.1.4.3. Operator Override Conditions

Under TBD conditions, the operator shall be capable of assuming control. The transition from computer to manual control shall be performed in accordance with TBD.

7.2. Nominal AHS Exit

7.2.1. Maneuver Description

7.2.1.1. Function:

Transition vehicle from automated operation on AHS lane(s) to non-automated operation

7.2.1.2. Subsumed Maneuvers:

~All

7.2.1.3. Inputs:

Vehicle status
Operator status
* Vehicle speed
* Vehicle position relative to AHS lane

7.2.1.4. Outputs:

* Speed commands

7.2.2. Operational Scenario Assumptions

This maneuver assumes as in the previous maneuver (7.1) that entrance and exit from the AHS is only feasible at pre-designated AHS interchange The exit interchange will consist of a deceleration and transition zone where control of the c& is returned to the operator prior to encountering non-automated traffic. When a vehicle is to exit AHS it must notify trailing vehicles of its intention to exit and must certify that the operator is prepared to resume control of the vehicle.

7.2.3. Absolute Requirements

7.2.3.1. Vehicle Certification

Coincident with release of the vehicle into non-AHS traffic, release of the vehicle computer control authority shall be verified. Failure to pass computer release verification shall cause TBD action.

7.2.3.2. Operator Certification

Prior to release of the vehicle into non-AHS traffic, the operator readiness shall be verified. Failure to pass operational verification shall cause the vehicle to continue in its current mode until the situation is resolved or an operator abort is received from the user interface.

7.2.3.3. Platoon Spacing Regulation

The exit operation shall not violate platoon spacing regulations in place on the AHS section, if applicable.

7.2.3A. AHS Operations Perturbation

The exit operation shall be performed in such a manner that the departure does not perturb traffic flow in the AHS section, in other words the exit operation shall be transparent to the other AHS users.

7.2.4. Conditional Requirements

7.2.4.1. Operator Safety

The exit operation shall be performed in such a manner as to maintain operator safety at all times.

The exit operation shall not subject the operator to unsafe acceleration profiles, either longitudinally or laterally.

7.2.4.2. Operator Awareness

The operator shall be provided TBD audible and/or visual status indicators apprising the operator of the vehicle operation status.

7.2.4.3. Operator Override Conditions

The system shall be capable of relinquishing control upon receipt of an operator override input from the user interface.

Editor's Note: Human factors and safety considerations may demand the ability for the user to take over control at any time. Liability issues may also require that control (and therefore responsibility) must always be, in the final analysis, in the hands of the operator. However, certain modes of operation may prohibit this due to the impossibly fast response time that would require of the operator. There may be an issue here of conflicting requirements.

7.3. Emergency Abort

7.3.1. Maneuver Description

7.3.1.1. Function:

Generate speed and direction commands to safely abort AHS Entrance maneuver

7.3.1.2. Subsumed Maneuvers:

All

7.3.1.3. Inputs:

Vehicle status
- * Operator status

Vehicle speed
Vehicle position relative to AHS lane
Emergency status

7.3.1.4. Outputs:
- * Speed commands
- * Direction commands

7.3.2. Operational Scenario Assumptions

This maneuver is invoked if it is determined during the acceleration phase of the AHS entrance maneuver that the vehicle will be unable to safely transition onto the AHS lane(s) or that operation of the vehicle on the AHS lane will a detrimental impact the efficiency of the AHS system.

7.3.3. Absolute Requirements

7.3.3.1. Vehicle Certification

Immediately prior to release of the vehicle into non-AHS traffic, release of the vehicle computer control authority and assumption of manual control shall be verified. Failure to pass computer release verification shall cause immediate-attention alarms to be triggered.

7.3.3.2. Operator Readiness

Immediately prior to release of the vehicle into non-AHS traffic, the operator readiness shall be verified. Failure to pass operational verification shall cause immediate-attention alarms to be triggered.

The abort operation shall be performed in such a manner that the departure does not perturb traffic flow in the AHS section, in other words the abort operation shall be transparent to the other AHS users.

7.3.3.4. Vehicle Safing

Upon receipt of an abort command, the system shall decelerate the vehicle into a safe state without entering the highway and either remove the vehicle from traffic flow or remerge into non-AHS traffic streams.

7.3.3.5. Operator Override Conditions There shall be no operator override to this maneuver.

7.3.4. Conditional Requirements

7.3.4.1. Operator Safety

The operator shall not be subjected to lateral and longitudinal acceleration environments in excess of the capabilities of the vehicle safety equipment.

7.3.4.2. Operator Awareness

The operator shall be provided TBD audible and/or visual status indicators apprising the operator of the vehicle operation status.

7.3.4.3. Platoon Spacing Regulation

The abort operation shall not violate platoon spacing regulations in place on the AHS section, if applicable.

7.4. System-Level Issues

7.4.1. AHS Entry Issues

7.4.1.1. Safe Queing Space

Safe queuing space is needed for entry that does not interfere with exit and entry abort queues and traffic patterns.

Assume the AHS is located adjacent to the non-AHS lanes (perhaps because the AHS lanes were taken from existing freeway lanes). Assume further that the AHS lanes are separated from non-AHS lanes by harriers. If so, then there must be periodic breaks in the barrier where vehicles can transition between the two modes. Transition zones should be designed with the following features:

- minimizes dangerous crossing traffic patterns (entry and exit zones not in the same region of the highway.
- provides for minimum slowing and stopping of vehicles in transition
- provides a zone for buffering vehicles so that spillback slows neither sets of lanes in high-density intervals,

Assuming that the two sections (AHS and non-AHS) are adjacent and parallel, and that the transition zone is no more than one lane wide, there are at least three possible types of configurations. Figure 7 depicts a configuration in which the exit lane appears upstream from the entry lane. This configuration gives rise to a potentially dangerous crossing traffic pattern, because the *traffic* exiting the AHS lanes will have to cross traffic entering. Due to the lack of speed synchronization on the non-AHS lanes, there could be significant speed differential causing a safety hazard.

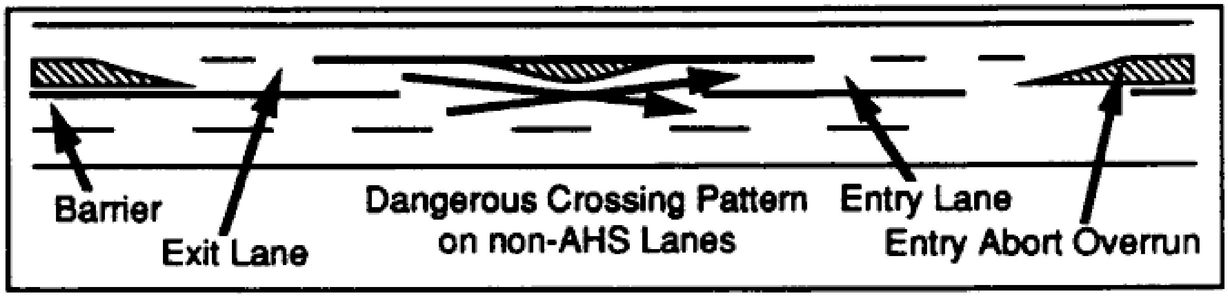


Figure 7. Upstream Exit Configuration

Figure 8 depicts the second configuration, in which the entry lane is upstream of the exit lane. This improves on 7.1 in two ways:

1) The exit lane can double as an entry abort zone. The space required for the dedicated entry abort overrun area is no longer required.
2) The crossing pattern is now in the AHS lanes. With speed regulation expected on the AHS, this is only slightly more desirable than the configuration of figure 6.

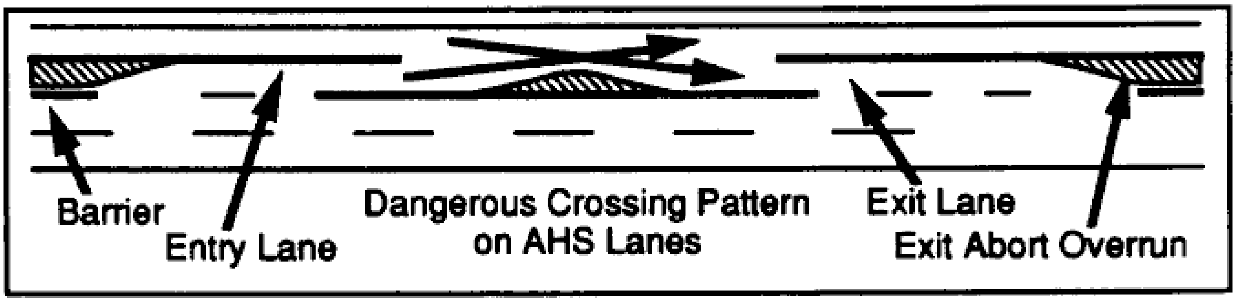


Figure 8. Upstream Entry Configuration

To avoid the crossing patterns, there must be space between the entry and exit zones. One way to use that extra space is to insert an entry abort zone between them, as shown in figure 9. This configuration minimizes the space requirement while providing the most capability.

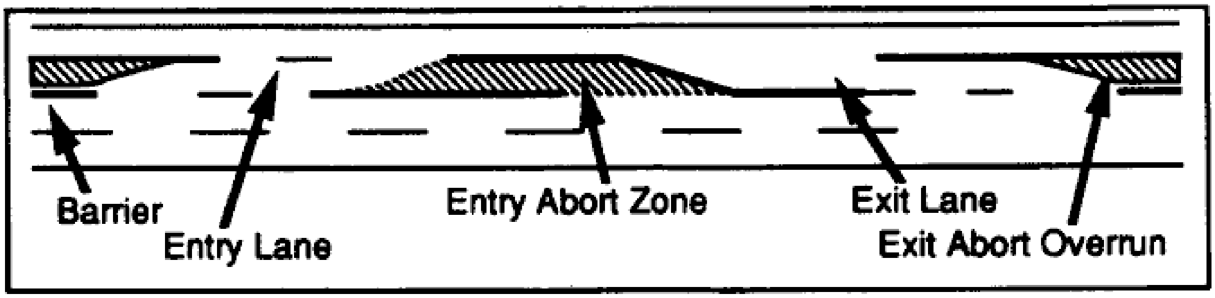


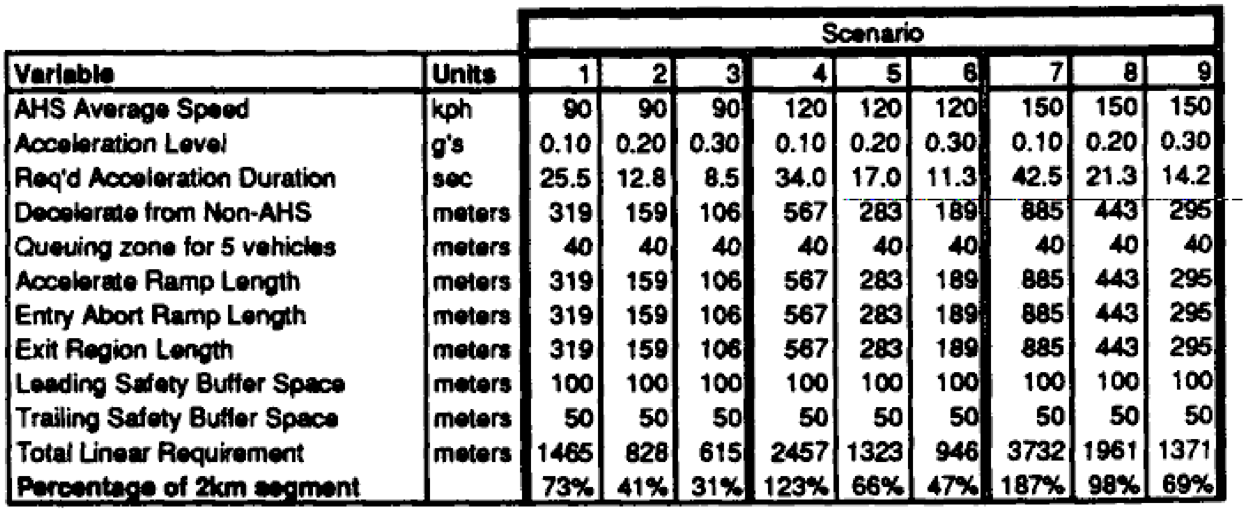
Figure 9. Upstream Entry with Entry Abort Zone

Consider the configuration of figure 9. This figure depicts an entry ramp upstream of the exit lane, but with an entry abort zone. This entry abort zone provides several advantages. First, because of the demanding timing requirement for entry into dense traffic, some significant percentage of time vehicles will miss their entry and have to abort. The entry abort zone provides a way for a vehicle to gracefully abort without interrupting other traffic flow. Second, it provides added highway length for entering and exiting vehicles to maneuver around each other.

In each of these configurations, the entry and exit ramps must be designed to be a buffer zone for enqueuing vehicles. This buffer must be long enough to:

1) decelerate vehicles being enqucued to a full stop-- this is a worst-case scenario wherein the AHS is very densely packed and enough vehicles will want entry frequently enough at a given entry point to have to wait for an opening).
2) hold some number of waiting vehicles -- the number will vary according to local traffic patterns, but the only alternative to a waiting zone is to reject entry.
3) permit aborting -- as noted before, the timing requirements are tight and missed opportunities are bound to occur, particularly if the acceleration phase is manually controlled.
4) allow for acceleration from a dead stop to AHS speed within acceleration performance limits of the least qualified AHS vehicle.

Table 3. Analysis of Merge Distance, Speed, and Acceleration



		Scenario								
Variable	Units	1	2	3	4	5	6	7	8	9
AHS Average Speed	kph	90	90	90	120	120	120	150	150	150
Acceleration Level	g's	0.10	0.20	0.30	0.10	0.20	0.30	0.10	0.20	0.30
Req'd Acceleration Duration	sec	25.5	12.8	8.5	34.0	17.0	11.3	42.5	21.3	14.2
Decelerate from Non-AHS	meters	319	159	106	567	283	189	885	443	295
Queuing zone for 5 vehicles	meters	40	40	40	40	40	40	40	40	40
Accelerate Ramp Length	meters	319	159	106	567	283	189	885	443	295
Entry Abort Ramp Length	meters	319	159	106	567	283	189	885	443	295
Exit Region Length	meters	319	159	106	567	283	189	885	443	295
Leading Safety Buffer Space	meters	100	100	100	100	100	100	100	100	100
Trailing Safety Buffer Space	meters	50	50	50	50	50	50	50	50	50
Total Linear Requirement	meters	1465	828	615	2457	1323	946	3732	1961	1371
Percentage of 2km segment		73%	41%	31%	123%	66%	47%	187%	98%	69%

This length requirement would appear to be in the vicinity of at least 500 meters, nominally. The space represents an Infrastructural cost in either lanes taken out of existing infrastructure or created anew by repartitioning the right of way or adding new right of way. Alternatives include:

1) Provide dedicated ramps, and separate the AHS from the non-AHS by more than just a Jersey barrier.

2) Avoid the use of barriers and provide access at any point along the way (that is, a dotted

line is the only separator).

7.4.1.2. Performance Requirements to Achieve Synchronization

Synchronizing speed and position to enter a hole can severely constrains Longitudinal performance requirements.

Assume that in the AHS of the future, high density will be the norm and not the exception. As such, we anticipate that the opportunities for merging (holes in the traffic pattern on the AHS into which an entering vehicle can merge) will be relatively infrequent, particularly during rush hours on urban freeways. This worst case scenario suggests there would be vehicles having to wait for opportunities to enter and thus sitting at a dead stop. The conclusion is that the presence of a hole must be detected and signaled to the waiting vehicle and its acceleration profile executed within moderately stringent timing and acceleration level constraints.

An alternative is to provide an external assist to the vehicle's acceleration. This assist could potentially take the form of a fixture slotted in the pavement that attaches to the car only during the acceleration interval, similar to the way aircraft carriers catapult aircraft into the air (though with obviously reduced acceleration levels). Such a mechanization would ensure the vehicle started at the right time and accelerated at the right rate.

7.4.1.3. Manual to Automatic Mode Transition

Should the transition from manual w automatic mode occur before en:?)? or once in the AHS lane? The trade is between System cost/complexity and do-ability.

The issue for system designers will be to determine how the system assures that conditions are right for engagement of automatic mode, and whether the responsibility for safe maneuvering into traffic lies with the automated system or with the driver. There are two broad classes of entry transition approaches:

1) *Engage automatic mode prior :0 entry into the System and automatically manage acceleration, speed Synchronization, and merging of traffic. This* approach requires the system to. It requires sensing the existence of the hole and managing upstream traffic to the extent required to assure the hole has sufficient size. It further requires monitoring the hole's approach speed (or tightly regulating that speed). Finally, it requires controlling the entering vehicle's position and acceleration profile. These requirements hold regardless of partitioning of function between vehicle and infrastructure. The sensing of the opportunity to merge must take place on the order of *0.5 or* 1.0 kilometer prior to the merge point to permit sufficient time to make the necessary adjustments in the traffic pattern and perform acceleration profile calculations for the entering vehicle.

   The control system must perform to fairly tight tolerances and have a means for sensing that conditions are not right For instance, consider the following scenario the hole in the traffic is approaching and the entering vehicle is given the signal to begin acceleration. As throttle is opened, the vehicle experiences a momentary power hesitation caused by lengthy engine idling and resultant heat buildup in the engine compartment. Because of the vehicle's age and condition, it does not have the acceleration capacity to make up for the lost time, but this is not apparent until part way down the acceleration lane. This unsafe condition must be detected and dealt with before the vehicle attempts to merge onto the AHS lane or a collision will result. Constant, low-latency monitoring of the progress of both the hole and the entering vehicle will be required of the vehicle, the infrastructure, or both throughout the maneuver.

This approach can be made more tractable (and indeed may even require) long entry lanes providing sufficient space for checkout, acceleration, position and velocity adjustments, exception condition detection, and exception response. Longer entry/exit lanes provide more time, reducing the performance requirements on the control system, but they also require more land and Infrastructural development and, hence, more cost.

2) *Have the driver maneuver the vehicle into traffic and manage Synchronization, etc., then engage automatic control by user input once the vehicle has been properly maneuvered into position.* This approach considerably reduces the complexity as it depends heavily on the driver to do the sensing, assessment, and control actions requlred to merge safely into traffic. It also reduces the safety requirements on the system design, since the vehicle is only required to perform lane tracking and headway maintenance functions.

However, this approach suffers from some significant drawbacks. The performance of the entering vehicle is now very much subject to the human responses, and therefore does little to further the AHS objective of reducing the number of incidents caused by human error. As traffic density on the AHS increases, the performance of the human driver becomes increasingly critical. The driver must sense the hole, time its approach, and judge that there is sufficient room to safely enter it. He must simultaneously assure that the vehicle that just took off in front of him did not abort and slow down in the acceleration lane. If we are to reap the benefits promised by AHS in terms of more laminar traffic flow at higher speeds and higher traffic densities, then the requirements on the human driver will be ever more demanding.

of course, the root of the problem is that the more automatic functionality required of the AHS system, the more expensive it becomes. The first option above will undoubtedly require substantial safety features in the design at considerable expense. The latter reduces the requirement on the system at the expense of placing more (perhaps unacceptably high) requirements on the driver, and further reducing the performance gains possible for a full-automated AHS in terms of safety and congestion alleviation.

7.4.1.4. Vehicle Certification: On-the-fly Versus Static Testing

Assuming physical barriers and limited access, should vehicle certification occur on the fly before or within the cones of the entry zone?

The issue here is to what extent certification checks must be performed, and the integrated impact of the full set of check-in requirements on the design of the entry zone. If there is any significant time required to complete all checks or download configuration data, map data, etc., then the direct impact will be on the amount of space required for the queuing zone and the design of the communication system throughout the length of the entry zone. For instance, one suggested approach to lateral control is to use differential, carrier-phase tracking GPS for high-precision map following as the primary lateral control mode [Galijan:94]. if this approach is taken, then the certification process must include checking to assure the integrity and proper version of the high-resolution map. If there is a version mismatch (suppose a change was installed to account for a construction zone), then there must be time for the download of the updated map and a verification check to assure correct transfer. This is a safety-critical requirement.

The problem here is that AHS check-in takes time. The process must include all certification, configuration management communications. built-in testing (BIT), and so on,. For any one or combination of several of these functions, ways can be devised to make them happen on the fly. However, the integration and sequencing of all these functions impacts the entry zone design in terms of length and high-quality communication for the length of the entry zone. Hence, they must be well understood *before* the design of the entry zone can be completed. The advantage is the elimination of a queuing area, *assuming that there is no need to queue for an entry "hole" to come along*. If holes are infrequent events (as will be the case under high-density conditions), the need for a queuing area will not be eliminated.

The other possibility is to make entering vehicles come to a stop while all check-in functions are performed Under this approach, the design of the entry zone becomes a problem in estimating necessary queuing area and managing queue spillback. This approach has the advantage of imposing easier time constraints on the check-in process, but compounds the problems of managing congestion for vehicles trying to enter the system.

7.4.1.5. Certification in a Barrier Free Configuration

If there is no physical separation between the AHS and non-automated laneS, where does certification take place?

If there is no barrier and dedicated entry zone, such as in the Calspan 11 and I2 configurations, then there is nothing except surveillance sensors to detect the presence of non-equipped vehicles in the AHS lane. This becomes an enforcement issue not unlike that of present-day HOV lanes.

However, the more serious issue is how to accomplish the check-in process in a transition lane. Presumably there must be some coordination between the infrastructure and the vehicle. This must occur via RF link

7.4.2. Nominal AHS Exit Issues

7.4.2.1. Exit Capacity

The System must provide an effectively unlimited capacity to leave the System. Inability to exit from the AHS at the desired time due to queuing congestion is unacceptable. Permitting queue spillback onto the highway to ensure exit is equally unacceptable. In either case, the performance benefits are lost if travelers cannot leave the system at the appropriate time. Therefore, the system must be designed with enough exit capacity to prevent either exit aborts or spillback congestion from occurring.

7.4.2.2. Relinquishing Control and Operator Readiness

How does the System certify the operator is ready to assume control upon exit from the System?

The system cannot require operator control if the operator is not ready. This gives rise to the question of how the system validates operator readiness, and what to do if readiness responses are not received. The latter could indicate inattention on the part of the operator, or a more serious medical condition.

The alternative of sending the vehicle out onto the non-automated highway without assuring operator preparedness is unthinkable.

If exit is to be done under automatic control, one reliability issue is how to handle the case of communications failure in the checkout mechanism?

Assuming that the checkout involves some form of communication with the infrastructure before relinquishing control back to the operator, how should the system respond to a failure to complete the query-response sequence? Does the vehicle stay on the highway? Does it coerce user take-over, even if manual control is not normally allowed while on the AHS?

For each individual degree of freedom, it is possible to either gradually remove the computer control from the system, or to abruptly remove the computer control This may not be an option for various system implementation:::. The most desirable capability might be to gradually soften the applicable degrees of freedom, until the system has no remaining control authority. This would allow the operator to gradually reengage in the task driving the vehicle.

Systems will have to be absolutely able to sense loss of any flinction that inhibits relinquishing control to the operator.

7.4.3. Emergency AHS Exit Issues

7.4.3.1. Guaranteeing Safe Emergency Exit

How much of a safety zone is required for emergency exit situations with respect to other vehicles or objects in adjacent lanes approaching from behind?

The problems of sensing object presence and approach speed behind and toward adjacent lanes is easier than collision avoidance for forward-looking sensors. Forward sensors must contend with stationary objects and distinguish threatening from non threatening ones. However, threatening objects behind can only be other vehicles, and the sensor system can filter out any receding objects.

The problem of determining a safe zone for an emergency lane change involves both forward and rearward zones. The area into which the departing vehicle is moving must not have any vehicles approaching that it would threaten, and must assure that the path ahead is unobstructed by either stationary objects or slower-moving vehicles.

The problem of determining a safe zone ahead is compounded by potential obstruction of the sensors' field of view by vehicles ahead. Suppose for instance a failure occurs and the vehicle must perform an emergency exit. Suppose further that the vehicle is in close following mode on a gentle left turn. Because of the obstruction, it is impossible to see whether the shoulder or lane on the right is clear more than a few feet ahead. The decision to move into that area could turn a potential impact with other AHS cars at low relative velocities into a potential impact with a disabled car on the shoulder at high relative velocity.

Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Task D: Lateral-Longitudinal Control Analysis

Volume III: AHS System Concept Definition Document

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-050
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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations Research and Development

NOTICE

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List of Abbreviations and Acronyms

AHS	Automated Highway System
FUR	Forward Looking Infrared
LIDAR	Laser Imaging Detection and Ranging
LLCS	Lateral/Longitudinal Control Study
MDFRD	Maneuver Definition and Functional Requirements Document
MMWR	Millimeter Wave Radar
mps	meters per second
mph	miles per hour
PSA	Precursor Systems Analysis
RSC	Representative System Configuration
SCDD	System Concepts Definition Document
SCED	System Concept Evaluation Document
TBD	To Be Determined

AHS System Concept Definition Document

1. Introduction

1.1. Purpose of the Document

This document describes the system concepts to be evaluated under the contract cited in the forward. The evaluation is intended to compare and contrast the various concepts, ultimately leading to an identification of major risks and issues surrounding deployment of an Automated Highway System (AHS) from the standpoint of lateral and longitudinal control. The sections following describe the methodology in detail.

1.2. Analysis Approach

Figure 1 on the next page illustrates the overall process used in this study. The boxes represent tasks, and the document icons represent the products of these tasks. The numbers enclosed in the various ellipses indicate the Statement of Work task corresponding to each box.
The first task was to develop a taxonomy of maneuvers as independent of the system concepts as possible. This taxonomy provided the outline structure for capturing the functional requirements, and evaluation criteria of tasks two and three. The products of three tasks were captured in the *AHS Maneuver Defininition and Functional Requirements Document* (MDFRD).

The next task was to develop and refine our system concepts, and describe them in a clear enough way to permit meaningful evaluation and comparison of the concepts. This was done by first roughly describing each concept, and then showing how it fulfilled the functional requirements outlined in the MDFRD. The product of that effort is described in this document, the *AHS System Concept Definition Document* (SCDD).

Concurrently with the above efforts, we undertook an effort to describe all the enabling technologies in a sensor taxonomy. The result was the *Sensor Taxonomy Description Document* (STTD). It classifies all the relevant sensor types and describes the basic technology, provides an assessment of each of the enabling technologies, and in some cases projects where the technology is going and what issues surround the use of that particular technology. In it we also collected all the information we were able to in a reasonably short interval from our archives, from a brief literature review, and from various sensor vendors with whom we are in frequent contact. The purpose of the STTD is to provide a technical foundation for the evaluation portion of this effort described below. From that document we draw an assessment of the sensor attributes needed to satisfy each concept. Since sensor technology is in many cases the dominant limitation on overall approaches, this mechanism for capturing, cataloging, and sharing data on sensor technologies may be particularly useful to the anticipated AHS Consortium.

The last step was to apply the evaluation criteria defined in the MDFRD to the concepts described in the SCDD and assess the merit of each of those candidate concepts. The primary objective was to capture along the way the issues surrounding implementation of an AHS and provide a first-look assessment at the broad merits of each of the candidates. This evaluation is recorded in the *AHS System Concept Evaluation Document* (SCED).

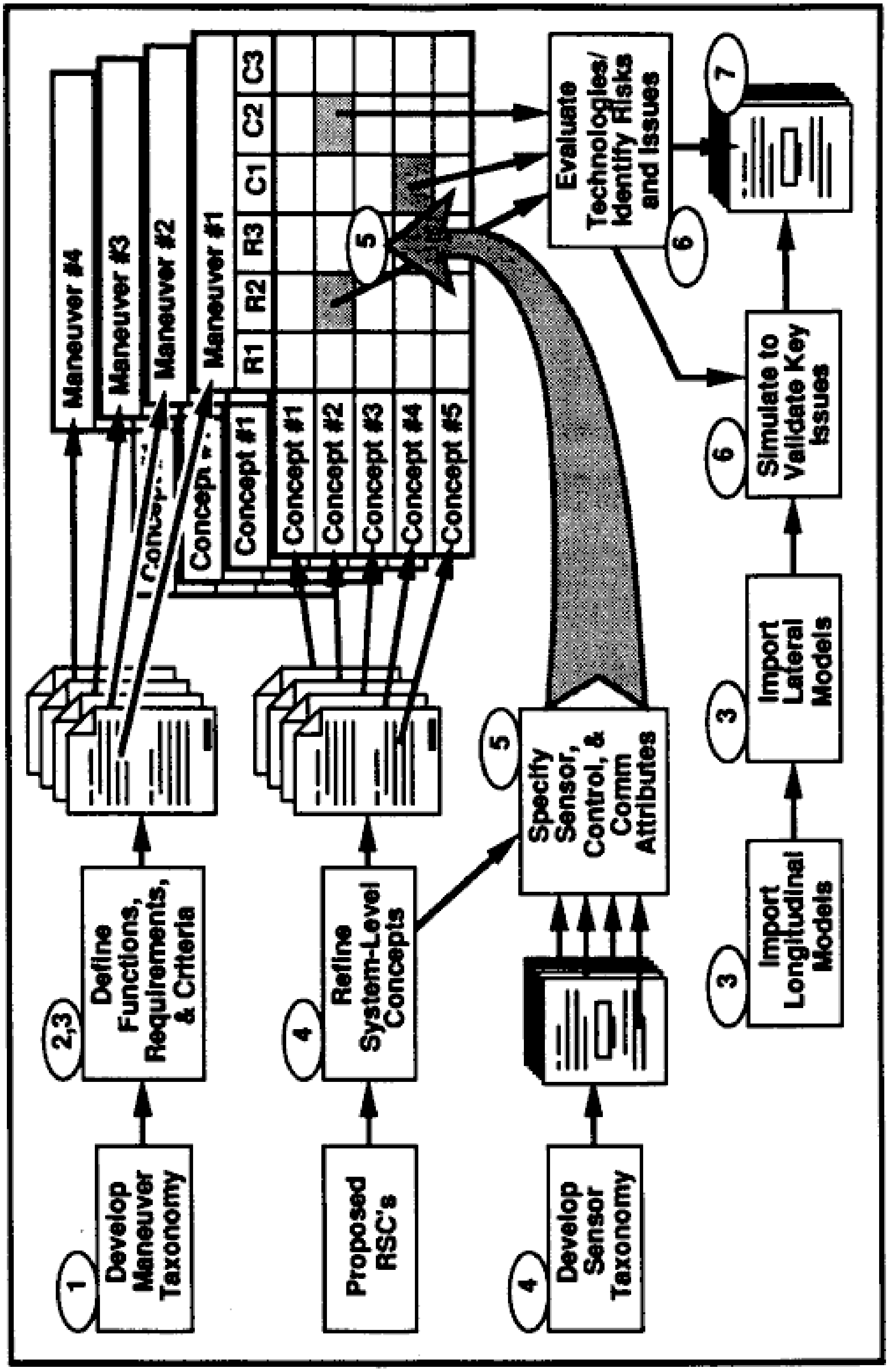


Figure 1. Lateral/Longitudinal Control Study Approach

The series of matrices in the upper right of the diagram represent the heart of this program: the evaluation of system concepts. The planes of this three-dimensional matrix are each captured as one Microsoft Excel spreadsheet Each plane corresponds to one of the maneuvers defined in the MDFRD. The rows of the matrices are the various concepts defined in the SCDD and referred to by the corresponding paragraph number in the SCDD. The individual columns are divided into requirements and evaluation criteria, referred to by paragraph number in the MDFRD. Requirements are developed in the paragraph describing each maneuver. Evaluation criteria are separately defined in section 3 of the SCED. Because of this extensive use of index references, the reader *must* understand the contents of the MDFRD and the SCDD in order to comprehend these sheets.

The method of rating concepts has two steps. The first step is to evaluate its ability to meet each requirement on a scale of (0-fails, 1=10w probability, 2=likely, 3=definitely meets requirements). This evaluation is accumulated into a "confidence rating" on that concept's ability to meet the full set of requirements. After the concept has passed the requirements gate, the second step is to evaluate it in terms of the evaluation criteria outlined in section eight of the MDFRD. The individual figures of merit are then combined using a weighted summation. The weight selection and their justifications are outlined in Section 9 that document, and the individual concepts are evaluated on an integer scale of 0 to 9,9 being the highest (best) score.

The spreadsheets provide several additional useful ways to collect and organize the results of this evaluation. Behind the spreadsheet is a set of notes detailing the factors contributing most to that evaluation datum. These notes are intended to provide the basis for qualitative summarization and identification of issues arising out of this study. The union of these issues will be discussed in our final report. In addition, the comparison sheets provide a means of developing graphical depiction’s of the evaluation.

Some concepts require quantitative analysis to provide the basis for evaluation. The simulation environment we developed provided the tools for this analysis. As areas requiring quantitative backup were identified, the various models and parameters for those models were developed. These models executed on various test scenarios to provide the needed quantitative data. A set of test cases was defined and executed to determine the maximum latency. This program did not have the time or scope of effort to simulate all aspects of all concepts, so due diligence was applied to the selection of particular conditions and concepts to be simulated.

The evaluation can only be relied upon to identify clear winners and losers in a broad sense, and to ascertain significant risks and issues associated with each. It is important to note that there are too many unknowns at this time to definitively establish both the weights and the specific evaluation numbers. There is therefore a large margin of uncertainty surrounding the resultant numerical evaluations. Instead, they are intended only to provide insight into which concepts are strongest and merit further consideration, which are weakest and may be dismissed. It is important to view the numerical results as "fuzzy indicators", not as a tool for absolute ordinal rankings.

These evaluations are by no means intended to be the last word on the subject. It is our expectation that the weights and evaluations are subject to some change as concepts are further refined or as new technologies become available. It is for precisely that reason that the spreadsheet formalism has been chosen; it provides a simple way to perform various sensitivity analyses. For instance, if the Federal Highway Administration chooses a different weighting scheme of importance factors for the evaluation criteria, or if new requirements are inserted, the comparisons could change dramatically. Various scenarios can be evaluated easily with this approach.

Due to scope limitations, our evaluation cannot be all-inclusive. There are a number of concepts being developed under the various PSA contracts which this contract will not have time to consider. When the results of all these contracts are available, it will be important to be able to compare and contest each project's results in a consistent manner. A common formalism is needed to accomplish that comparison meaningfully. As new concepts are developed, they can easily be added to the structure we have outlined. It is our hope that the Federal Highway Administration or the anticipated AHS Consortium will be able to apply this technique to a complete comparison of all the candidate concepts.

1.3. Classification of System Concepts

To help the reader distinguished the concepts clearly, we have classified each concept along three descriptive axes, depicted in Figure 2. The first axis is the complexity onboard the vehicle. High complexity can be measured in terms of capability, maintainability, technology maturity, kinds and amounts of equipment required, depth of safety and redundancy design needed, or any of a number of other parameters. Ultimately, high impact in any of these areas equates to high per-vehicle costs. The second axis is Infrastructural complexity. Like vehicle complexity, most of the describing parameters drive system cost. For both vehicle and Infrastructural impact, these costs must include both acquisition and recurring operational and maintenance costs. The third axis is communication. The information needed by either the vehicle or the infrastructure can be obtained either win communications. by inference, or by direct sensing. If there is a large requirement for communication, we believe that this will have a gross impact on the system architecture. Communication dependency is measured by a combination of low latency, high bandwidth, or both.

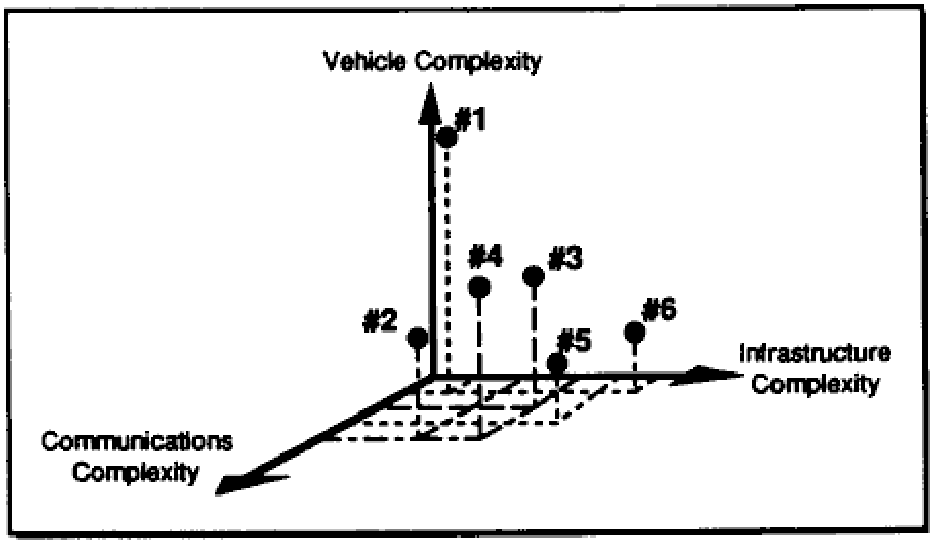


Figure 2. System Concept Classification Axes

There are a variety of other parameters we considered as possible descriptors for system concepts.

One grouping was active vs. passive controls and active vs. passive sensing. However, these tended to differentiate the concepts along implementation lines and ultimately could be cast into the representation of Figure 2. In the interests of descriptive simplicity, we ignored these dimensions. Another group of descriptors we considered includes safety, reliability, evolvability, and likelihood of user acceptance. However, we concluded that these are more properly considered evaluation criteria, not descriptors of fundamental system differences. Yet a third possibility we considered was to separate the description according to the method for achieving lateral control and the method for achieving longitudinal control. While this proposal had some arguments in its favor, it had the disadvantage of requiring the reader to mentally integrate the system concept for purposes of comparison with other concepts. The fourth dimension we considered is the amount of centralization or distribution of control. For instance, a high degree of centralized control would be the case if the infrastructure dictated all lane changes. Further consideration led us to believe that this can be mapped into vehicle, infrastructure, and communications complexity

In the end, we concluded that the simplest possible space of no more than three dimensions was needed for clarity. It became apparent that most of the evaluation criteria we defined were grossly affected by system complexity. It was equally apparent that a clear distinction could be drawn between vehicular and Infrastructural complexity. That left us with one dimension to distinguish along. It seemed reasonable that if two dimensions referred to the complexity of instrumentation and processing of the two major system segments, then the third should measure the degree of interface interaction between them. This axis is, in a sense, a measurement of the integration complexity (or conversely, the degree of modularity) in the system definition. One very useful way to measure that complexity is by the speed (latency) and volume of communications.

Figure 2 illustrates these classifications as applied to the six concepts described in this document. The first concept, being fully autonomous, has a high impact on the vehicle due to the complex sensing and processing burden, but a modest (if any) impact on infrastructure and communications. The second concept, based on an extension of the work at the PATH program, has a somewhat more significant impact on the infrastructure and considerably higher impact on communications, but a greatly reduced complexity on board the vehicle. The third concept depends on the infrastructure heavily, reducing the complexity of the vehicle segment and of communications. The placement of these concepts on the axes is intended to be a qualitative (10w, medium, high) ~ placement Without detailed designs, precise comparisons are not possible. Doubtless, some will contend with the authors' assessments, and we welcome any constructive criticism.

The reader should keep in mind that this classification scheme is driven by the perspective of sensing and control of lateral and longitudinal motion of the vehicle in a coordinated setting. This representation may not be universally useful to other precursor study areas (such as institutional barriers, alternative propulsion, or human factors). However, it provides a convenient model for distinguishing the concepts contained in this document and evaluated in the remainder of the associated effort It is solely for the purpose of distinguishing these concepts in the readers' minds in the context of this study that this depiction is provided.

1.4. Overview of System Concepts

This section provides a highly abbreviated description of each of the concepts detailed in the sections that follow. One note of caution to the reader: In evaluating concepts it will be important for the reader to pay attention to the notes attached to the individual ratings. The concepts in this document are not competing on a "level playing field." For instance, the first concept below contains obstacle avoidance as part of its overall approach, while the second concept ignores obstacle avoidance. If one only looks at the bottom line evaluation without carefully examining the supporting notes, an inappropriate conclusion could be drawn from the data

This concept places the burden for the maximum amount of AHS functionality on the vehicle. Sensing and control of lateral position, longitudinal position, presence of and range to vehicles, obstacle detection, and prevailing traffic conditions is the responsibility of the vehicle. The highway provides no support, active or passive, for any sensing functions. Speed control is completely asynchronous within limitations dictated by internally maintained knowledge-based determination of what is allowed for that particular highway segment and autonomously sensed environmental conditions.

Evaluation is based on experience out of existing research and development from the field of mobile robotics. The motivator behind this concept is to include in the evaluation a minimal Infrastructural impact model, under the presumption that the major difficulty in the initial implementation of an AHS will be the amount of Infrastructural improvement required before the first vehicle can traverse the first segment of AHS highway. The supporting belief is that to the extent that the concept requires little to no improvement to existing highways, the system startup will be completely dependent on the individual's ability and desire to pay for the required capability.

1.4.2. Magnetic Reference / Infrared Cooperating Active Targets Concept

This concept is based on an augmentation of the idea upon which research at the PATH program is based. Specifically, lateral control is achieved via a magnetic reference placed in the highway. Longitudinal control is achieved via infrared sensing with active, cooperating targets. This system provides no obstacle detection. The infrastructure is responsible for determining the desired operating parameters (speed range, platoon length, etc.) and communicating those desired operating parameters via broadcast medium. Speed and longitudinal position control is distributed and asynchronous.

1.4.3. Millimeter Wave Radar-Guided Concept

This concept is based on using millimeter wave radar as the primary sensor for information external to the vehicle. In this concept, the system senses lane position, existence and proximity of in-lane obstacles, and closure rate based on millimeter wave radar transceivers on the vehicle. It also senses proximity of other vehicles in adjacent lanes by using rearward pointing transceivers. Sensing is in the active mode with little or no assistance from other vehicles. The infrastructure (median barriers) may contain corner reflectors to augment the signal return for sensing lateral position.

In this concept, the AHS lanes are separated from the non-AHS lanes by physical barriers. The presence of barriers is assumed for two reasons. The first is that some studies by the Path program indicate that physical separation is needed to assure safe operation, since statistical studies show that a significant risk of accident is due to lane intrusion ~. Their analysis shows that, without separation barriers, the introduction of AHS technology and the concomitant increase in density would lead to approximately a doubling of accident and fatality statistics. With separation, the numbers will reduce by approximately a factor between six and twelve. The second reason is that the barriers are used for "feeling" the vehicle's position relative the lane which presumes that the barrier would be accurately placed a fixed distance from the lane center.

This concept is mostly autonomous in that lateral position and longitudinal position sensing are performed by sensors on board the vehicle. It adds the capability for sensing and avoiding obstacles not present in the concept.

1.4.4 RF-Beacon “Socialist” Concept

This concept distinguishes itself from the others in this report in that it employs a centralized control of individual vehicle behaviors. Lateral control is individually performed using triangulation of low-power, semi-directional RF beacons placed some TBD (nominally 100 meter) intervals along the highway. The beacons' energy is modulated with timing data for more accurate positioning of the vehicle. The potential exists for also providing dynamic and static highway information via this medium.

Longitudinal control is provided by controlling synchronous "time slots" within which the vehicle must remain, providing both speed and headway control which processing elements in the infrastructure regulate. One fail-operational/fail-safe processing element will control each TBD segment of highway (nominally 1 kilometer). These processing elements are connected to one another in daisy-chain fashion along a fiber-optic bus that is connected to a regional traffic control center.

1.4.5. Inductive Drive for Lat and FMCW Radar for Long

This concept is based on the notion of using linear inductive drive for powering the vehicle and concurrently using the ability to sense the fields generated by the linear drive for primary lateral control sensing. To provide the necessary capability for longitudinal control, we have added Frequency-Modulated Continuous Wave radar in the microwave region to detect other vehicles and obstacles in the lane of travel and adjacent lanes also. A limited field of view is presumed (nominally around i45~ from the body centerline) with a range of no less than 200 meters. Speed is assumed to be synchronous with the field rate of the linear motor, but may be reduced from that speed condition under exceptional conditions by individual vehicles' sensing and control functions.

This concept incorporates the notion of short range, low-bandwidth UHF communication among vehicles and between the vehicles and the infrastructure for limited coordination purposes. Speed control is completely asynchronous and Independently determined, though sensitive to operating limitations imposed by the infrastructure based on prevailing traffic and environmental conditions.

The purpose of incorporating this concept is that it has been under consideration in other areas for a number of years and has recently surfaced as an AHS candidate. It represents one of the more extreme cases from an Infrastructural cost and complexity standpoint and we felt that it merited serious consideration vis-a-vis some of the more popular ideas that are currently extant in the community.

1.4.6. Direct Pickup, Shared Transit

This concept is for direct-drive electric motors on each vehicle operating on a dedicated set of infrastructure. Private and commercial vehicles and share the same infrastructure with public transit vehicle. Private and commercial vehicles are assumed to be hybrid vehicles capable of operating on normal highways using internal combustion power, and then transitioning onto the AHS by coupling into a direct pickup electrical power source. Longitudinal control is performed by mechanical means through the power pickup mechanism. Longitudinal control is performed by operating at set speeds on the highway, with internally-maintained radar for headway sensing. In formation on current highway conditions and operating modes and states is obtained from the infrastructure via low-bandwidth RF broadcast Speed management would autonomous and distributed within infrastructure determined parameters.

This section lists the assumptions we have employed throughout the course of this study. These assumptions were required, for the most part, as a way of bounding the problem space under consideration.

1.5.1. Urban highway operation is the starting point

For our considerations, we have heavily weighed the costs and benefits of each concept while operating under urban freeway conditions. This is not to belittle the importance of rural IVHS scenarios, commercial vehicle operations, or other operating domains. However, we believe that the urban freeway setting will be the first application of AHS technology because it is the place where the maximum benefit can be realized in the short term. The goals of reducing congestion effects, improving overall fuel economy, reducing emissions, and improving safety are all most affected where the density is the highest.

1.5.2. Vehicles always merge with platoons from the rear

Our initial analysis for platooning maneuvers, coupled with our assumption that the system design had to be evaluated in the context of dense traffic conditions (where the anticipated benefits will be most needed. In dense traffic conditions, any slowing maneuvers intended to create space will likely cause a compression wave of slowing upstream from the point of the maneuver. Coupled with this are the problems of the fairly precise control required for an accelerating vehicle to maneuver into the smallest possible opening (minimized to keep the compression effect down). Finally, the coordination of vehicle behaviors is much more complicated for mid-platoon merges with relatively little benefit compared to merges onto the tail. Rather, it seemed less dangerous, less complex, and more effective to simply require all vehicles to merge into the spaces between platoons and then enter platoons from the rear.

This argument does not preclude the need to demerge from the middle of a given platoon. Vehicles need to be able to exit when their time comes. The coordination behaviors required and the spacing required for safety are much less for exiting vehicles than for entering vehicles. Obviously, this assumption is moot for concepts precluding platooning.

1.5.3 Platooning is a required capability, not a parameter of RSC definition

For the purposes of this study, we have elected to consider platooning as a functional requirement (one of the defined maneuvers), rather than to use it as a way of distinguishing among concepts. In attempting to define a preliminary set of requirements, it seemed to us that platooning was not so much a concept as a capability which any of a number of concepts might be able to implement. However, we acknowledge that this assumption is from the limited perspective of lateral-longitudinal control, and that other study areas (such as legal issues) might approach it from the standpoint of concept viability and therefore it would become a concept in its own right.

This is not to suggest that either position is correct or even advisable. Rather, we merely state that it is an operative assumption for the scope of this study only.

2. Concept #1: Autonomous Vision-Guided System

2.1. Summary Description

This concept is based on a fully-autonomous vehicle using visible light cameras as the primary input source for information about the environment outside the vehicle (roadway other vehicles, environmental variables, etc.). Own-vehicle state information is determined by other dedicated on-board sensors, such as a transmission-mounted tachometer for determining current speed or a GPS for determining earth-relative position.

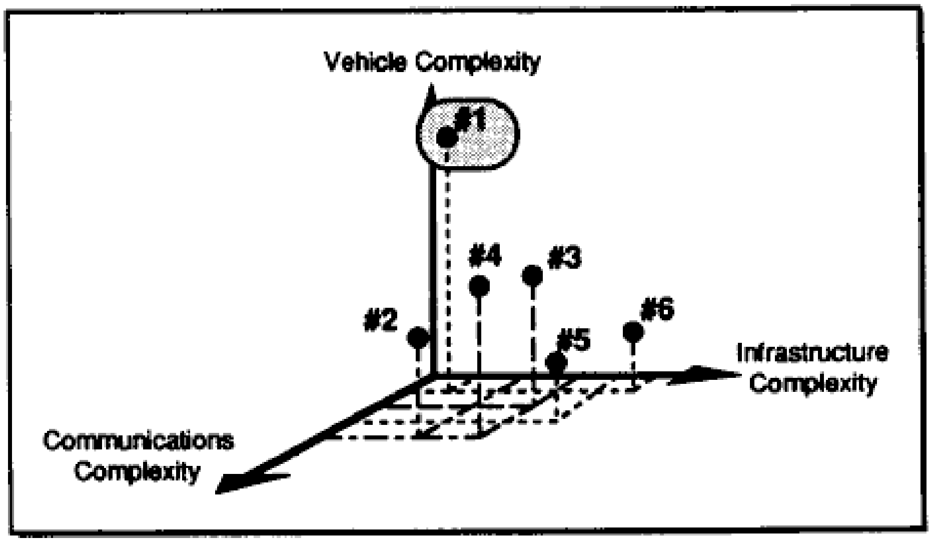


Figure 3. Classification of Concept #1

This concept is *completely* autonomous in that it requires nothing of the infrastructure to assure its viability. We have postulated this system concept as a vehicle-intensive benchmark to permit assessment of the applicability of current robotics research and to establish one of the extreme in our evaluation space. The reader should note that the current evaluation is not concerned with assuring from the outset that the concept is completely viable within any specified time frame. Rather, this concept is one which has been experimented with and we believe it instructive to evaluate it within the disciplined structure we have defined for this effort.

Another attribute of this concept is that it is completely distributed in control. There is no central authority telling vehicle when to enter or exit, when to change lanes, what speed to operate at, or even whether there is any situation ahead warranting mode changes. All that the vehicle or operator knows is based on sensed information. While it is possible to develop a hybrid concept merging informational updates from the infrastructure with the autonomous, vision-guided control, we have deliberately avoided inserting that form of communication into this concept to provide a benchmark on the importance (or lack thereof) of externally provided information and/or control on performance.

This concept is appealing in that it requires no Infrastructural improvement, and therefore a road map for phased implementation is readily apparent along two dimensions: the technology approach for gradual inclusion for new functionality can be projected, and the gradual introduction of new capabilities into the national fleet of vehicles does not have to wait for improvements to be approved by the taxpaying public and executed by regional transportation authorities; whatever the buyer can afford drives the level of implementation. Philosophically, this approach is not too distant a cousin from the path the domestic auto makers are currently following in that near-term implementations involve some form of completely autonomous intelligent cruise control, followed by layering added capability as market forces permit. The major difference is the type of sensor (cameras) and the control implementation (feature tracking in an image processing paradigm).

2.1.1. Summary of Approach for Lateral Control

Steering control is based on processing camera inputs to extract salient features which are tracked as the vehicle moves. As the important features move laterally in the field of view, steering commands are generated based on the known dynamics of the vehicle and the current speed.

In closely-spaced vehicle following mode, the image processing system uses lateral position of the vehicle in front to command steering. In this mode, we presume that there will be no knowledge of the location of the lane center, since the vehicle in front obstructs the field of view.

Special Note: There are several current experimental systems employing this approach at present. One is the Carnegie-Mellon University NavIsab, which uses neural nets processing color imagery to perform lateral control. Another is the work or Dr. Ernst Dickmanns at the *HochschLde der B£u~swehr* in Munich, Germany. His method is based on a more classically controls-orientated processing of heuristically-defined image features extracted by dedicated algorithms and processed into controls commands based
on. A third set of ongoing research is being performed at the National Institute of Standards and Technology. This concept description does not distinguish between any of these approaches, nor does it presume a specific implementation. Rather, we have deliberately broadened the scope of the definition to include all vision-guided autonomous approaches for the sake of a more general evaluation.

2.1.2. Summary of Approach for Longitudinal Control

Speed control in its various forms is also managed based on current speed and visual inputs. If there are no obstacles detected in the field of view is based on regulating current speed. If there is a visually-detectable change in the vertical profile of the roadway, then speed is adjusted accordingly to optimize energy consumption.

Objects and obstacles are recognized by a combination of feature recognition and stereo ranging techniques. In the presence of moving obstacles on the roadway, the vehicle's speed is adjusted to match as appropriate. Relative speed and acceleration is sensed by image processing techniques as well, based on rate of change in relative size of the detected moving object. Static objects are also detected visually. This presumes that the cameras have sufficient resolution to discriminate objects from, say, color texture, and can detect any object large enough to damage the automobile or cause an accident sufficiently far in advance to safely execute corrective or evasive action.

Closely-spaced vehicle following is also accomplished using visual input. The image processing system uses passive stereo range data to determine relative spacing and velocity.

2.1.3 Summary of Approach for Coordinating Behaviors

Inter-vehicle interactions will be based on individual reactions to the vehicle in front, according to well-defined (currently TBD) protocols. No knowledge if the vehicle(s) behind is presumed, but the protocols will be set up based on performance limitations of the least capable vehicle in the system defined by safety limitation.

No communication of state or intent is presumed from one vehicle to another. Activities such as entry and exit or platoon merge/demerge are performed based on forward-looking sensor information and established protocols. Each vehicle is responsible for executing unobtrusive action in a safe and predictable manner.

For instance, merging onto a platoon is presumed to always occur by the entering vehicle attaching at the platoon rear. The new vehicle must perform all clearance checks and is responsible for controlling its speed and lane changes in a manner that does not interrupt traffic flow or cause other vehicles to have to take emergency evasive action.

2.2. Distinguishing Characteristics

2.2.1. Allocation of Sensing Functions

2.2.1.1. On the Vehicle

All required state information is observed via on-board sensing. State information for elements of the environment and other vehicles or static objects is determined by image processing techniques. Own vehicle state is determined by dedicated sensors. While one could postulate use of image processing techniques such as image flow to determine speed, this concept ignores such possibilities as overkill.

The primary image sensing is a pair of video cameras rated down to at least TBD (nominally *0.5)* lux. The camera pair are calibrated to converge at infinity and optics are matched to allow stereo image processing.

Vehicle earth-relative position is determined using GPS combined with dead reckoning using tachometry and fluxgate magnetometers to sense vehicle heading. Vehicle roll and pitch are not sensed.

2.2.1.2. In the Infrastructure

This concept requires no sensing in the infrastructure, nor does it require any special fixtures to be added to the infrastructure. It does assume the presence of high definition in the roadway striping, suggesting more frequent maintenance (painting) of the roadway.

2.2.2. Allocation of Control Functions

2.2.2.1. On the Vehicle

All control functions are performed by on-board vehicle resources. There is no assumption of human control or intervention unless stated below under the various exceptional maneuvers. Standard actuation is presumed; we anticipate no extraordinary requirements under this concept.

No control is exerted by the infrastructure; this is equivalent to saying that required coordination control is performed in a distributed fashion among the vehicles on the highway according to a pre-specified set of protocol.

For evaluation purposes, this concept presumes free access to the AHS lanes at any point along the roadway. The AHS lanes are not restricted by barriers or s-fled entry/exit points. Speeds on the AHS lane are not significantly faster than adjoining non-AHS lanes (within 30 kph). This proviso arise from the inherent attributes of the vision-based concept Rather, we presume as a way of minimizing the Infrastructural implications of the concept

2.2.3. Allocation of Processing Functions

2.2.3.1. On the Vehicle

All sensor data processing and control processing is performed on-board the vehicle. This system implies the existence of image capture at video frame rate of the full resolution of which the cameras are capable. It also implies sufficient processing power to perform all required image processing functions within one video frame interval. While required throughput is difficult to assess without a detailed design, we speculate that this design would require at least 50 MIPS of processing power.

2.2.3.2. In the Infrastructure

No processing is allocated to the infrastructure. All vehicle interactions are managed by programmed behaviors on-board each vehicle according to pre-assigned protocols. Since non-differential GPS is assumed on the vehicle, there is no presumption of static receivers. Vehicle flow rate and density may be sensed by the infrastructure, but that information is not communicated to the vehicles.

2.2.4. Allocation of Communications Functions

2.2.4.1. Vehicle to Vehicle

None. This concept specifically excludes intervehicular communications as a means of deriving data for control purposes. There are some issues arising out of noncommunicative control we hope to force by this somewhat arbitrary definition.

2.2.4.2. Vehicle to Infrastructure

None. This concept specifically excludes vehicle/infrastructure communications as a means of deriving data for control purpose. The concept does not exclude communications for traveler information purposes.)

2.3. Maneuver Requirements Satisfaction

2.3.1. Lane Tracking

This function is performed by recognizing salient features in the visual scene in front of the vehicle. It presumes that lane markings are clearly discernible and well-maintained, but requires no extraordinary material (such as radar-reflective paint).

Speed control in an unobstructed environment is performed using existing cruise control technology, except that the commanded speed is variable depending on the curvature of the road ahead. This concept presumes an image processing system capable enough to determine the apparent lateral movement of lane makings sufficiently far ahead to modulate commanded speed without excessive braking or acceleration.

2.3.3. Spacing Regulation

When other vehicles are in the lane of travel, the system detects their presence and determines range based on stereo inputs. Using range rate data derived from the passive stereo ranging, the speed is regulated to maintain the desired separation.

2.3.4.. Lane Change (Nominal)

Nominal lane change is performed manually. if the operator initiates a lane change with a gradual input that could be misconstrued by following vehicles as a normal lane curvature, the system will respond by vibrating the steering column and resisting the lane change.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance.

2.3.5. Lane Change (Exceptional)

Exceptional lane change is performed manually. We assume that the an exceptional lane change is defined by an abrupt change of lane. The operator is responsible for determining safe clearance. if a sudden torque is applied to the steering column, the system assumes an override exception and releases control to the operator. The need to have the operator initiate such a maneuver is determined by the operator or by TBD process within the system that notifies the operator through a TBD annunciator.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance.

2.3.6. Vehicle Following (Nominal)

Close-interval platooning is performed by using passive stereo range detection as a feedback signal for speed regulation. The two-dimensional stereo processing is based on video camera input. A full-field range image is developed by the stereo that is segmented and used for determining following range as well as obstacle detection.

2.3.7. Vehicle Following (Exceptional)

When in close following and the vehicle in front exits the lane, there is no way for this system to be aware of that condition.

2.3.8. Emergency In-Lane Stop

The system shall detect stationary obstacles using image processing techniques on the range data derived from stereo image correlation. Minimum detectable obstacle size is TBD (4 inches) in vertical extent (either height for above-grade obstacles or below-grade for holes). Obstacle detection algorithms shall be capable of operating at distances sufficient to stop the vehicle before collision.

Emergency stopping involving lane change cannot be accomplished automatically under this concept since there is no information on lane clearance available to the system. Under emergency stopping situations, the system will be constructed to permit the operator to usurp control and manually execute a lane change. However, this mode of operation is highly suspect since we presume that the operator situation awareness is limited by inattention while the system is operating under autonomous control in most cases.

2.3.10. Platoon Merge

Detection of the presence of a vehicle suitable for following is performed using a combination of image processing for vehicle recognition and stereo range detection for range and range rate determination. When a platoon situation arises, an indicator on the operator's display indicates such and awaits a ratification signal from the operator. Conditions for acquiring a platoon are detection of a vehicle at a speed differential of is kph and an initial spacing of 5 to 200 meters. The purpose of the minimum separation is to assure proper safety and spacing to allow for speed and spacing transients.

Platoon acquisition from another lane is not allowed, since this concept does not provide for safe lane changes under autonomous control. The operator is responsible for setting up the proper merging conditions.

2.3.11. Platoon Departure (Nominal)

Departure from the platoon under nominal conditions is an operator-initiated event. The operator signals the system of his intent and the system initiates a mild deceleration sufficiently large to cause following vehicles (if any) to disengage, after which the operator is expected to perform a lane change at the earliest opportunity.

Vehicles following are expected to detect this threshold deceleration (0.1 g nominally) and disengage from the platoon, fall back to a safe following distance, and await a maneuver by the vehicle in front to depart the lane. if the vehicle in front does not depart the lane after (TBD -20 seconds) and platoon merge conditions still exist, the system will automatically attempt the merger.

This concept presumes no communication between vehicles in this mode; the deceleration protocol is the signal of the departure event.

2.3.12. Platoon Departure (Exceptional)

Platoon departure under exceptional conditions is assumed to occur under one of two circumstances:

1) the platoon leader detects an obstacle and initiates evasive or corrective action

2) a platoon follower detects sudden deceleration of the vehicle in front of it

In either case, the vehicle detects the condition visually and decelerates as abruptly as possible without unduly endangering potentially following vehicles. Detection is done autonomously; no communications among vehicles is implied in this concept.

Entry into the AHS system occurs under manual control. Once in the system, mode changes within the AHS context are accomplished by a combination of sensed conditions and operator interaction, as described elsewhere in this section.

2.3.14. AHS Exit (Nominal)

Exit from the AHS occurs under manual control. There are no special provisions in the system for automatically sensing safe conditions.

This concept presumes that the vehicle is not in platooning mode during the exit. In order to exit while platooning, a nominal platoon demerge must first be safely executed, then the operator may initiate an AHS exit. If the operator attempts a gradual lane depart while platooning, the system will signal the situation by vibrating the steering column.

Departure under emergency conditions is as described in section 2.3.5. above.

2.3.15. AHS Entry Abort

Entry abort is assumed to happen under one of the following conditions:

1) equipment failure during the entry process
2) occurrence of an incident during the entry process
3) presence of other obstructing entities in the vicinity during entry.

Since entry into the system is under manual control, abort is also presumed to occur under manual control, entry abort is a manual process, though if the conditions for an abort arise, the operator must be advised though visual and aural cues to *guarantee* operator awareness even if his attention is elsewhere (such as back over his shoulder where approaching vehicles are).

2.4. Required or Supporting Assumptions

Roadway markings are well-maintained and easily detectable.

- For nighttime operations, the cameras are sensitive enough to distinguish makings based on lighting from the vehicle's headlights.

- A mechanism for keeping the camera optics free of accumulated water, dust, mud, or other lens obscurants is also presumed.

- The roadway is within line of sight for at least TBD meters at all times. This constraint is satisfied via road curvature limits, vehicle speed limits for curves (wherever different from nominal speed limits), and road grades.

2.5. Concept-related Issues

2.5.1. Image Processing Robustness

State of the art image processing techniques are not very robust with respect to environmental effects such as rain, snow, nighttime lighting, changes in pavement coloration, etc. Considerable research and development may be needed to assure adequate safety.

There is considerable work underway nationally and internationally on vision-guided driving based on various image processing techniques. In many cases, work has transitioned from the laboratory environment to actual outdoor conditions. However, the testing tends to emphasize daylight conditions, and in no case that we know of has the testing involved adverse environmental conditions. This is not to criticize the on-going work, but rather highlights the early developmental nature of these technologies.

2.5.2. Dirty lenses and lens coverings

Image-based sensing is subject to degradation when lenses or windows covering the optics become dirty, coated, or speckled with water droplets.

This is primarily an engineering issue in terms of how to prevent degradation of the image under adverse conditions. But testing to date with vision-guided approaches has not dealt in depth with robustness with respect to degraded images from these effects, so the impact on system performance is unmeasured at this time.

2.5.3. Obscuration in platooning modes

The problems of operating in close following conditions include the possibility of the vehicle in front obscuring critical sensing modes, depending on sensor configuration. However, even with optimal placement, it is not likely that the automated system can match the performance of human operators capable of looking through the windows of the car in front to see what is happening beyond.

When in close following mode, the vehicle immediately in front will dominate the field of view of most sensors, depending on configuration and placement. While this effect will not impact the ability to perform following, it does reduce the "situation awareness" of the sensor system in that the ability to perceive obstructions on the highway and presence of other vehicles in front and in neighboring lanes is dramatically reduced. For instance, in a situation where the highway gradually bends to the right, the ability to sense other vehicles in the adjacent lane on the left is reduced, even if sensors are mounted on the side of the vehicle and looking forward, because the vehicle immediately in front will obstruct the view. This, in turn, will impede the safety of lane change maneuvers.

One suggested forward-looking sensor placement for the best field of view is at the top center of the windshield. However, this configuration will not mitigate the problem. By contrast, human drivers frequently can detect a variety of cues (deceleration, brake lights, unexpected motion) by looking through the windows of the vehicle in front to the developing situation beyond. However, present and near-future sensory systems and algorithms will not be able to match that level of performance.

2.5.4. Sensor performance, safety, and the "lemming effect"

It may be mandatory for vehicles to be able to distinguish between intentional emergency lane-change maneuvers and system failures of the vehicle in front.

This concept's information stream is purely sensor-based. Because there is no way to determine the system health of the vehicle in front from sensory input, it is impossible to tell if a sudden lane change maneuver is due to a system malfunction or an intentional emergency maneuver to avoid a stationary obstacle. In the former case, the following vehicle should not be permitted to follow a failed system into potentially dangerous conditions. We refer to this as the "lemming effect," wherein one failure leads to another because of blind following.

On the other hand, it is highly desirable (if not mandatory) that vehicle following be continued even under emergency conditions. The reason is that the very act of performing close-order following restricts the following vehicles' field of view and therefore makes it impossible under any condition to autonomously detect an obstacle until the leading vehicle is out of the way. If the obstacle is detected at lower limit of sensor performance, there is provably too little time to detect and respond, and collision is then inevitable. At this point, the trade becomes between risking potential side-on collision at low relative velocity in the adjacent lane (assuming no rear-quarter sensing) versus a sure direct collision at high relative velocity.

3. Concept #2: Magnetic Reference Infrared Range Detection

3.1. Summary Description

This concept builds upon the lateral control work being done at the Path program. That work centers on the use of magnetic markers buried in the pavement as a lateral position reference. To that, we have added the use of infared detection and ranging using an active cooperating target. This concept provides low-moderate Infrastructural complexity (installation of nails) coupled with low to moderate vehicle complexity (magnetometers and low-cost IR detectors) while providing the major functions of lane tracking, headway maintenance, and close vehicle following.

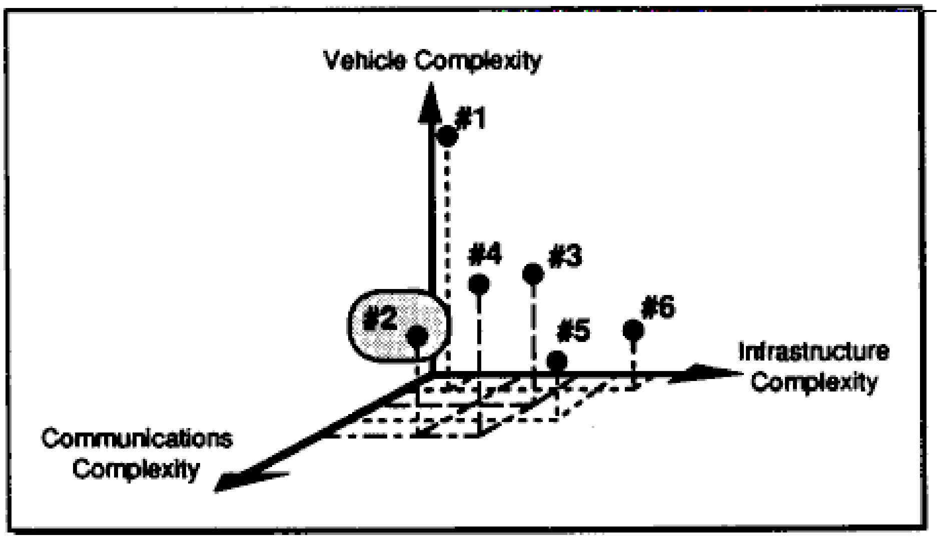


Figure 4. Classification of Concept #2

3.1.1. Summary of Approach for Lateral Control

This concept uses the approach suggested by the research at the Path program using magnetic "nails" embedded in the highway as a lateral reference. Ceramic magnets are placed in holes drilled into the pavement at a TBD interval (nominally 1 meter spacing). After they are installed they are covered with paving material to prevent their being disturbed. As the vehicle travels down the roadway, the passage of the magnets beneath the vehicle is detected by several magnetometers placed near the front of the vehicle. Lateral deviation from the centerline is determined by comparing relative field strength sensed by the magnetometers. This differential provides the feedback used by the steering control laws.

There are a number of appealing features to this approach:

- The reference is completely passive, with a life expectancy of 30 years or more before replacement is required.
- The reference does not require periodic calibration or maintenance unless the pavement is disturbed (which happens relatively infrequently)
- The reference operates equally well under night and adverse weather conditions
- Static information can be coded into the highway based on polarity of the magnetic field,

permitting the vehicle to "read" the highway's static features

- Vehicle speed can be accurately estimated if the markers are placed at defined intervals.

Longitudinal control is performance though a hybrid of current-generation cruise control and IR-based sensing of vehicles in front Speed Control when not in vehicle following mode uses current-generation cruise control technology.

Headway control is maintained by superimposing on the speed control system a delta speed command needed to maintain the desired spacing. Range estimates are based on stereo correlation of an infrared 'beacon in the center of the rear of each vehicle. A convenient location would be in the third brake light in late model automobiles. A pair of linear detector arrays is mounted on the front of each vehicle with cylindrical focusing elements to detect the azimuth to the beacon relative to the sensor centerline. Cylindrical optics makes the sensor insensitive to elevation angle, so the vertical position of the beacon is unimportant. The use of a one-dimensional detector array also simplifies the sensor data processing considerably compared to 2-D image processing, particularly stereo processing.

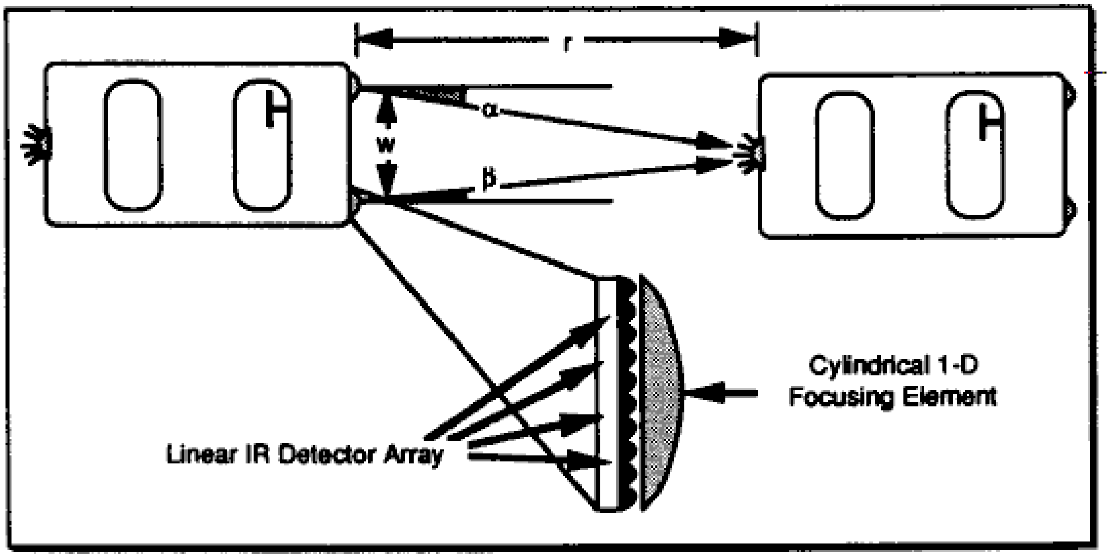


Figure 5. IR Sensor Configuration for Vehicle Following Capability

Figure 5 depicts the geometry of the infared beacon on the vehicle in front and detectors on the vehicle behind. The relationship for calculating range is:

$$r = \frac{w}{\tan \alpha + \tan \beta}$$

where w is a known, calibrated value and α and β are measured by the linear arrays. Note that both angles are defined as positive toward the center.

This configuration is based on two major assumptions:

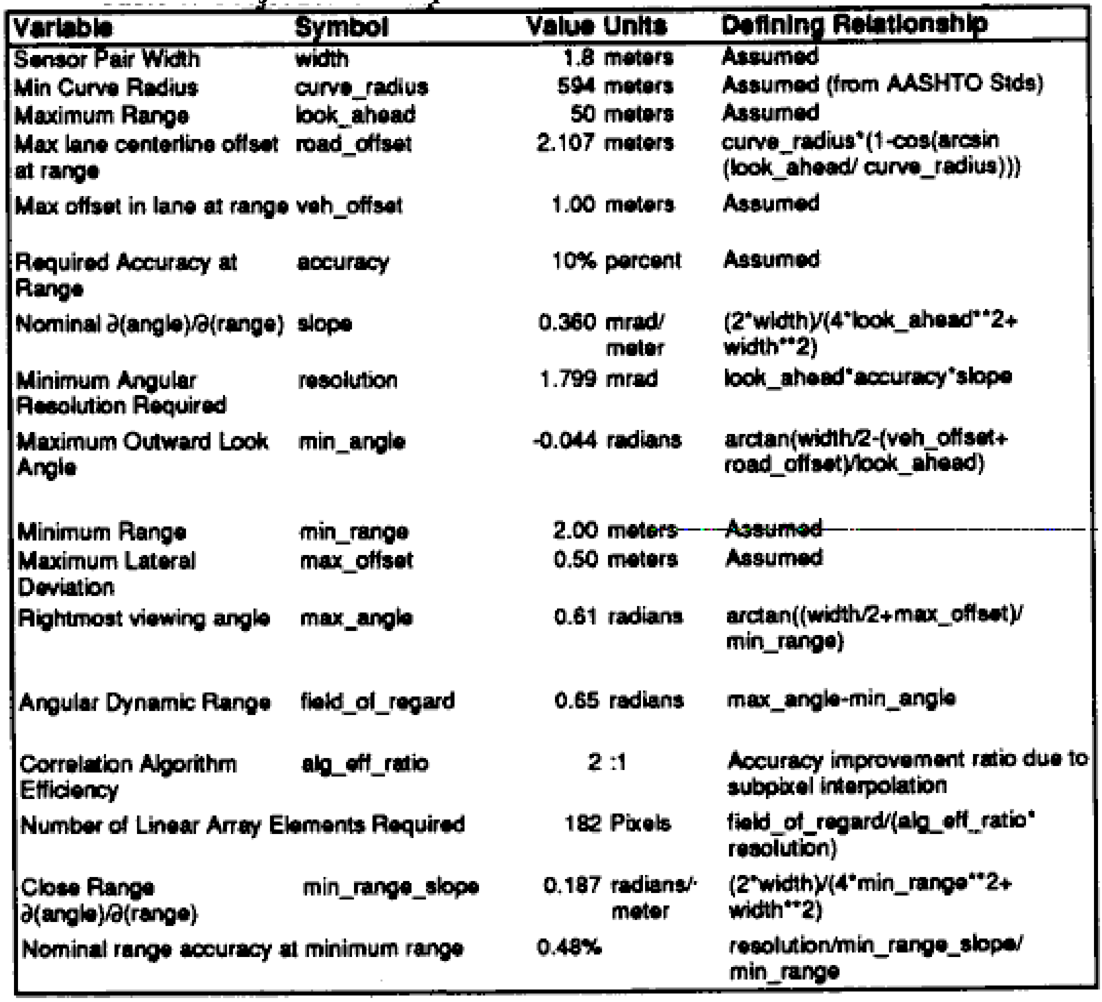
1) The vehicle in front is required to have the IR beacon lit at all times while in the AHS lanes, and that a failure will cause the vehicle to initiate an exit sequence. Since IR emitters are inexpensive, dual redundancy will likely be required for this concept.

2) A detector of sufficient resolution, sufficient sensitivity to operate at range, and having wide enough field of regard is feasible.

The latter assumption merits some discussion. We believe sensitivity is not an issue. The sensitivity required of the detector is a function of the emitted power, atmospheric attenuation, and signal/noise characteristics of the detector elements. The important point is that designing a combination of detectors and emitters that could be made to operate in the ranges in question is possible using off-the shelf components, unless the beacon is used for high-rate communication. For the purposes of this concept, we are not presuming using the beacon for communication, as it would only provide a one-way channel.

Do sensor resolution and field of regard requirements lie within the realm of feasibility? Preliminary analysis, summarized in Table 1, suggests that current generation technology will suffice. Sensor resolution is driven by two factors: 1) what angular resolution is required to provide range discrimination of a specified level at the maximum range the sensors is required to operate at, and 2) what field of regard is required to support the near-range operating constraints. These two factors combine to form the requirement for the number of detector elements in the array and the type of optics required.

Table 1. Projection of required Stereo Sensor Resolution and Accuracv



Variable	Symbol	Value	Units	Defining Relationship
Sensor Pair Width	width	1.8	meters	Assumed
Min Curve Radius	curve_radius	594	meters	Assumed (from AASHTO Stds)
Maximum Range	look_ahead	50	meters	Assumed
Max lane centerline offset at range	road_offset	2.107	meters	curve_radius*(1-cos(arcsin (look_ahead/ curve_radius)))
Max offset in lane at range	veh_offset	1.00	meters	Assumed
Required Accuracy at Range	accuracy	10%	percent	Assumed
Nominal ∂(angle)/∂(range)	slope	0.360	mrad/ meter	(2*width)/(4*look_ahead**2+ width**2)
Minimum Angular Resolution Required	resolution	1.799	mrad	look_ahead*accuracy*slope
Maximum Outward Look Angle	min_angle	-0.044	radians	arctan(width/2-(veh_offset+ road_offset)/look_ahead)
Minimum Range	min_range	2.00	meters	Assumed
Maximum Lateral Deviation	max_offset	0.50	meters	Assumed
Rightmost viewing angle	max_angle	0.61	radians	arctan((width/2+max_offset)/ min_range)
Angular Dynamic Range	field_of_regard	0.65	radians	max_angle-min_angle
Correlation Algorithm Efficiency	alg_eff_ratio	2	:1	Accuracy improvement ratio due to subpixel interpolation
Number of Linear Array Elements Required		182	Pixels	field_of_regard/(alg_eff_ratio* resolution)
Close Range ∂(angle)/∂(range)	min_range_slope	0.187	radians/ meter	(2*width)/(4*min_range**2+ width**2)
Nominal range accuracy at minimum range		0.48%		resolution/min_range_slope/ min_range

Using some nominal design parameters, we have determined the approximate configuration required in the table above. The items for which the defining relationship is "assumed" are those that are subject to design specifics and subject to variation. The values selected for these items were deemed to be reasonable ones to provide a "ballpark estimate" of the required resolution and near-field range accuracy. For instance, we have assumed the detector separation to be 1.8 meters based on a typical automobile's front end configuration and likely placement points. The minimum roadway curvature radius is borrowed from AASHTO highway design standards for 65-70 mph roads.

There are two conclusions that one may draw from Table 1. The first is that the number of pixels or detector elements in the linear array is well within current detector manufacturing capability. Manufacturers are currently producing 51 2x5 12 focal plane arrays in the IR domain. A linear array of 200 pixels will be relatively inexpensive to manufacture. The second conclusion is that the sensor's range accuracy is more than adequate for close range vehicle following. if the vehicle spacing is two meters, the range resolution accuracy is 0.0096 meters. We believe this to be well below the accuracy required to achieve good, stable tracking performance (insofar as the sensor is the determining factor -- there are other effects, such as drive train performance, that have a significant impact).

Several lines in the chart require some explanation. One is the "Correlation Algorithm Efficiency" line. Current work in stereo correlation has shown that using sub-pixel interpolation, it is possible to improve upon the angular resolution of the sensor. The effect of these algorithms is to reduce by a factor of two to three times the number of pixels required to achieve a given degree of range resolution compared to non-interpolated correlation techniques. We have incorporated a conservative guess of the resolution reduction as a factor. Also, the maximum operating range parameter is the maximum range at which initial headway maintenance will begin. This is not the detection range; we assume that detection of a vehicle ahead will occur at longer ranges that is possible for accurate range determination using stereo correlation. Finally, the relationship for the derivative 5a/& is derived in Appendix A.

3.1.3. Summary of Approach for Coordinating Behaviors

In this concept, there is relatively little coordination between the vehicles. A low-power, low bandwidth RF communications system would be used for coordinating vehicle behaviors in close-following mode, such as performing request" acknowledge sequences for platooning activities. Vehicle and/or platoon state information is transmitted from one vehicle to the next over a low-power, low-beamwidth, line-of-sight link to prevent communication among non-adjacent vehicles. Platoon lead vehicles are expected to derive behavior-limiting information (such as maximum permissible platoon length and operating speed for the next segment) from Infrastructural transmitters placed roughly one kilometer apart. The infrastructure would derive the needed traffic flow information on which to base operating limits from currently available sensor and processing technology.

For instance, merging into a platoon is presumed to always occur by the entering vehicle attaching at the platoon rear under this concept. The new vehicle must perform all clearance checks and is responsible for controlling its speed and lane changes in a manner that does not interrupt traffic flow or cause other vehicles to have to take emergency evasive action. However, this concept distinguishes itself from the first concept in that a vehicle may not merge into a platoon without first requesting clearance from the vehicle at the tail of the platoon it wishes to join and receiving acknowledgment. This coordination provides the ability to limit platoon length.

3.2 Distinguishing Characteristics

3.2.1. Allocation of Sensing Functions

3.2.1.1. On the Vehicle

Lateral position sensing is achieved by magnetometers placed at several calibration points near the front of the automobile.

Speed is sensed though odometry coupled with pulse rate sensing from the magneto-meters as a backup.

Presence detection of preceding vehicles is by a combination of IR detector arrays on the trailing vehicle and an IR transmitter beacon on the vehicle in front. This beacon will be modulated at low frequency using a random pattern to discriminate among vehicles' transmitters. Two detectors will be employed for purposes of stereo ranging, providing built-in detection redundancy (since only one detector is needed to sense presence, while two are required for ranging).

Range sensing is performed by performing stereo correlation on the angular position of the two detectors' view of the beacon on the vehicle ahead.

3.2.1.2. In the Infrastructure

The infrastructure is assumed to contain sensing of traffic density and average speed via common lane sensing mechanisms (such as loop detectors).

3.2.2. Allocation of Control Functions

3.2.2.1. On the Vehicle

All motion control is performed on board the vehicle. 'Lane tracking, speed control, headway maintenance is autonomously performed using the sensed and communicated information described in §3.2.1 and §3.2.3 respectively.

Lane changes are not required to be performed automatically. However, automatic control is possible in this concept.

3.2.2.2. In the Infrastructure

In this concept, there is no control of vehicle behaviors on the part of the infrastructure.

3.2.3. Allocation of Processing Functions

3.2.3.1. *On* the Vehicle

All sensor data processing, control processing, and behavior determination is performed on the vehicle. The level of complexity of the detection functions is moderate, and we expect that this concept will require approximately 20 MIPS of processing throughput for all functions.

3.2.3.2. In the Infrastructure Processing in the infrastructure is limited to the following:

- estimating the impact of traffic conditions sensed on downstream highway segments on a given segment's

- determining the desired operating parameters appropriate for the current segment (nominal speed, speed upper and lower bounds, max. platoon length, etc.) an providing that guidance to the vehicles as the progress down the highway.

This processing may be done in a distributed fashion or in a centralized fashion; this concept is not sensitive to that distinction. Very modest throughput is expected to be required of each segment, and the volume of communication required of a centralized processing scheme is also quite low.

3.2.4. Allocation of Communications Functions

3.2.4.1. Vehicle to Vehicle

Communications for vehicle--vehicle coordination is needed primarily for platoon merge/demerge functions and for relatively small amounts of state information on a continuous basis (such as acceleration/deceleration state to eliminate sensing latency). Vehicle to vehicle communications can be accomplished using low-power, low-bandwidth (estimated to be 10 *KB/s* or less) ornnidirectional broadcast communications such as UHF FM radios. Power levels will be kept low (≤5w) to limit range and the amount of crosswalk among vehicles.

3.2.4.2. Vehicle to Infrastructure

Vehicle to infrastructure communications is performed via low-power RF signals in the TBD band. Transceivers are placed on the infrastructure at TBD intervals (nominally 1 km). Vehicles receive broadcast information of prevailing highway conditions, and two-way communication is only with platoon leads. Individual vehicles not in platoons are considered to be "platoon leads" in this sense.

3.3. Maneuver Requirements Satisfaction

3.3.1. Lane Tracking

This function is performed by sensing the lateral movement of the magnetic field set up by the buried lane markers relative to the vehicle centerline. Where smooth control of the vehicle requires some anticipation of curvature, information on upcoming highway geometry or other operating parameters are encoded into the orientation of the sequence of magnetic markers.

3.3.2. Speed Maintenance Tracking

Speed control in an unobstructed environment is performed using existing cruise control technology, except that the commanded speed is variable depending on the curvature of the road ahead. This concept presumes that highway-dependent static operating parameters (such as maximum speed for curves where it is below the highway's speed limit) are encoded in the orientation of the sequence of magnetic references.

3.3.3 Spacing Regulation

When there are other vehicles in the lane of travel or adjacent lanes, the on-board system detects their presence and determines range based on stereo correlation of the beacon on vehicles in front. Using one-dimensional stereo correlation, range and range rate relative to the vehicle ahead is used to calculate a speed reference that is superimposed on the normal speed controller.

3.3.4. Lane Change (Nominal)

Nominal lane change is performed manually. if the operator initiates a lane change with an unsignalled gradual input that could be misconstrued by following vehicles as a normal lane curvature, the system will respond by vibrating the steering column and resisting the lane change.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance. This capability is not precluded by the concept.

3.3.5. Lane Change (Exceptional)

Exceptional lane change, defined by an abrupt change of lane, *is* performed manually. The operator is responsible for determining safe clearance. *if* a sudden torque is applied to the steering column, the system assumes an override exception and releases control to the operator.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance.

3.3.6. Vehicle Following (Nominal)

Close-interval platooning is performed by using passive stereo range detection with an active cooperating infrared (IR) target. Range and range rate are used as a feedback signal for speed regulation. The one-dimensional stereo processing is based on input from a linear array of IR detectors. A scalar range value is developed at high update rates (~O Hz) that can be differentiated to determine range rate as well.

The low-bandwidth RF vehicle to vehicle link provides a minimal amount of state data to provide some anticipatory information and reduce latency as compared to a sensor-based approach. Specifically, the vehicle in front provides a health-check heartbeat, velocity, acceleration, and steering updates. These data are used as part of the feedback set used by the controller.

3.3.7. Vehicle Following (Exceptional)

The low-bandwidth RF link provides the needed link to be able to distinguish between failure and intentional emergency lane change. In the latter case, the following vehicle continues to track the beacon of the vehicle in front. In the former case, the vehicle behind begins slowing to create additional headway for safety, until the leading (failed) vehicle has cleared the lane of travel.

This maneuver would be excited by an excessive closure rate detected by the lead vehicle. This concept, however, does not provide the capability for detecting and avoiding generic obstacles (objects not having visible IR emitters) cannot be accomplished without detection sensors.

Stopped vehicle detection requiring emergency response is performed using processing range data from the stereo inputs. This maneuver would be excited by an excessive closure rate detected by the lead vehicle (or single vehicle in the non-platooned case) in situations where adjacent lanes are determined to be occupied. This concept, however, does not provide the capability for detecting and avoiding generic obstacles (objects not having visible IR emitters).

3.3.9. Emergency Out-of-Lane Stop

Emergency stopping involving lane change cannot be accomplished automatically under this concept since there is no information on lane clearance available to the system. Under emergency stopping situations, the system will be constructed to permit the operator to usurp control and manually execute a lane change. However, this mode of operation is highly suspect since we presume that the operator situation awareness is limited by inattention while the system is operating under autonomous control in most cases.

The reader might question why emergency lane change is permitted while emergency lane stop is not. The answer is that an emergency lane change may create a serious situation if there are vehicles in the adjacent lane, but will not result in large disparities in relative velocity. Emergency out-of-lane stops however can create dangerous closure rates in the adjacent lane, exacerbating the interruption of flow on the AHS by extending one lane's problem to another and creating a potentially very hazardous situation.

3.3.10. Platoon Merge

Detection of the presence of a vehicle suitable for following is performed using the stereo infrared range detection. Range and range rate preconditions must be met for a vehicle to be considered suitable for joining. Conditions for acquiring a platoon are detection of a vehicle at a speed differential of i8 kph and an initial spacing of 5 to 50 meters. The purpose of the minimum separation is to assure proper safety and spacing to allow for speed and spacing transients. When a platoon situation arises, intervehicle communication executes a request/acknowledge sequence.

Platoon acquisition from another lane is not allowed, since this concept does not provide for safe lane changes under autonomous control. The operator is responsible for setting up the proper merging conditions.

3.3.11. Platoon Departure (Nominal)

Departure from the platoon under nominal conditions is an operator-initiated event. The operator signals the system of his intent and the system initiates a mild deceleration sufficiently large to cause following vehicles (if any) to disengage, after which the operator is expected to perform a lane change at the earliest opportunity.

Vehicles following are expected to detect this threshold deceleration (0.1 g nominally) and disengage from the platoon, fall back to a safe following distance, and await a maneuver by the vehicle in front to depart the lane. If the vehicle in front does not depart the lane alter ('TBD --20 seconds) and platoon merge conditions still exist, the system will automatically attempt the merger.

This concept presumes no communication between vehicles in this mode; the deceleration protocol is the signal of the departure event.

3.3.12. Platoon Departure (Exceptional)

Platoon departure under exceptional conditions is assumed to occur under one of two circumstances:

1) the platoon leader detects an obstacle and initiates evasive or corrective action

2) a platoon follower detects sudden deceleration of the vehicle in front of it In either case, the vehicle detects the condition visually and decelerates as abruptly as possible without unduly endangering potentially following vehicles. Detection is done autonomously; no communications among vehicles is implied in this concept.

3.3.13. AHS Entry (Nominal)

Entry into the AHS system occurs under manual control. Once in the system, mode changes within the AHS context are accomplished by a combination of sensed conditions and operator interaction, as described elsewhere in this section.

3.3.14. AHS Exit (Nominal)

Exit from the AHS occurs under manual control. There are no special provisions in the system for automatically sensing safe conditions.

This concept presumes that the vehicle is not in platooning mode during the exit. In order to exit while platooning, a nominal platoon demerge must first be safely executed, then the operator may initiate an AHS exit. If the operator attempts a gradual lane departure while platooning, the system will signal the situation by vibrating the steering column.

Departure under emergency conditions is as described in section 2.3.5. above.

3.3.15. AHS Entry Abort

Entry abort is assumed to happen under one of the following conditions:

1) equipment failure during the entry process
2) occurrence of an incident during the entry process
3) presence of other obstructing entities in the vicinity during entry.

Since entry into the system is under manual control, abort is also presumed to occur under manual control, entry abort is a manual process, though if the conditions for an abort arise, the operator must be advised though visual and aural cues to *guarantee* operator awareness even if his attention is elsewhere (such as back over his shoulder where approaching vehicles are).

3.4. Required or Supporting Assumptions

- Vehicles will not be permitted on the AHS without a fully functioning IR beacon.

- A mechanism for keeping the IR detector optics free of accumulated water, dust, mud, or other lens obscurants is also presumed.

- The roadway is within line of sight for at least TBD meters at all times. This constraint is satisfied via road curvature limits, vehicle speed limits for curves (wherever different from nominal speed limits), and road grades.

3.5.1. The time-varying nature of optimal platoon length

Flow-based platoon length optimization may adversely impact traffic flow under high-density conditions because of the need to dynamically change formations along the length of the highway.

This concept states that the maximum platoon length is to be regulated by the infrastructure on a segment-by-segment basis. The length of a highway segment is not definitively determined by the concept, but the idea is that a segment is covered by one infrastructure transceiver, each of which has an operating range of about 1 km.

The objective in regulating platoon length is to optimize the traffic throughput while providing ample opportunity for vehicles to enter the highway and merge into the traffic flow. Without such regulation, the platoon length may tend to grow without bound. As traffic density increases, longer platoon lengths will mean fewer and fewer slots into which an entering vehicle can merge. This, in turn, will cause growing entry queues, particularly under "rush hour" conditions.

if the maximum platoon length reduces from one segment to the next, the impact on traffic flow will be to induce a slowing transient at the transition point which could, under high-density conditions, set up a compression wave that travels upstream from that point if the platoon length requirement is static from segment to segment, the issue becomes how that parameter is optimally determined as a flinction of segmental or regional flow?

3.5.2. Effect of emergency lane changes on sensor requirements

Transient dynamics for the full closed-loop system under emergency conditions will be a driver on sensor update rate requirements, field of view requirements, or both.

The analysis suggesting the required field of view for the stereo detector arrays does not account for transients associated with sudden lane changes for obstacle avoidance.
Assuming that an abrupt lateral movement of four meters can be accomplished in less than a second, the field of view of the stereo sensor can possibly be violated before the following vehicle can respond (assuming processing and actuation latencies of on the order of 0.4-0.5 seconds). While the relative motion in one sensor data interval is small if the update rate is high enough, it is the total system response time that dictates if the leading vehicle will leave a given field of view at any time during the transients of the lane change.

3.5.3. Anticipation by communicating velocity

This concept provides for improving performance through communicating velocity. Which velocity state is communicated is an issue with profound implications for aggregate system stability and complexity.

if a platoon lead's velocity is the communicated parameter, it significantly eliminates the growing error by providing anticipation to the vehicles to the rear. However, this configuration does not allow for variations of velocity interior to the platoon. if those variations are significant, the

if interior states are to be communicated, the data volume grows

How does the controller account for disturbances in the nth vehicle in the chain if I only communicate the change in velocity of the lead vehicle? Doesn’t this reduce me to the level of the non-communicating platoon?

3.5.4. Stereo Ambiguity

When performing stereo correlation on point sources, the presence of other point sources in the field of view can create ambiguities that are difficult to resolve without continuous tracking of the sources. By contrast, whole-scene stereo has sufficient other cues to resolve such ambiguities. This issue is particularly acute £f the two sensors are not covering the same field of view.

A problem to be overcome is assuring that the beacon images being correlated are the same. This problem is illustrated in Figure 6. Suppose there are two vehicles are *50* meters away in adjacent lanes. Each sensor "sees" only one beacon. if the correlation algorithm attempts to correlate them, the result will be an indication of a single beacon at very close range in the vehicle's own lane.

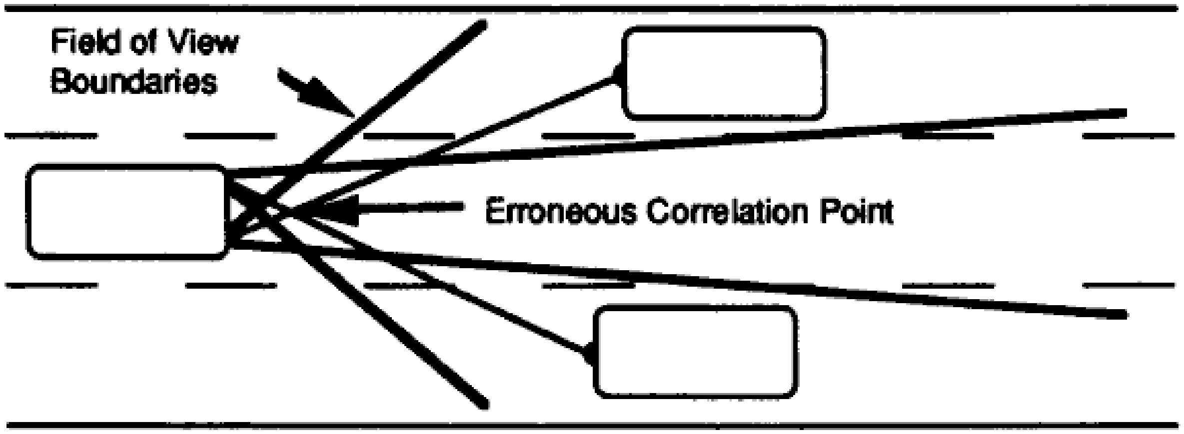


Figure 6. Stereo Miscorrelation Due to Field of View Effect

One method of overcoming this problem is to have identical fields of view and correlating the left most beacon in the left sensor with that of the right sensor, and so forth. The problem with this approach is that it increases the field of view required of each sensor and therefore the number of pixels required. Another approach is to incorporate tracking algorithms over time to disambiguate sources, but this requires added complexity. A third approach is to use three detector arrays. Trinocular stereo has shown the ability to disambiguate most stereo conditions, and the third sensor head provides fault-tolerant redundancy. A fourth and less expensive approach would be to use some form of low-frequency modulation of the beacon that uniquely identifies it, such as a swept-frequency "chirp" that is correlated between the two sensors. No two vehicles would have perfectly synchronized chirps, so correlating among multiple points would be easy. This tactic is easily and inexpensively implemented, but will tend to reduce the effective range of the beacon somewhat.

4. Concept #3: Radar-guided Semiautonomous Vehicle

4.1. Summary Description

This concept is based on using millimeter wave radar as the primary sensor for information external to the vehicle. In this concept, the system senses lane position, existence and proximity of in-lane obstacles, and closure rate based on millimeter wave radar transceivers on the vehicle. It also senses proximity of other vehicles in adjacent lanes by using rearward pointing transceivers. Sensing is in the active rnode with little or no assistance from other vehicles. The infrastructure (median barriers) contain corner reflectors to augment the signal return for sensing lateral position.

In this concept, the AHS lanes are separated from the non-AHS lanes by physical barriers. The presence of barriers is assumed for two reasons. The first is that some studies by the Path program indicate that physical separation is needed to assure safe operation, since statistical studies show that a significant risk of accident is due to lane intrusion ~. Their analysis shows that, without separation barriers, the introduction of AHS technology and the concomitant increase in density would lead to approximately a doubling of accident and fatality statistics. With separation, the numbers will reduce by approximately a factor between six and twelve. The second reason is that the barriers are used for "feeling" the vehicle's position relative the lane which presumes that the barrier would be accurately placed a fixed distance from the lane center.

This concept also presumes that there are no more than two adjacent AHS lanes. If more were permitted' the lateral radar would not have a guaranteed unobstructed line of sight to the barrier. For instance, suppose the concept permitted ~ lanes, and that the traffic density in all three lanes is sufficiently high. In this case, the vehicle cannot be guaranteed line of sight from the center lane to either the left or right barriers.

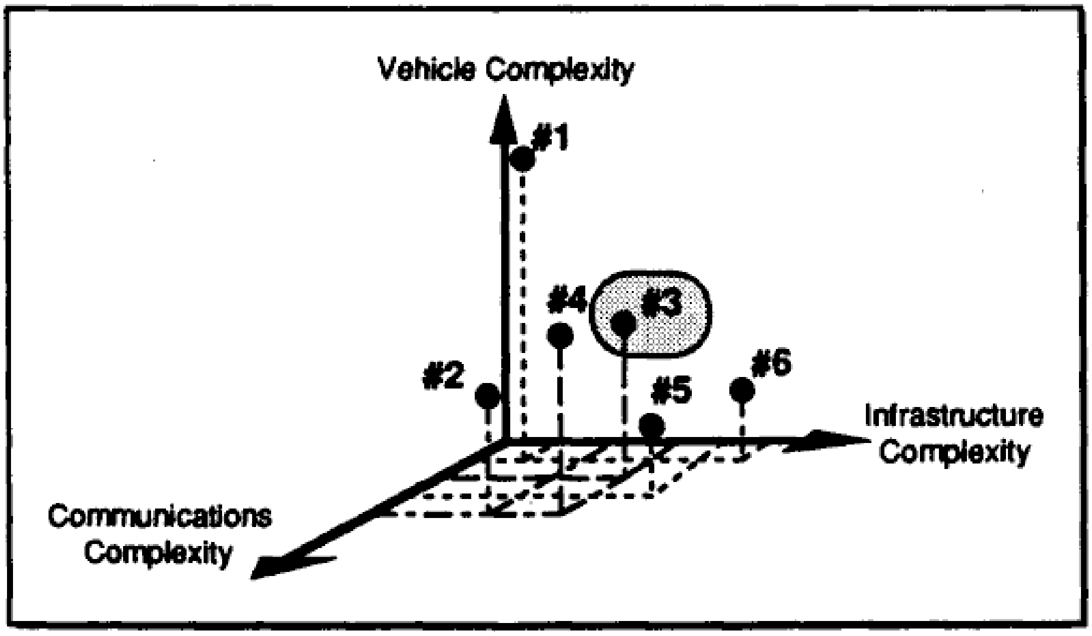


Figure 7. Classification of Concept #3

In terms of our classification scheme, we rated this concept as high on infrastructure impact, moderate in its communication dependency, and moderate in vehicle complexity. Its location in our classification structure is depicted in Figure 7 above. The bases for these assessments are as follows:

- The infrastructure will contain barriers to isolate AHS lanes. These barriers also produce a source of radar reflection for sensing lateral position.
- It performs no imaging, but only proximity sensing. Therefore, signal processing requirements are considerably lower than for processing image data.
- There will be moderate amounts of communications between vehicles, and possibly between vehicles and the infrastructure. The primary mode of communication between vehicles will be to augment sensing in headway maintenance mode and platooning mode of operations.

Millimeter wave radar is appealing in several regards:

- it has a higher operating frequency than traditional microwave radar and therefore provides better distance resolution than microwave,
- it provides more bandwidth for encoding unique identifiers in the signal modulation to separate users' signals from one another and thereby eliminate the interference of one's own sensor by to other vehicles,
- it is less susceptible to attenuation by carbon dioxide, water vapor and mist, and
- it is less susceptible to the effects of dirt, dust, mud, and moisture accumulation on the lens or exposed window.

Using a common sensor for all external sensing modes is one way to reduce system costs. A variety of sensors complicates data acquisition and signal processing, and can also give rise to potential problems arising from the need to perform data fusion across dissimilar sensors. Using a single sensor enhances the possibility of multiplexing a single set of data acquisition and signal processing electronics, and may also simplify the algorithmic complexity.

Though this concept uses the same type of sensor for both lateral and longitudinal sensing, they will perhaps operate in different modes (Doppler versus range sensing) and tuned to different frequencies, or modulated with different chirps to eliminate common mode errors and crosswalk. For instance, the if the lateral sensors are aimed slightly forward to compensate for forward motion and latency in the control system, then there is a strong possibility of the lateral sensor exciting the longitudinal receiver via energy bouncing from the barrier to the vehicle in front and thence to the forward-looking receivers.

4.1.1. Summary of Approach for Lateral Control

In this concept, lateral control is achieved by controlling the vehicle's steering based on sensing the lateral position of the vehicle with respect to the lane center by illuminating the scene with millimeter radiation and sensing the position relative to either the left side or right side barriers. From the position of the lateral radar return, a lane center is calculated for either a fixed distance in front of the vehicle or a fixed time of travel in front of the vehicle, depending on sensor characteristics such as beamwidth and material reflectivity. Figure ~2 illustrates the notional beam patterns for both lateral and longitudinal sensing beam. The lateral beams are tilted forward to provide some lead to compensate for sensing and processing latency. The beamwidth and pointing angle will have to be optimized based on traveling speed as well as sensor performance.

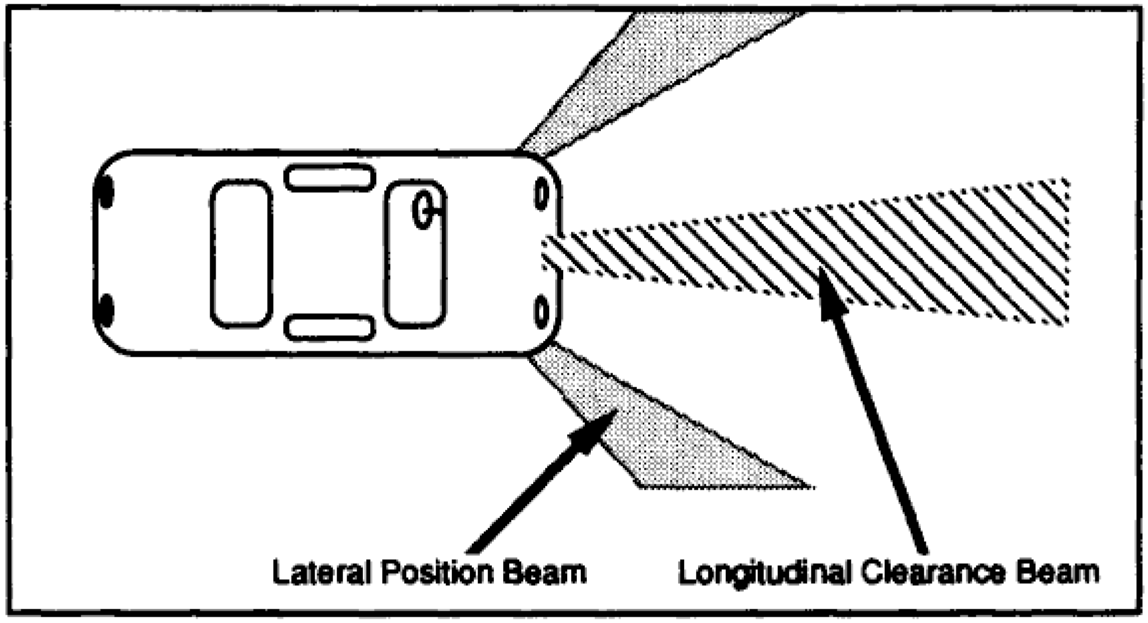


Figure 8. Millimeter Wave Radar Sensor Configuration

The lateral beam must be capable of tracking a curvature of radius r_{min} at some distance in front of the vehicle. The higher the vehicle speed the greater the distance becomes. This requirement is derived from work performed at Carnegie Mellon University (1) which concludes that a pure-pursuit guidance methodology yields the best trajectory tracking results. For the pure-pursuit model, the following equation is provided (4)

$$\frac{1}{r} = \gamma_{pp} = \gamma_{path} - \frac{2}{d^2}\Delta y - \frac{2}{d}\Delta\theta \text{ , where :}$$

γ_{pp} is the pure-pursuit curvature (i.e. the vehicle command) ,
γ_{path} is the nominal path curvature (i.e. the road) ,
d is the look-ahead distance ,
Δy is the lateral position error , and
$\Delta\theta$ is the heading error

Lateral acceleration is given by the product of the curvature and the square of the vehicle speed, or :

$$a_y = V^2\gamma_{pp} = V^2\gamma_{path} - \frac{2V^2}{d^2}\Delta y - \frac{2V^2}{d}\Delta\theta$$

Note that as velocity increases, look-ahead distance must increase to maintain a fixed ratio. The preceding relationship can be used to define the required look-ahead distance for the lateral control system for a given lateral acceleration constraint and allowing for lateral and heading errors. Experimentation at NIST has shown that a look ahead distance of 12 meters provides suitable performance at 70 kph (4) However, this work did not quantify the lateral acceleration environment experienced by the vehicle passengers.

Note also that there are two data points which constrain the beam width and look angle for the lateral sensors. The first is the minimum left-hand curve radius, and the second is the minimum right-hand curve radius. This is illustrated by the cross hatched regions in figure 9.

4.1.2. Summary of Approach for Longitudinal Control

Longitudinal control is achieved in one of three model.

1) If the lane is clear in front, then speed control will be accomplished in the same manner that current vehicles perform ordinary cruise control.

2) If there are vehicles in front and the vehicle is not operating in platooning mode, then the system will seek to maintain a set headway clearance to the vehicle in front. Modulation of the forward beam will indicate headway maintenance mode. Vehicles in front will be aware through a rearward-looking sensor capable of discriminating modulation patterns. This sensor will be attuned to a range of power levels consistent with nominal ranges of headway maintenance to filter out signal bounce from other vehicles nearby.

3) If the vehicle is in platooning mode (this presumes that there is a vehicle in front), the system seeks to maintain a considerably closer headway spacing. The radar's modulation pattern will signal that it is in close following

From a purely graphical standpoint, one can argue that the 'search region' for the longitudinal sensor must consist of the region from the front of the vehicle through the apex of the minimum left-hand curve to the apex of the minimum right-hand curve radius. This region is indicated by the dotted area in Figure 9 on the next page, and is labeled as 'Minimum longitudinal Beam Pattern'.

4.1.3. Summary of Approach for Coordinating Behaviors

4.2. Distinguishing Characteristics

4.2.1. Allocation of Sensing Functions

4.2.1.1. On the Vehicle

Primary responsibility for sensing functions is allocated to the vehicle. The vehicle contains active sensing elements, which interrogate the environment in order to extract information pertaining to lateral and longitudinal guidance data.

4.2.1.2. In the Infrastructure

Although not an active allocation, the infrastructure is expected to make allowances which are key to this RSC. Specifically, the following constraints are imposed:

1) The infrastructure shall provide barriers to maintain physical separation of the AHS and non-AHS lane. This is necessary for safety optimization.

2) The AHS lane allocation shall be no more than two traffic lanes. This is necessary to assure line of sight to reflective markers and/or barriers at all times.

3) Wherever possible, the infrastructure shall provide for optimization of reflection patters by incorporating reflective targets into the barrier design. This is necessary to optimize system performance.

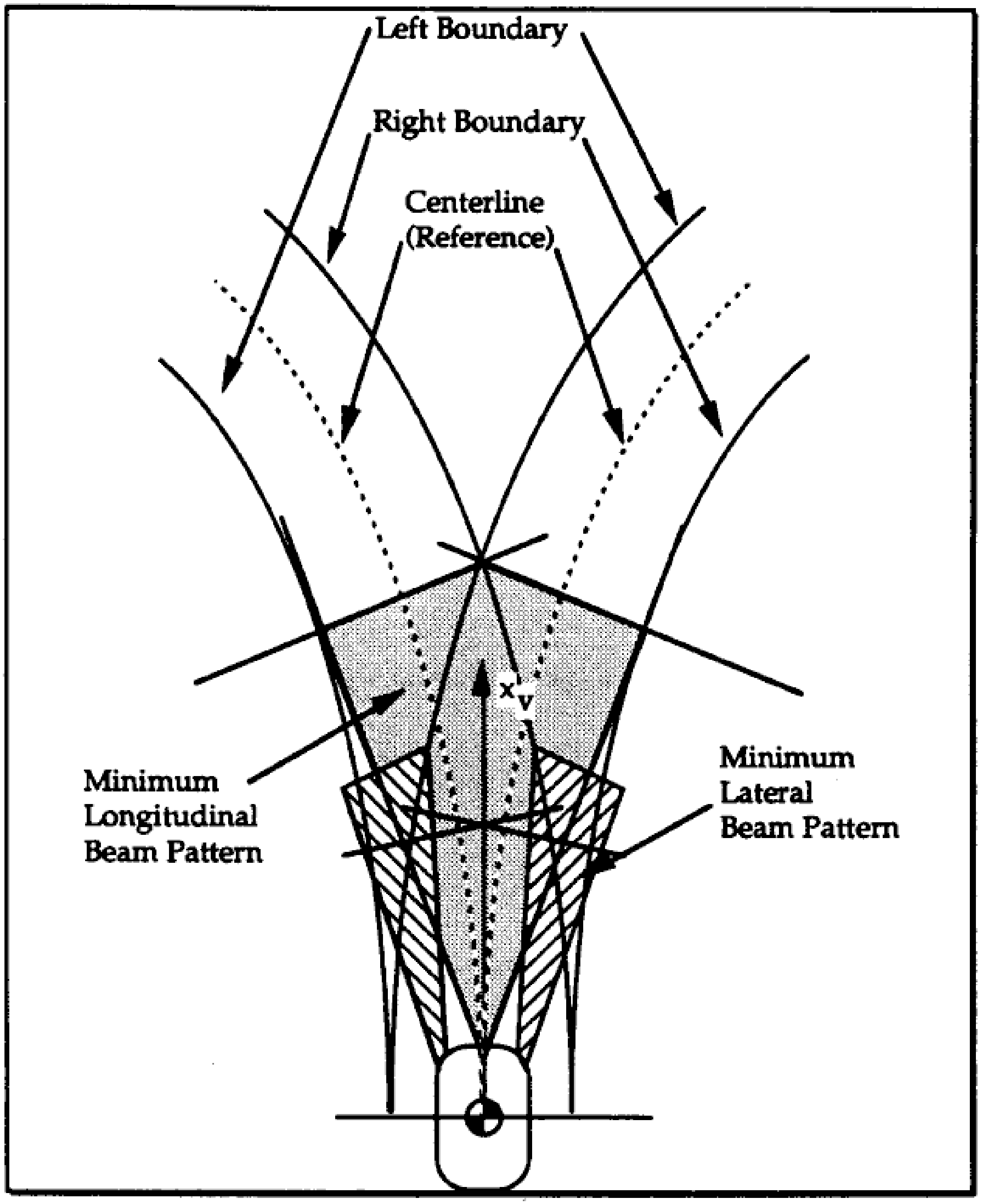


Figure 9. Lateral and Longitudinal Beam Patterns

4.2.2. Allocation of Control Functions

4.2.2.1. On the Vehicle

The vehicle performs all required sensing, sensor processing, and control related functions. All data necessary for control is derived from on-board measurement of the external environment.

4.2.2.2. In the Infrastructure

The infrastructure provides no control functions. The infrastructure does provide for improvements to optimize the conditions for the vehicle based sensing and control.

4.2.3 Allocation of Processing Functions

4.2.3.1. On the Vehicle

All relevant sensing, processing, and control function are performed on-board the vehicle. Vehicle state determination is performed by dedicated on-board sensors and related processing.

4.2.3.2. In the Infrastructure

There are no active sensing, processing, or control functions which are performed by the infrastructure.

4.2.4. Allocation of Communications Functions

4.2.4.1. Vehicle to Vehicle

Assuming that vehicles are equipped with rear-facing detectors, the vehicle will be able to observe the millimeter-wave signature from vehicles behind. Assuming also that unambiguous detection may be performed, the vehicle should be able to detect the modulation pattern of the longitudinal sensor array from the trailing vehicle. This information will communicate the mode of operation to the leading vehicle. No other intra-vehicle communications is identified as part of this concept.

4.2.4.2. Vehicle to Infrastructure

At this time, there are no needs identified which require vehicle to infrastructure communications.

4.3. Maneuver Requirements Satisfaction

4.3.1. Lane Tracking

Lane tracking is performed by detecting range to left and right barriers using the lateral sensors.

The system must be designed to be capable of arbitrating between the left and right barriers as lateral reference designation sources For example, the time of flight to the right barrier is much less than the time of flight to the left barrier, then the system can conclude that the vehicle is in the right lane. Accordingly, the return from the right barrier is weighted heavier in the lateral position tracking than is the left-most barrier.

4.3.2. Speed Maintenance Tracking

Speed control in an unobstructed environment is performed using existing cruise control technology, except that the commanded speed is variable depending on the curvature of the road ahead. This concept presumes the lateral sensing system is capable enough to determine the lateral displacement of lane boundaries sufficiently far ahead to modulate commanded speed without excessive braking or acceleration.

4.3.3. Spacing Regulation

Spacing regulation is achieved via on-board longitudinal millimeter wave sensors. Then sensors provide range as a direct output. Range rate can be derived by differentiating multiple range measurements.

4.3.4. Lane Change (Nominal)

Nominal lane change is performed manually. If the operator initiates a lane change with a gradual input that could be misconstrued by following vehicles as a normal lane curvature, the system will respond by vibrating the steering column and resisting the lane change.

The presence of vehicles to the rear should be known by the vehicle changing lanes, either through communications or sensing, since their presence might impede the lane change. One implementation would be to have lateral sensors on the trailing vehicles in the platoon providing needed coverage.

4.3.5. Lane Change (Exceptional)

Exceptional lane change is performed manually. We assume that the an exceptional lane change is defined by an abrupt change of lane. The operator is responsible for determining safe clearance. If a sudden torque is applied to the steering column, the system assumes an override exception and releases control to the operator.

4.3.6. Vehicle Following (Nominal)

Close-interval platooning is performed by using active range detection as a feedback signal for speed regulation. Derivation of range rate requires suitable range quantization and sample period coordination.

4.3.7. Vehicle Following (Exceptional)

When in close following and the vehicle in front exits the lane, there is no way for this system to be aware of that condition.

4.3.8. Emergency In-Lane Stop

Obstacle detection requiring emergency response is performed using processed range data from the longitudinal sensor input.

4.3.9. Emergency Out-of-Lane Stop

Emergency stopping involving lane change cannot be accomplished automatically under this concept since there is no information on lane clearance available to the system. Under emergency stopping situations, the system will be constructed to permit the operator to usurp control and manually execute a lane change. However, this mode of operation is highly suspect since we presume that the operator situation awareness is limited by inattention while the system is operating under autonomous control in most cases.

4.3.10. Platoon Merge

Detection of the presence of a vehicle suitable for following is performed using a combination of range and range rate determination from the longitudinal sensor system. When a platoon situation arises, an indicator on the operator's display indicates such and awaits a ratification signal from the operator. Conditions for acquiring a platoon are detection of a vehicle at a speed differential of i8 kph and an initial spacing of 5 to 200 meters. The purpose of the minimum separation is to assure proper safety and spacing to allow for speed and spacing transients.

Platoon acquisition from another lane is not allowed, since this concept does not provide for safe lane changes under autonomous control. The operator is responsible for setting up the proper merging conditions.

The leading vehicle will be able. to detect a converging vehicle from the rear, via sensing of the trailing vehicle longitudinal sensor environment interrogations.

4.3.11. Platoon Departure (Nominal)

Departure from the platoon under nominal conditions is an operator-initiated event. The operator signals the system of his intent and the system initiates a mild deceleration sufficiently large to cause following vehicles (if any) to disengage, after which the operator is expected to perform a lane change at the earliest opportunity.

Vehicles following are expected to detect this threshold deceleration (0.1 g nominally) and disengage from the platoon, fall back to a safe following distance, and await a maneuver by the vehicle in front to depart the lane. If the vehicle in front does not depart the lane after (TBD --20 seconds) and platoon merge conditions still exist, the system will automatically attempt the merger.

This concept presumes no communication between vehicles in this mode; the deceleration protocol is the signal of the departure event.

4.3.12. Platoon Departure (Exceptional)

Platoon departure under exceptional conditions is assumed to occur under one of two circumstances:

1) the platoon leader detects an obstacle and initiates evasive or corrective action

2) a platoon follower detects sudden deceleration of the vehicle in front of it In either case, the vehicle detects the condition using the longitudinal sensor and decelerates as abruptly as possible without unduly endangering potentially following vehicles. Detection is done autonomously; no communications among vehicles is implied in this concept.

4.3.13. AHS Entry (Nominal)

Since this concept precludes automated lane changes, entry into the AHS system occurs under manual control. Once in the system, mode changes within the AHS context are accomplished by a combination of sensed conditions and operator interaction, as described elsewhere in this section.

4.3.14. AHS Exit (Nominal)

Since this concept precludes automated lane changes, Exit from the AHS occurs under manual control. There are no special provisions in the system for automatically sensing safe conditions.

This concept presumes that the vehicle is not in platooning mode during the exit. In order to exit while platooning, a nominal platoon demerge must first be safely executed, then the operator may initiate an AHS exit. If the operator attempts a gradual lane departure while platooning, the system will signal the situation by vibrating the steering column.

4.3.15. AHS Entry Abort

Entry abort is assumed to happen under one of the following conditions:

1) equipment failure during the entry process
2) occurrence of an incident during the entry process
3) presence of other obstructing entities in the vicinity during entry.

Since entry into the system is under manual control, abort is also presumed to occur under manual control, entry abort is a manual process, though if the conditions for an abort arise, the operator must be advised though visual and aural cues to *guarantee* operator awareness even if his attention is elsewhere (such as back over his shoulder where approaching vehicles are).

4.4. Required or Supporting Assumptions

This concept assumes the following minimum requirements:

- Barriers will be used as reflectors for lateral sensing as well as for isolating the AHS lanes.

- AHS lanes will be designated out of existing lane structure. Entry and exit points will be established by the placement of barriers

- Close-order following of large vehicle count platoon assemblies is not required for efficiency of an AHS, as this concept precludes stable large platoons since vehicle-to- vehicle communications is not provided.

4.5. Concept-related issues

4.5.1. Lane limitations on lateral sensing concepts

Lateral position sensing using out-of-lane Infrastructural elements may limit AHS implementation to no more than two adjacent lanes.

A number of concepts have been proposed using some form of sensing of Infrastructural elements to the side of the lane for lateral position data Examples of this type of sensing include triangulation of RF beacons placed at a fixed interval, radar corner reflectors at fixed intervals, visual tracking of reflectors, visual tracking of barriers, and the concept in this section of using radar reflection from the barriers. All of these implementations have a common limitation. In almost all of these concepts, if the line of sight is obstructed, the ability to sense lateral position is degraded or eliminated.

Under dense traffic conditions where vehicles are traveling in close spacing, the middle lanes of a three or more lane configuration will be obscured most of the time. Assuming that the AHS does not eliminate dense traffic, but merely makes the system efficiently handle high traffic volumes, the likelihood of obscuration is very high during the times that the capability is most needed. Allowing for platoons in adjacent lanes will exacerbate the problem because the close spacing may make lateral sensing impossible anywhere along the platoon length. Therefore, one may conclude that any concept using side-looking sensors and Infrastructural references outside the lane will limit AHS implementation to no more than two adjacent lanes.

This is particularly a problem for urban freeway situations, where the number of total lanes in the highway can be up to six lanes. For rural intestate highways, the number of total lanes is usually no more than three in each direction, and the number of AHS lanes that would be assigned would likely be less than three. However, the winning AHS concept *must* be capable of working in urban as well as rural freeway conditions.

If each lane has barriers on each side, then the issue is moot, but at substantially increased Infrastructural cost. Unless there other reasons (e.g., safety) for completely cordoning off each lane, the cost impacts of installing barriers for the purposes of sensing are likely to be too high relative to the anticipated benefit and compared to other concepts.

4.5.2. Disambiguating vehicles from passive barriers

To a non-image forming radar, a barrier and a vehicle in the adjacent lane may be difficult to discriminate between.

When using Infrastructural elements as a means of determining lateral position, special provision must be made for distinguishing the barrier from vehicles passing on that side. This concept was designed to use either left or right barriers and required barriers on both sides so that vehicles in either right or left lanes can sense a barrier's presence and develop a lateral position estimate.

One way to disambiguate barriers from vehicles is to place corner reflectors at a fixed interval on the barrier. Sensing the periodic strong return will be a means of assuring that the radar signal returned is from the infrastructure itself.

4.5.3. Lane tracking accuracy and harrier positioning

One shortcoming of this is that the lane tracking accuracy is dependent upon the combination of barrier and vehicle accuracy. What would an accident in the adjacent manual lane (or an incident in the AHS lane) do to the barrier accuracy?

In this context, the position of the barrier becomes a key component of ride quality control in the closed-loop system. If the system is determining lateral position error by the distance to one or both barriers, and if the barriers are not aligned properly (as might happen after an accident has occurred), then the lateral accelerations felt by the system's erroneous attempts to correct lateral position may induce unacceptable ride quality or possibly even safety concerns. This translates to a need to keep the barriers aligned, which in turn creates somewhat higher Infrastructural maintenance costs. If this concept is to be examined in more depth, then some study will be required to determine the minimum acceptable lateral alignment errors for barriers.

5. Concept #4: RF Beacon Triangulation in a Socialist Architecture

5.1. Summary Description

This concept distinguishes itself from the others in this report in that it employs a centralized control of individual vehicle behaviors. Lateral control is individually performed using triangulation of low-power, semi-directional RF beacons placed some TBD (nominally 100 meter) intervals along the highway. The beacons' energy is modulated with timing data for more accurate positioning of the vehicle. The potential exists for also providing dynamic and static highway information via this medium. Longitudinal control is provided by controlling synchronous "time slots" within which the vehicle must remain, providing both speed and headway control which processing elements in the infrastructure regulate. One fail-operational/fail-safe processing element will control each TBD segment of highway (nominally 1 kilometer). These processing elements are connected to one another in daisy-chain fashion along a fiber-optic bus that is connected to a regional traffic control center.

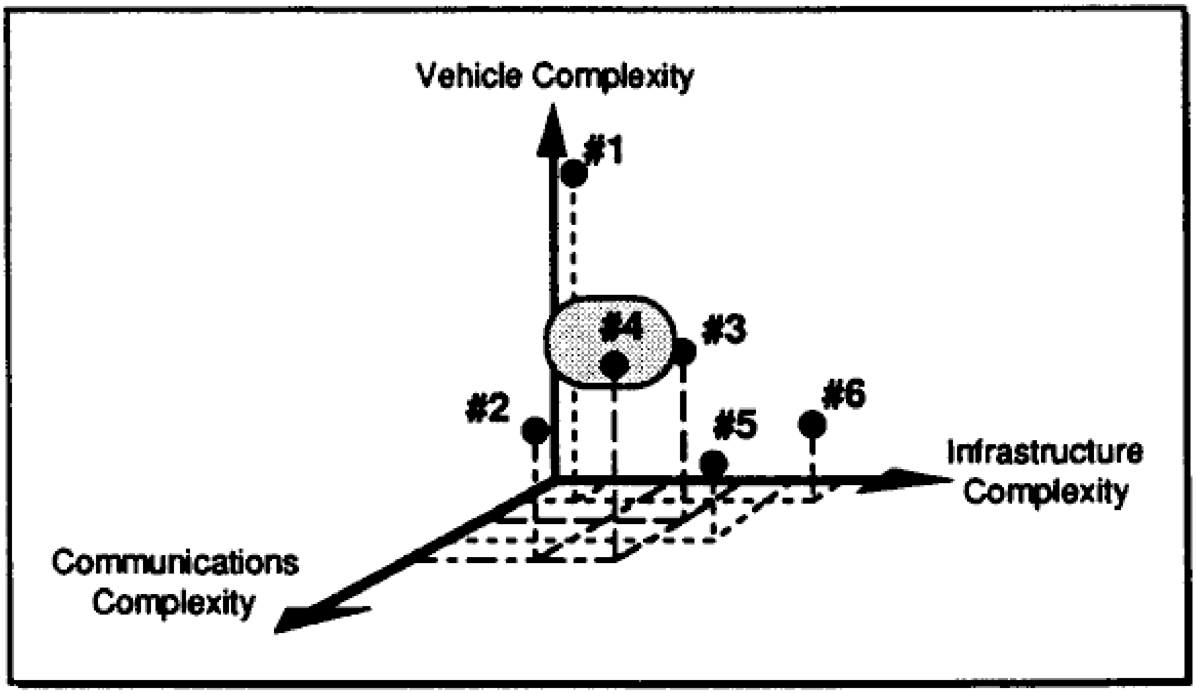


Figure 10. Classification of Concept #4

In terms of our classification scheme, we rated this concept as moderately high on infrastructure impact, high in its communication dependency, and moderate in vehicle complexity. Its location in our classification structure is depicted in Figure 10 above. The bases for these assessments are as follows:

- The infrastructure will contain barriers to isolate AHS lanes. In addition, the infrastructure will provide some communications support as well as navigation beacons.
- This concept requires no imaging, as did concept number 1, rather, this concept performs a combination of beacon triangulation and TBD in order to perform the required guidance functions. These signal processing requirements are considerably lower than for processing image data.
- Segment processing is responsible for providing tiling signals to the beacons, calculating optimal speed and headway regulation factors, reducing data from sensors in the traffic segment or estimating from adjacent segments and entry/exit traffic, and communicating with adjacent segments. This will require a moderate processing burden we believe will easily be handled in a single current generation RISC processor.

5.1.1. Summary of Approach for Lateral Control

The control process for each vehicle consists of three problems; lateral reference generation, lateral state determination, and algorithmically verifiable convergence to the reference signal , i.e. a control law.

The lateral reference signal is designated by the decision vehicle, where there is one decision vehicle per section. Note that if there are no vehicle in a given section, then there is no decision vehicle in that section. The lateral reference signal is updated at a 1 sample per 5 second (TBD) rate. The signals are broadcast for all vehicles in the section at a single time. The reference signals are defined based upon lane number and percentage of segment covered, and will consist of two data elements per lane; base velocity (also the initial segment velocity) and velocity change. The sum of the two elements defines the end velocity for each lane per segment.

When more than one vehicle is operating independently, i.e. a platoon situation, the platoon leader shall communicate all state changes with the following vehicles. The communications path shall provide a per vehicle relay capability. The information communicated shall include the lateral parameter set, the lead vehicle state, and TBD other information germane to the lateral control problem.

Lateral state determination is performed by using radio-frequency (RF) beacon navigation. The beacons will be placed so as to form beacon pairs for system operation. Each vehicle in segment 'n' will utilize the beacon-pair in segment 'n+1' for guidance. Figure 11 provides a conceptual illustration of the beacon system.

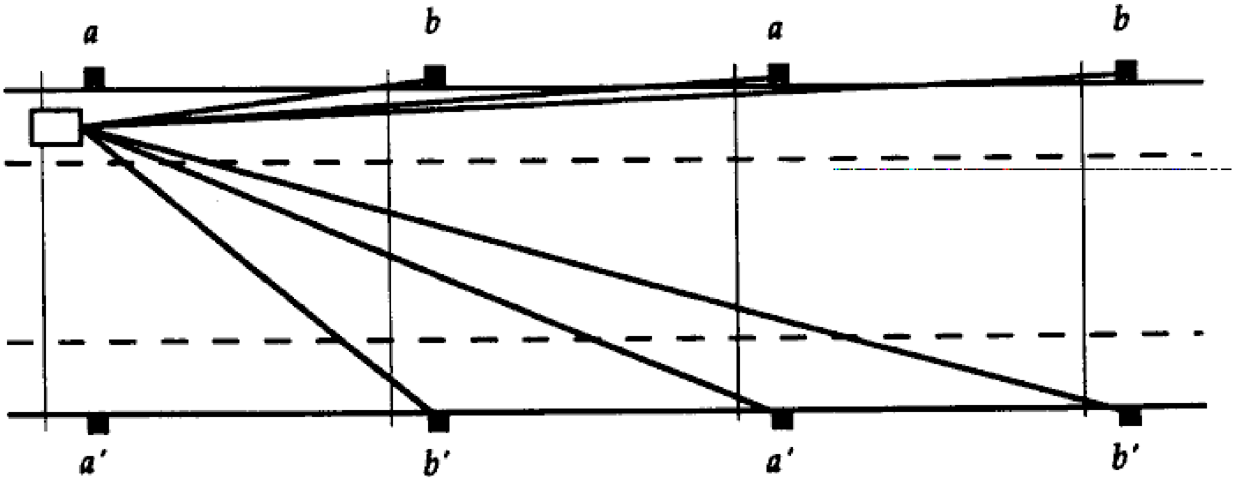


Figure 11. Conceptual Diagram for RF Beacon longitudinal Navigation System

The beacon pair in each segment will be placed so as to avoid geometrically ill-conditioned longitudinal guidance data from resulting, i.e. the look angle to the beacon will never exceed 45 degrees relative to the vehicle. The beacons will utilize a minimum of two precise frequencies in TBD frequency band, the system may use more than two if this is shown to provide significant advantages. The beacons will also provide a regulated RF power output. By constraining the system in this manner, a vehicle will be able to detect failed beacons, due to a lack of change in modulation frequency. The vehicle ranging will be accomplished by determining the angles to the target beacon pair.

Range rate can either be detected from angular change, or from Doppler shift resulting from the vehicle motion. Each vehicle will be responsible for determining it's own state. Each vehicle will be required to screen out the weaker signals from longer range beacons (note that due to the geometry, the stronger signal will also have the greatest angle). Since the angle to the beacon will never exceed 45 degrees, the antenna may be designed to greatly attenuate signals from sources outside 45 degrees. The beacons will be designed so that they phase lock to each other; however the actual beacon broadcasts will be 90 degrees out of phase, with the right side lagging the left side of the road. By measurement of both beacon angle and relative beacon phase, lateral positions may be extracted from the broadcasts.

5.1.2. Summary of Approach for Longitudinal Control

The control process, for each vehicle, consists of three problems; longitudinal reference generation, longitudinal state determination, and algorithmically verifiable convergence to the reference signal , i.e. a control law.

The longitudinal reference signal is designated by the director, where there is one director per section. The longitudinal reference signal is updated at a 1 sample per 5 second (TBD) rate. The signals are broadcast for all vehicles in the section at a single time. The reference signals are defined based upon lane number and percentage of segment covered, and will consist of two data elements per lane; base velocity (also the initial segment velocity) and velocity change. The sum of the two elements defines the end velocity for each lane per segment.

When more than one vehicle is operating independently, i.e. a platoon situation, the platoon leader shall communicate all state changes with the following vehicles. The communications path shall provide a per vehicle relay capability. The information communicated shall include the longitudinal parameter set, the lead vehicle state, and TBD other information germane to the longitudinal control problem.

Longitudinal state determination is performed by using radio-frequency (RF) beacon navigation. The beacons will be placed so as to form beacon pairs for system operation. Each vehicle in segment 'n' will utilize the beacon-pair in segment 'n+1' for longitudinal guidance. Figure 11 provides a conceptual illustration of the beacon system. Section 5.1.1 included a description of the RF beacon system, as well.

5.1.3. Summary of Approach for Coordinating Behaviors

Behaviors are not only coordinated, they are directed on a per-vehicle basis for each vehicle in the segment by the infrastructure. Each highway segment (nominally 1 kilometer) has a processing element whose responsibility is to determine segment operating parameters, communicate limits and timing data to the vehicles, and control vehicle coordination behaviors. This processing element will be referred to henceforth as the "director."

The scope-of commands for the director includes longitudinal and lateral set points for all independent vehicles and for all platoons. In the case of platoons the director will communicate only with the platoon leader; thus, if the platoon leader is not in the segment, the director does not communicate with that platoon. The operative presumption here is that that platoon will very soon be fully in the next segment. This, of course does not allow for very long platoons.

All maneuvers requiring intervehicle coordination are arbitrated by the director.

The director will also communicate with adjacent directors. The purpose of this communication is to receive lane speed information from subsequent sections, and to communicate lane speed information from the present segment In this way$_1$ downstream incidents can be managed by optimizing traffic flow in the present segment.

5.2. Distinguishing Characteristics

The primary distinguishing characteristic of this concept is the notion of a centralized management function at the segment level.

5.2.1. Allocation of Sensing Functions

5.2.1.1. On the Vehicle

Each vehicle is responsible for all RF beacon triangulation processing required to unambiguously define it's state to within the required accuracy. The common vehicle will utilize 'TBD independent instrumentation to augment these computations, if required. Each vehicle is not responsible for defining the state of any vehicles surrounding it!

5.2.1.2. In the Infrastructure

The infrastructure provides RF beacons, to TBD specifications, which support vehicle navigation. The infrastructure does not assure that the segment state has updated prior to providing the information to up-stream segments, but the data will be no more than one cycle old, at most.

5.2.2. Allocation of Control Functions

5.2.2.1. on the Vehicle

Each vehicle performs all low-level control functions, including speed, heading, and lateral position control. In addition, each vehicle performs trajectory generation and execution capabilities required to smoothly transition between the set-point commands.

5.2.2.2. In the '[infrastructure

The director is responsible for directing all changes in multiple-vehicle states, including lane assignment, time slot assignment. The director also regulates time signature of the RF beacons.

5.2.3. Allocation of Processing Functions

5.2.3.1. on the Vehicle

Each vehicle is allocated the functions of trajectory generation, trajectory execution, and vehicle state computation. The trajectory generation receives the set-point commands from the director and provides a smooth trajectory from the present vehicle state to the commanded set-point state. This process is intended to be implementable within the 5 second director period, thus the director is requlred to assure that the set points are close to the vehicle states (which are assumed to be the commanded states from the previous command sequence! The trajectory execution consists of essentially closed-loop servocontrols of the required vehicle degree of freedom, and assures smooth execution within bounded performance limits. The vehicle state computations include lateral and longitudinal position and velocity determinations, as a minimum. Any other required vehicle state information is computed here, as well.

The director performs all of the processing defined for each vehicle, which is applied to it's own guidance problem. In addition, the director specifies all the set-points for all vehicles in the present segment. The director also interfaces with the infrastructure to share and receive segment information. The director also arbitrates between service requests from vehicles in the segment, by servicing the top three requests which are allowable at the particular time.

The infrastructure provides the RF beacon reference system, as well as supporting sharing of information between road segments.

5.2.4. Allocation of Communications Functions

5.2.4.1. Vehicle to Vehicle There is no vehicle to vehicle communication.

5.2.4.2. Vehicle to Infrastructure

Under this concept the director exchanges information with the vehicles in its segment and coordinates behaviors by commanding maneuvers where changes are required. The infrastructure provides a save and forward type of function by relaying the present segment status to the downstream segments.

5.2.4.3. Within the Infrastructure

The infrastructure also provides support to sensing down- stream segment performance by communicating with adjacent directors in the same direction of travel.

5.3. Maneuver Requirements Satisfaction

5.3.1. Lane Tracking

All vehicles are provided set-point lane assignment commands. Combined with this command are parameters defining the lanes, on a parametric basis. Each vehicle determines, by incremental triangulation, it's speed and position, both laterally and longitudinally. Each vehicle minimizes any local tracking error between the sensed and commanded lateral position and heading. When position changes are required (i.e. lane changes), each vehicle computes a position trajectory, which is the subject to the error minimization, described previously.

The director is responsible for providing valid, i.e. implementable, set-point commands.

5.3.2. Speed Maintenance Tracking

All vehicles are provided set-point speed commands. Each vehicle determines , by incremental triangulation, it's speed and position, both laterally and longitudinally. Each vehicle minimizes any local tracking error between the sensed and commanded speed. When acceleration or deceleration is required, each vehicle computes a speed trajectory, which is the subject to the error minimization, described previously.

The director is responsible for providing set-point commands such that there are smooth velocity transitions for each lane between segments. The director is also responsible for providing valid, i.e. implementable, set-point commands.

5.3.3. Spacing Regulation

All vehicles are required only to implement the speed commands received from the director.

The director is required to distribute speed set-point commands to all vehicles which maintain proper headway spacing of all vehicles.

5.3.4. Lane Change (Nominal)

All vehicles are required to comply with commands issued from the director. If a lane change is desired, each vehicle must request a lane change from the director. The director will evaluate the lane change request, when service order and priority permit. The director will examine the segment to determine when a suitable opening appears. At the appropriate time, the director will issue the commands to change lane. The director will give priority to lane changes directed out of the AHS system

5.3.5. Lane Change (exceptional)

This maneuver is not applicable to this concept. This concept allows for vehicle in response to commands received from the director.

5.3.6. Vehicle Following (Nominal)

This maneuver is not applicable to this concept. Vehicles do not maintain position relative to other vehicles, but rather control to a moving time slot at the speed and headway characteristics determined by the director.

5.3.7. Vehicle Following (Exceptional)

Same argument applies as in 5.3.6.

5.3.8. Emergency In-Lane Stop

This concept allows for vehicle in response to commands received from the director.

5.3.9. Emergency Out-of-Lane Stop

This maneuver is not applicable to this concept. This concept allows for vehicle in response to commands received from the director.

5.3.10. Platoon Merge

Platooning is not permitted in this concept.

5.3.11. Platoon Departure (Nominal)

Platooning is not permitted in this concept.

5.3.12. Platoon Departure (Exceptional)

Platooning is not permitted in this concept.

The vehicle will enter the AHS highway segment as a common vehicle. The entry will take place under the director's control. The entry will take place in response to a command from the director to accelerate and merge into traffic.

The director is responsible for commanding suitable profiles to the entering vehicle to allow a successful transition.

5.3.14. AHS Exit (Nominal)

The exit will take place in response to a command from the director to decelerate and merge out of traffic. The director is responsible for commanding suitable profiles to the exiting vehicle to allow a successful transition, and for assuring that vehicles perform the appropriate maneuver to safely exit at their desired location.

5.3.15. AHS Entry Abort

As part of the commands received by the merging vehicle, each vehicle will receive error bounds. The error bounds will be parameterized so as to allow real-time self evaluation of the vehicle's performance in synchronizing vehicle speed and location. If at any time the vehicle exceeds the error bounds, then the vehicle will perform an entry abort. The entry abort profile will be supplied as part of the entry command, and will contain sufficient information to leave the vehicle in a safe condition.

5.4. Required or Supporting Assumptions

5.5. Concept-related Issues

5.5.1 Segment to segment boundary condition mismatches

Boundary conditions across the segments must be managed to prevent discontinuities leading to performance-reducing state changes.

Speed changes from segment to segment must be minimized to prevent inducing congestion under heavy traffic loads similar to what occurs presently when there is curiosity slowing on a high traffic density segment. Intersegment coordination will likely have to extend several segments in each direction to average out speed variations and manage boundary conditions.

5.5.2. Inability to Detect Spacing Without On-Vehicle Sensing

This concept relies on the use of infrastructure-based coordination for maintaining vehicle spacing. There is little provision for incident detection and reaction without bi-directional communication between infrastructure and vehicles and signifcant processing burden to maintain track histories of all vehicles in a given segment.

Unless the infrastructure has a way of sensing exact locations of every vehicle in each segment, there is no way to sense or react to exceptional conditions (vehicles unexpectedly slowing, accidents). The simple concept of periodic transmitters to provide synchronous moving slots for vehicles works in the nominal case, but requires many times more complexity to handle off-nominal cases. The concept will have to be augmented by on-board sensing to be able to handle incidents and accidents. Approaches and algorithms for managing this optimization do not exist at present and warrant some study and possible development.

Reflections from other vehicles may create timing ambiguities leading to accuracy problems. The extent of this effect is a function of frequencies selected for the RF beacons. Unforunately, the frequencies needed for resolving position with sufficient precision are the frequencies at which RF travels only in unobstructed line-of-sight paths and also reflects well from metallic objects (such as vehicles).

There are many causes for multipath effects, only some of which can be compensated for. While reflections from static sources of interference (e.g., concrete retainer walls and signs) could be "tuned out" by the local configuration, reflections from vehicles traveling in the same direction will likely be a serious design problem For example, a vehicle traveling down a highway near a large tractor trailer combination having metal sides may induce multipath effects on the RF pulses that will be very difficult to disambiguate. Figure 5-3 illustrates the problem.

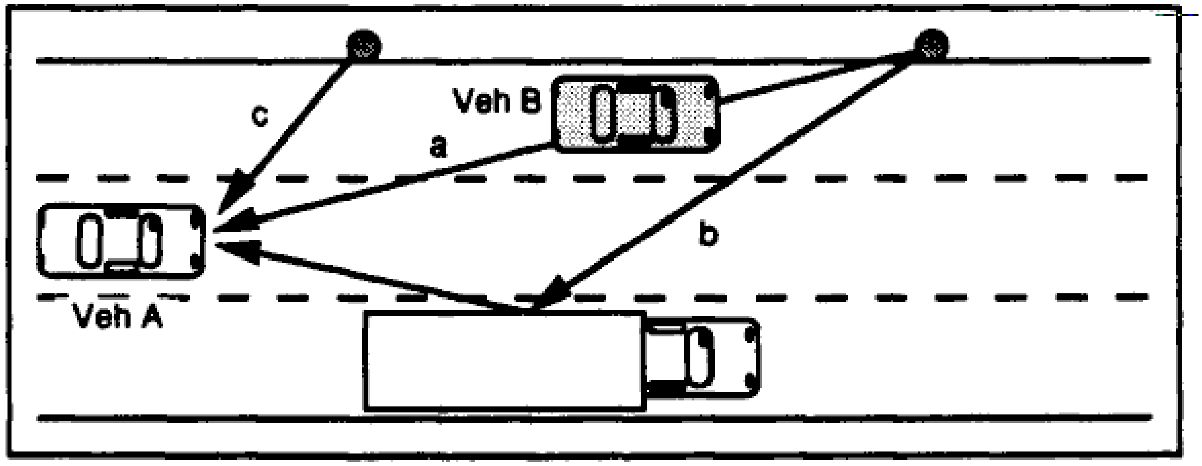


Figure 12. Multipath Effects illustration

In this example, the path length a and *c* are the correct path lengths for an accurate solution, but because of obscuration by Vehicle B in the left lane, path length *b* is the one that is sensed. This configuration gives rise to an accurate time delay for the near transmitter but an approximately *15%* longer time delay for distance *a.* A purely time-differential-based solution will in this case place vehicle A to the left and further back than it currently is. If this information is the basis for lateral and longitudinal control, then a serious and potentially dangerous situation could develop such as the vehicle trying to move to the right lane thinking that's where the center lane is.

Because of the precision required by this concept's use of these signals for lateral control, the wavelength must be in the millimeter region to provide the discriminating power. At these wavelengths, metal bodies become excellent reflectors, giving rise to many potential paths for the RF pulses to travel from the transmitter in the infrastructure to the vehicle. (For concepts where the receiver is on the infrastructure as well, the problem is doubly difficult) Differing path lengths will give rise to ambiguous signal timing, which in turn creates a positional accuracy ambiguities.

This problem can be alleviated by several means. One method is to use highly directional antennae to receive only those signals coming from the appropriate directions. The longest path length ambiguities will come from behind, and the next longest will come from the lanes farthest from the beacons. These can be eliminated with a directional receiving antenna, but if multiple beacons must be sensed simultaneously, a high-gain antenna cannot be used. If beacons were place well above the roadway, obscuration would be mitigated, but obscuration in closely spaced platooning situations might still be a problem.

Another solution is special filtering such as is used in military communications like the Hazeltine Packet Switched Radio. These filters significantly increase the equipment costs. A third solution is to provide the receivers with the ability to discriminate azimuth of the source, but that requires a considerably more expensive phased array receiver set.

6. Concept #5: Inductive Cable With FMCW Radar Concept

6.1. Summary Description

The use of inductive cables buried under the roadway has been a recurrent concept. A traveling magnetic field is set up that is the linear analog to the rotating field in an ordinary motor. The magnetic force delivered by the moving field provides the locomotive force to the vehicle.

This approach has been suggested as one way to not one power vehicles, but also to provide a lateral reference. The lateral control concept is quite simple: a magnetic field is generated by the buried cable which is picked up by an induction coil in the vehicle and transformed to mechanical energy to power the drive train. However, this concept requires augmentation to meet AHS longitudinal control requirements.

To accomplish this, the concept presented here postulates the use of FMCW (frequency modulated continuous wave) radar. Using data from this sensor, coupled with the normal vehicle state sensing (such as tachometry for determining speed), one can meet speed control, vehicle following, and platooning requirements. Providing collision avoidance with respect to other vehicles in or near the lane of travel is also feasible using this technology, but general obstacle detection and avoidance is not covered by this concept.

Figure ~1 places the concept in our classification scheme. The complexity on board the vehicle is estimated to be low to moderate, since fairly unsophisticated sensors, processing and control is required. The impact on the infrastructure is moderately high, because of the installation of the inductive cable and the highly reliable power supply needed to assure fail-safe operation.

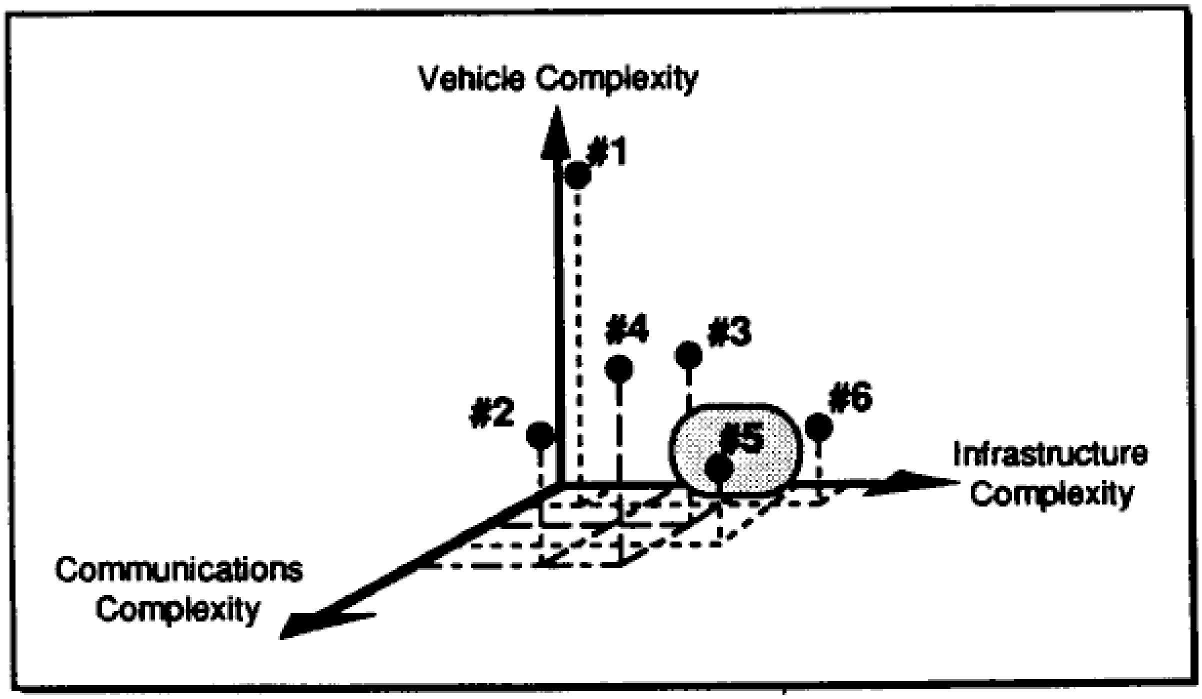


Figure 13. Classification of Concept #5

6.1.1. Summary of Approach for Lateral Control

In this concept, lateral control is achieved by sensing the presence of the electromagnetic field emanating from a cable buried under the pavement in the center of the lane. Like the magnetic nails concept, this concept requires multiple sensors across the front of the vehicle for fault tolerance and to provide better lateral range than a single sensor can afford. Unlike the flails, the field also provides power, and therefore coils require much more size and weight than simple magnetometers, providing vehicle designers with a much more complex design problem.

Steering control is identical to most other concepts in that it requires some degree of processing and complete, fault-tolerant actuation design on board the vehicle.

6.1.2. Summary of Approach for Longitudinal Control

Longitudinal control is performed though a hybrid of current-generation cruise control and radar-based sensing of vehicles in front. Speed control when not in vehicle following mode uses current-generation cruise control technology. Speed control is completely asynchronous.

Headway control is maintained by superimposing on the speed control system a delta speed command needed to maintain the desired spacing. Range estimates are based on active radar returns. Based on early simulation results, samples need to be taken at a rate of 10-20 Hz, permitting pulsed operation of the radar. Duty cycles of radar pulses should be kept as low as possible to reduce the amount of noise from large numbers of vehicles operating in the same vicinity. Sensor range must be designed to permit acquisition of vehicles in front at a minimum range of 100m on straight roads.

6.1.3. Summary of Approach for Coordinating Behaviors

Vehicles on the highway will operate at the synchronous speed of the linear inductive motor. Vehicles will be accelerated to the proper speed before entering the assigned slot on the highway. Infrastructure-based sensing and commands for acceleration and deceleration will be based on static timing relationships. Once on the highway, speed is maintained at a constant until exit. Since the speed is not independently maintained, coordination is not required.

Platooning is not required under this concept, as vehicles operate in synchronous spatial "slots" along the highway. Because vehicles individually enter and exit from assigned spatial slots, intervehicle coordination is not required.

As a backup, spacing regulation will be provided by the FMCW radar detection of vehicles in front, in case speed is not maintained for some reason (such as after an accident).

6.2. Distinguishing Characteristics

6.2.1. Allocation of Sensing Functions

6.2.1.1. On the Vehicle

Each vehicle is wholly responsible for sensing lane-relative lateral position based on cable position. Lateral position sensing is achieved by magnetometers placed at several calibration points near the front of the automobile.

Speed is sensed though multiple-wheel odometry.

Presence detection of preceding vehicles is by time-of-flight range sensing of the radar return. Each vehicle is responsible for maintaining separation between it and the vehicle in front. Radar signals may need to be modulated to provide the ability to reject energy emitted by other vehicles in the area. Range and range rate gating may also provide some filtering capability.

6.2.1.2. In the Infrastructure

Timing and position data on all vehicles within a control segment of TBD length (nominally a 1 -km stretch of road) will be maintained by the infrastructure.

6.2.2. Allocation of Control Functions

6.2.2.1. On the Vehicle

All motion control is performed on board the vehicle. the tracking, speed control, headway maintenance is autonomously performed using the sensed and communicated information described in §6.2.1 and §6.2.3 respectively.

I-ane changes are not required to be performed automatically. However, automatic control is possible in this concept.

6.2.2.2. In the Infrastructure

6.2.3. Allocation of Processing Functions

6.2.3.1. On the Vehicle

All sensor data processing, control processing, and behavior determination is performed on the vehicle. The level of complexity of the detection functions is moderate, and we expect that this concept will require approximately 20 MIPS of processing throughput for all functions.

6.2.3.2. In the Infrastructure

Processing in the infrastructure is limited to the following:

- calculating current traffic conditions such as traffic density, average speed
- estimating the impact of traffic conditions sensed on downstream highway segments on a given segment's
- determining the desired operating parameters appropriate for the current segment (nominal speed, speed upper and lower bounds, max. platoon length, etc.) an providing that guidance to the vehicles as the progress down the highway.

This processing may be done in a distributed fashion or in a centralized fashion; this concept is not sensitive to that distinction. Very modest throughput is expected to be required of each segment, and the volume of communication required of a centralized processing scheme is also quite low.

6.2.4. Allocation of Communications Functions

6.2.4.1. Vehicle to Vehicle

Vehicle to vehicle communications is accomplished using low-power, low-bandwidth (5 KB/s or less).

Vehicle to infrastructure communications is performed via low-power RF signals in the TBD band. Transceivers are placed on the infrastructure at TBD intervals (nominally 1 km). Vehicles receive broadcast information of prevailing highway conditions, and two-way communication is only with platoon leads. Individual vehicles not in platoons are considered to be "platoon leads" in this sense.

6.3. Maneuver Requirements Satisfaction

6.3.1. Lane Tracking

This function is performed by sensing the lateral movement of the magnetic field set up by the buried lane markers relative to the vehicle centerline. Where smooth control of the vehicle requires some anticipation of curvature, information on upcoming highway geometry or other operating parameters are encoded into the orientation of the sequence of magnetic markers.

6.3.2. Speed Maintenance Tracking

Speed control in an unobstructed environment is performed using existing cruise control technology, except that the commanded speed is variable depending on the curvature of the road ahead. This concept presumes that highway-dependent static operating parameters (such as maximum speed for curves where it is below the highway's speed limit) are encoded in the orientation of the sequence of magnetic references.

6.3.3. Spacing Regulation

When there are other vehicles in the lane of travel or adjacent lanes, the on-board system detects their presence and determines range and range rate based on radar returns from those objects.

6.3.4. Lane Change nominal)

Nominal lane change is performed manually. if the operator initiates a lane change with an unsignalled gradual input that could be misconstrued by following vehicles as resulting from normal lane curvature, the system will respond by vibrating the steering column and resisting the lane change.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance.

6.3.5. Lane Change Exceptional)

Exceptional lane change, defined by an abrupt change of lane, is performed manually. The operator is responsible for determining safe clearance. if a sudden torque is applied to the steering column, the system assumes an override exception and releases control to the operator.

Automated lane change is not possible because of a lack of sensors behind to detect lane clearance.

6.3.6 Vehicle Following (Nominal)

Close-interval platooning is based on direct feedback of radar range and range rate information. A scalar range value is developed at high update rates (±20 Hz) that *can* be differentiated to determine range rate as well.

The low-bandwidth RF vehicle to vehicle link provides a minimal amount of state data to provide some anticipatory information and reduce latency as compared to a sensor-based approach. Specifically, the vehicle in front provides a health-check heartbeat, velocity, acceleration, and steering updates. These data are used as part of the feedback set used by the controller.

6.3.7. Vehicle Following (Exceptional)

This concept does not allow sufficient information to track lateral motion of the vehicle in front. When an emergency event is signaled, the vehicle behind must begin slowing to create additional headway for safety, and signal the operator that the vehicle in front has executed an abrupt lane change.

This maneuver would be excited by an excessive closure rate detected by the lead vehicle. This concept, however, does not provide the capability for detecting and avoiding generic obstacles cannot be accomplished without detection sensors.

6.3.8. Emergency In-Lane Stop

Stopped vehicle detection requiring emergency response is performed using processing range and range rate data from the radar. This maneuver would be excited by an excessive closure rate detected by the lead vehicle (or single vehicle in the non-platooned case) in situations where adjacent lanes are determined to be occupied. This concept, however, does not provide the capability for detecting and avoiding generic obstacles.

6.3.9. Emergency Out-of-Lane Stop

Emergency stopping involving lane change cannot be accomplished automatically under this concept since there is no information on lane clearance available to the system. Under emergency stopping situations, the system will be constructed to permit the operator to usurp control and manually execute a lane change. However, this mode of operation is highly suspect since we presume that the operator situation awareness is limited by inattention while the system is operating under autonomous control in most cases.

The reader might question why emergency lane change is permitted while emergency lane stop is not. The answer is that an emergency lane change may create a serious situation if there are vehicles in the adjacent lane, but will not result in large disparities in relative velocity. Emergency out-of-lane stops however can create dangerous closure rates in the adjacent lane, exacerbating the interruption of flow on the AHS by extending one lane’s problem to another and creating a potentially very hazardous situation.

6.3.10. Platoon Merge

Detection of the presence of a vehicle suitable for following is performed using the radar range detection and range rate information. Range and range rate preconditions must be met for a vehicle to be considered suitable for joining. Conditions for acquiring a platoon are detection of a vehicle at a speed differential of ±8 kph and an initial spacing of 5 to 50 meters. The purpose of the minimum separation is to assure proper safety and spacing to allow for speed and spacing transients. When a platoon situation arises, intervehicle communication executes a request/acknowiedge sequence.

Platoon acquisition from another lane is not allowed, since this concept does not provide for safe lane changes under autonomous control. The operator is responsible for setting up the proper merging conditions.

6.3.11. Platoon Departure nominal)

Departure from the platoon under nominal conditions is an operator-initiated event. The operator signals the system of his intent and the system initiates a mild deceleration sufficiently large to cause following vehicles (if any) to disengage, after which the operator is expected to perform a lane change at the earliest opportunity.

Vehicles following are expected to detect this threshold deceleration (0.1 g nominally) and disengage from the platoon, fall back to a safe following distance, and await a maneuver by the vehicle in front to depart the lane. If the vehicle in front does not depart the lane after (TBD --20 seconds) and platoon merge conditions still exist, the system will automatically attempt the merger.

This concept presumes no communication between vehicles in this mode; the deceleration protocol is the signal of the departure event.

6.3.12. Platoon Departure (Exceptional)

Platoon departure under exceptional conditions is assumed to occur under one of two circumstances:

1) the platoon leader detects an obstacle and initiates evasive or corrective action

2) a platoon follower detects sudden deceleration of the vehicle in front of it In either case, the vehicle detects the condition visually and decelerates as abruptly as possible without unduly endangering potentially following vehicles. Detection is done autonomously; no communications among vehicles is implied in this concept.

6.3.13. AHS Entry (Nominal)

Entry into the AHS system occurs under manual control. Once in the system, mode changes within the AHS context are accomplished by a combination of sensed conditions and operator interaction, as described elsewhere in this section.

6.3.14. AHS Exit (Nominal)

Exit from the AHS occurs under manual control. There are no special provisions in the system for automatically sensing safe conditions.

This concept presumes that the vehicle is not in platooning mode during the exit. In order to exit while platooning, a nominal platoon demerge must first be safely executed, then the operator may initiate an AHS exit. If the operator attempts a gradual lane departure while platooning, the system will signal the situation by vibrating the steering column.

Departure under emergency conditions is as described in section *2.3.5.* above.

6.3.15. ASH Entry Abort

Entry abort is assumed to happen under one of the following conditions:

1) equipment failure during the entry process
2) occurrence of an incident during the entry process
3) presence of other obstructing entities in the vicinity during entry.

Since entry into the system is under manual control, abort is also presumed to occur under manual control, entry abort is a manual process, though if the conditions for an abort arise, the operator must be advised though visual and aural cues to *guarantee* operator awareness even if his attention is elsewhere (such as back over his shoulder where approaching vehicles are).

6.4. Required or Supporting Assumptions

6.5. Concept-related Issues

6.5.1. Failure of the Power Source and Loss of Control

Use of an active lateral control references probably mandates fully redundant, fail-s~ lateral control system.

If the system is critically dependent on the use of an active element in the infrastructure, the effects of loss of power to that element is a key reliability problem. Loss of power would result in loss of the lateral reference, effectively "blinding" all vehicles in the affected region for lateral control purposes. Particularly in areas where there are significant curves, such loss could be catastrophic without a backup of some form. The expense required for backup (such as redundant inductive cables in the highway or other forms of lateral sensing) may make the concept unworkable.

If a backup system is to be provided, it most likely will not be in the form of a second inductive element. The second element, if present, could not be active, ready for immediate takeover, because the interference from the two would cause unacceptably high line losses, even if the frequencies were different. Current switching transients when changing from primary to backup systems would be a key design constraint, forcing the system design to be driven by inordinately high peak current loads.

On the other hand, using the human operator as the backup control mode has serious implications. The human factors considerations of a requirement for sudden operator takeover when the operator has not been attentive to the situation may be the most demanding safety-related requirement of all. Ordinarily, lateral control has significantly faster dynamics than longitudinal control, and the response to loss of reference will have to be correspondingly fast. Immediate human takeover is probably not practical, particularly under high-speed, high density conditional.

6.5.2. Power Distribution and Use Would Be Expensive Initially

Power requlrements for a guideway-powered highway are quite high under heavy loads and also highly variable, making design and installation of a power distribution network potentially quite expensive.

Except for efficiency factors, this issue is very similar to that of section 7.5.4. The reader is referred to that section for a qualitatively similar discussion.

Experience shows that the most efficient linear motor applications are those for which speeds exceed 150 mph.

In general, linear motors are inferior to rotary motors of the same relative surface speed between rotor and stator. The one significant difference is when the speeds involved become high enough that centrifugal forces within the rotary motor rise beyond the tolerable limit. Centrifugal force is proportional of v^2_9 while efficiency of an electric motor (linear or rotary) is proportional to v, and somewhere around 150 mph the advantage of the linear motor becomes clearly superior. (3)

For automobile applications, where in some cases speeds slower than 60 mph will be required over protracted periods, this criterion suggests infeasibility.

6.5.4. Efficiency Versus Configuration

The more efficient configurations of linear motors require an electrical pickup for the vehicle. negating the physical advantages of linear motors.

Most efficient (rotary) motor designs do not provide power through a commentator, as many suppose. Instead, the stator windings in the motor case are powered with an alternating field and the rotor relies on inductive back-emf to provide the motive force. Hence, one side is "active", and the other "passive". This point is important in considering linear motor configurations.

If the goal is to have the guideway power the vehicle, the first inclination would be to provide the windings in the guideway (the "stator" or "primary windings") with electrical power. In this configuration, the vehicle is passively pulled along by the moving fields. Energy is transferred to the vehicle with no direct connection, and the problems of an exposed electrical power source are obviated.

The problem with this approach is that the entire guideway must be energized all the time, and resistive losses are incurred whether or not vehicles are moving down the guideway. Over distances of many miles of roadway each having many turns of windings, these losses quickly add up to unacceptable levels.

This second approach is best illustrated by the "Electropult" developed by Westinghouse during WWII. In considering the use of linear inductive configurations for aircraft carrier catapults, Westinghouse engineers showed that to energize a track of several hundred feet to the horsepower needed for accelerating an aircraft to takeoff speed would require the output of a moderately-sized power station. The only way out of this difficulty is to interchange the roles of rotor and stator, in which case the whole stator current is gainfully employed. In this configuration, the vehicle side is actively powered and the roadway side is passively reactive through the magnetic circuit. (3)

While being many times more energy efficient, the downside of this configuration is that energy must be transferred to the vehicle through collectors sliding along slip tracks, much like is currently used in electrically powered trains. This configuration, while more efficient, is no more advantageous than a rotary motor drive.

6.5.5. Efficiency Versus Positioning Accuracy

Efficiency of the inductive motor is partially a function of the width of the coils, but more coil width reduces the ability to discriminate lateral position.

Electromagnetic efficiency is related in part to the width of the stator coils (W) relative to the the pole pitch *(p),* which in turn is related to frequency q) of the power supply. A tradeoff between the efficiency of the electromagnetic effect and the ability to use the field for lateral position reference exists that may make effective use of the induced field for positioning difficult The pole pitch is related to speed of the field movement by the relationship:

$$p = {}^{v_s}\!/_{2f}$$

If the desired speed is 25 mps and power comes from a 60Hz source, the pole pitch must be 0.208 meters. For electrical efficiency, the pad width should be at least ten times the pole pitch to make the end-turn loop resistance a minimal part of the losses, or 2.08 meters. This means the pad width will be roughly six feet across.

In the case where the roadway carries the powered side of the linear motor (the "primary" or "stator"), if the field strength were to be plotted against lateral lane position, the plot might look something like Figure 14 below:

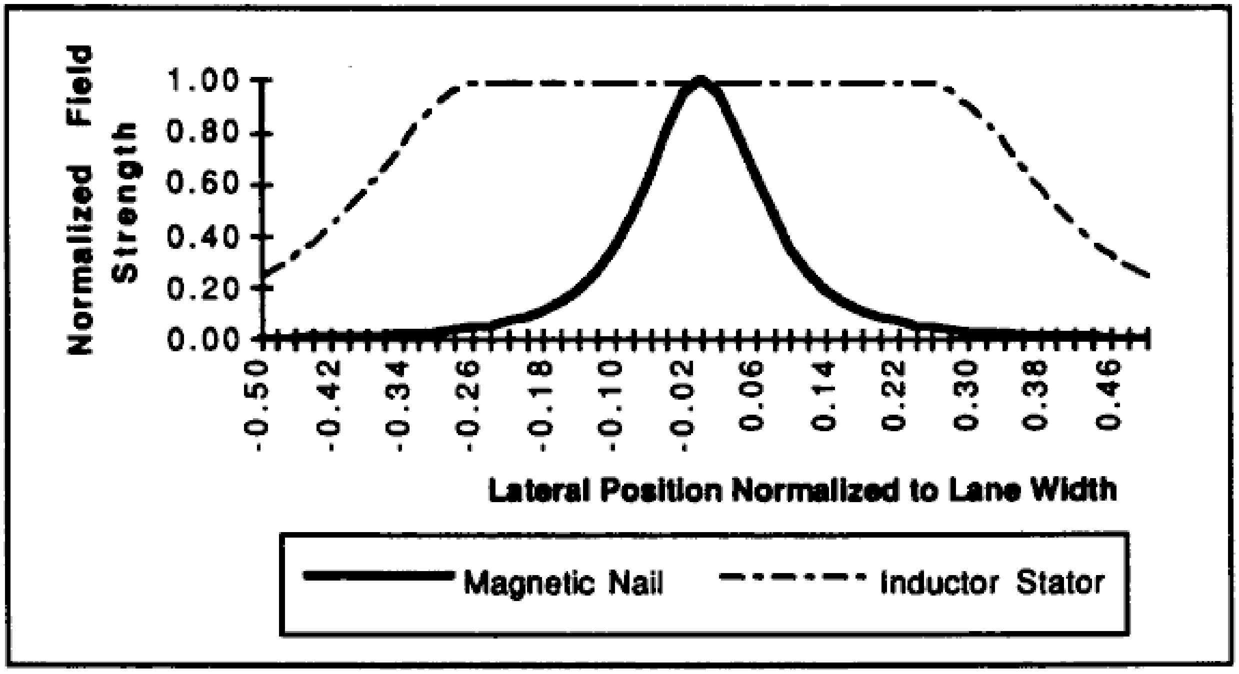


Figure 14. Shape of field strength as a function of lane width.

The relative magnitude of the two fields is not intended to be proportionate in this diagram, since field strength is a function of separation between magnetic field source and magnetometers, materials used, mechanical configuration, current strength, and other design parameters. However, this plot is indicative of the fact that, as a rule of thumb, magnetic field strength varies as the inverse r^3. Since the stator has a finite pad width, the field is much wider and has somewhat less steeply sloping sides. A magnetometer will feel the effect of the full width of the the stator as it moves laterally.

The logical consequence one may draw qualitatively is that magnetometers will have less sensitivity to lateral position offset than is true for magnetic nails because of the large interval of ambiguity near the center. In addition, the presence of the magnetic fields around the component on the car will further obscure readings. For the case where vehicle carries the active current loops, the lateral position may in fact be impossible to determine with any accuracy due to the strong, constantly changing magnetic fields around those elements.

Reducing the width of the pad to localize the field is not a good solution because doing so has two drawbacks:

1) it reduces the area over which the electromagnetic force acts, leading to higher current loads for the same level of motive force, and

2) it increases the portion of the windings around the ends of the loops that are outside the slots in the stator and therefore are not contributing to the development of electromagnetic force, leading to reduced efficiency.

6.5.6. Roadway Vertical Variation Tolerances

For a flat-bed coil configuration in the center of the roadway, vertical tolerances along the roadway length will be critical, and normal road wear and seasonal heaving of the roadway will be a problem.

The single largest determinant in system efficiency is the size of the air gap between the rotor and stator. The closer the tolerance, the more efficient the motor. For linear motors, this means that there must be very little clearance between the vehicle and the guideway portions of the motor. Low clearance tolerances means that stiff suspensions will have to be used, or the coils on the vehicle will have to be independently and perhaps even actively suspended.

The biggest problem with tight vertical tolerances is that roadway heave due to seasonal effects will cause unintentional contact between stator and rotor. This effect is very difficult to control for at-grade highway construction. Elevated highway construction can obviate this problem, at considerable extra per-mile construction costs.

6.5.7. Attractive Force Versus Motive Force

For most linear motor configuration, the attractive force is approximately ten times greater than *the force in the direction of travel.*

Electric motors are subject to magnetic and electromagnetic forces. The former acts to pull the rotor and stator toward each other, while the latter acts as a shearing force and is hence where the motive force comes from. Rotary motors distribute the magnetic force around the circumference of the rotor, canceling the effect out, while linear motors concentrate all the magnetic force along the same vector. Since the electromagnetic force is only one-tenth that of the magnetic force, for each Newton of force required to pull a vehicle forward, ten Newton's of downward force is applied to the vehicle and ten Newton's of upward force is felt by the roadway.

One consequence is that, on uphill grades, the mechanical engineering on the roadway portion will have to be very stout, driving up the installation costs per mile. A second consequence is that the high downward force, coupled with the need for very small variations in the gap, mean that the coils on the vehicle must have a very low compliance suspension, essentially making it necessary to decouple it from the vehicle for ride quality reasons.

6.5.8. Speed Control

There are two primary means of providing synchronous speed control: variable frequency power and pole switching. Both methods complicate the engineering and lead to considerably more complicated hardware designs.

If the stator (powered current loops) is in the guideway, there is no means for individually controlling vehicle speed other than braking, which is wasteful of energy. If the stator is on the vehicle, pole-switching is feasible for a limited number of speed settings, but causes the vehicle costs to grow. The alternative is to let the motor "slip", which induces energy inefficiency and heat buildup.

6.5.9. Heat Dissipation

Electromagnetic field "slip" translates into heat building up, in the coils that must be dissipated.

If vehicles are not running at the field propagation speed (called the synchronous velocity), the result is termed "slip." A motor running at less than its synchronous velocity builds up heat at a rate proportional to the rate of slip. This buildup occurs primarily in the primary (stator) windings and can gradually cause insulation breakdown. If built into the highway, heat buildup during high-density traffic can gradually cause breakdown of insulation. If carried on the vehicle, extra heat rejection weight and bulk must be designed into the vehicle.

6.5.10. Fairly Charging for Power Use

Power drawn from the infrastructure will need to be metered on the vehicle and use data downloaded at checkout time. This requirement will add to the cost and complexity of the vehicle.

Power use in a vehicle is subject to many variables. Vehicle efficiency may vary as a function of how well maintained the vehicle is and the loading on the vehicle relative to its designed capacity.

Wind resistance is a function of vehicle size. Rolling resistance is a function of tire pressure, wear, and gross weight. Power use on grades is a function of both gross weight and plant efficiency. With all other factors held constant, average efficiency is also affected by how well tuned the control system is and what degree of throttle excursions are used in maintaining speed and/or spacing control.

Because of all these factors, establishing charging as a flinction of vehicle type and mileage used would not be completely fair. It is doubtful that the public would accept a system that charges per axle, as is done on many toll roads today (such as the New York State Thruway) because of the cost inequities that would result. Even establishing average power per mile for each vehicle type is not accurate. Almost certainly, power use would have to be metered to be fair. Metering would have to be on board the vehicle, since detecting the actual power use from the Infrastructural side would be very difficult to accomplish. On-board metering is conceptually easy to accomplish, but adds to the cost of the system. Not only is the cost of the metering and logging of use required, but a way of automatically exchanging the results

6.5.11. Environmental Effects of Electromagnetic Fields

Constant exposure to electromagnetic fields has been an environmental concern in recent years, particularly for individuals residing near high-voltage transmission lines. The intensity of fields from linear induction motors is potentially higher, and the health and environmental effects are not known.

This issue of the health effects of long-term exposure to strong electromagnetic fields is surrounded by speculation and uncertainty. At the very least, concerns of this sort could be a serious impediment to implementation, if for no other reasons than public perception.

The use of radar for obstacle and collision detection has been pioneered in the aviation industry, but: the techniques used there do not translate easily to the ground environment. Achieving reliable, fail-safety obstacle detection with non-imaging devices will require substantial research and development activity.

The ground vehicle domain is considerably more complex from the standpoint of performing general obstacle avoidance than the airborne analog. In our estimation, a non-image forming radar would not be suitable in the ground vehicle domain. In aircraft, obstacle avoidance is a function of determining the azimuth, elevation, and range to any object and determining if that object is on a collision trajectory. A non-image forming radar that merely keeps track of detected objects and then analyzes the history of that track file is sufficient. Since any object reflecting significant radar energy is suspect, discrimination is not a problem.

In the ground vehicle domain, the problem is considerably more complex. There are many objects in the field of view that apparently approach the vehicle on collision trajectories. For instance, the approach of a bridge abutment when the road curves gently in the vicinity of a bridge would appear to be a collision-bound object, when in fact it should be ignored. A large rock on the shoulder in a fallen rock zone could likewise provide a false alarm. Other vehicles on adjacent approaching lanes on the inside of a curve would also be difficult to reject. Discriminating any object large enough to damage the vehicle requires forming a narrow beam. Discriminating only those that lie in the lane of travel or might cross the lane of travel within the safety zone requires fairly sophisticated processing. The combination of a narrow beam and the sophisticated processing probably makes the sensor too expensive to consider.

7. Concept #6 Direct Pickup, Shared Public/Private

7.1. Summary Description

This concept departs *from* the other five in this report in two major aspects. First, it provides for sharing of infrastructure with public transit vehicles on dedicated transit "tracks", and second, it uses centrally-supplied, direct pickup electric power. In this concept, privately-owned vehicles would be equipped with the physical devices necessary to share transit lanes with busses and other "people movers." The lanes would be constructed to provide power via direct-contact electrical pickup. Public transit vehicles would share the lanes and power with private users.

The design of the lanes themselves is open under this concept. They could be at grade or elevated. Power pickup could be to the side or in the lane center. Lane width would be subject to the selection of transit vehicle design, but might be constrained by the size of current day busses if a retrofit of existing transit was part of the plan. The design constants are that there must be an electrical supply rail for the direct pickup coupling, and a passive form of lane guidance via physical linkage. Dual-mode vehicles would likely have to be designed to retract their guidance and power pickup mechanisms when operating on normal highways for safety and reliability reasons.

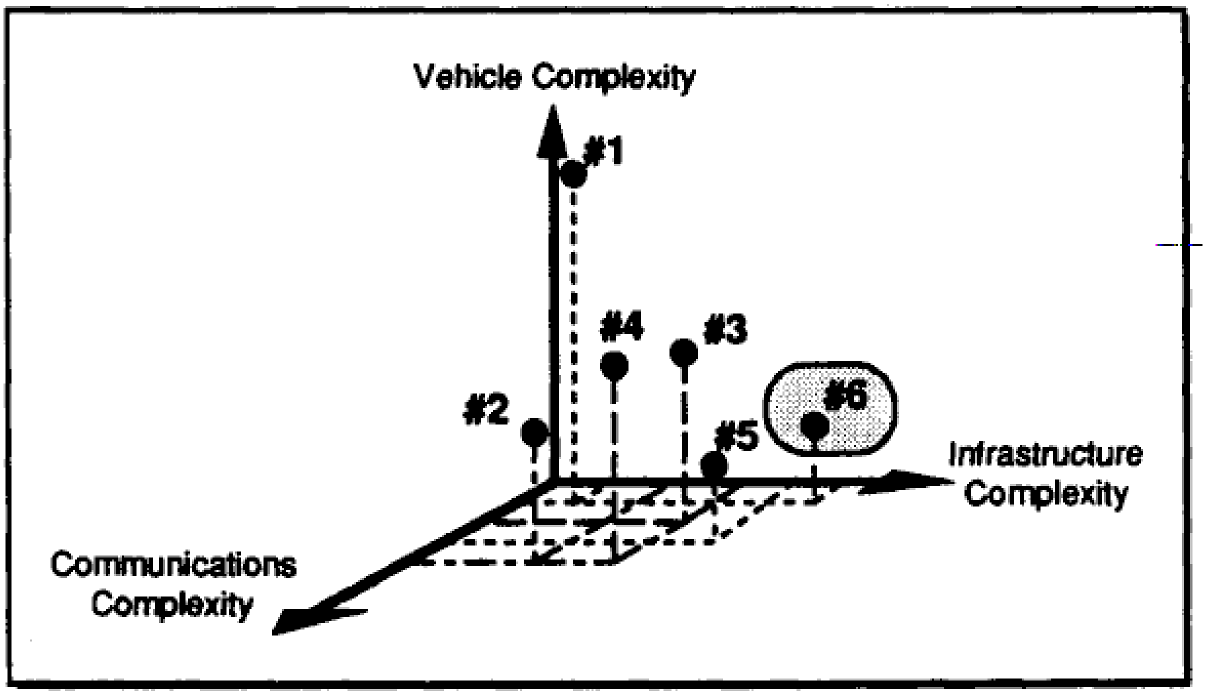


Figure 15. Classification of Concept #6

In terms of our classification scheme, this concept is rated low on vehicle complexity, low on communications complexity, and high on infrastructure complexity. The high infrastructure rating is mostly driven by the cost of the design, construction, and maintenance of the dedicated lanes, and the power distribution infrastructure associated with centrally-supplied power. The design of the vehicle itself is modeled somewhat by the need for an electric drive mechanism, but this concept presumes that in the not too distant future that vehicles will commonly have all-electric or hybrid drives anyway.

7.1.1. Summary of Approach for Lateral Control

Lateral control is achieved by a physical linkage to the track that couples to the vehicle's steering mechanism. The coupling could be direct physical linkage, or via a "feeler" mechanism that drives actuation to allow for variances in design tolerances, vehicle sizes, operating speeds, vehicle dynamics, etc. The infrastructure mechanism providing power could double as the steering mechanism as well.

This concept's steering is no more complicated than that of electrically-driven people movers in operation today at numerous airports and urban centers around the country. The major difference is that vehicles will have to be equipped for operation on normal highways as well. One other significant difference might be the necessity of providing multiple lanes of travel in a given direction with the ability to change between lanes. Under this concept, the lane crossover points and entry/exit points would be designed at periodic points along the highway, and lane changes would be restricted to these points. For evaluation purposes, these points would be at no less than 0.5 kilometer intervals.

7.1.2. Summary of Approach for Longitudinal Control

Speed would be centrally monitored and controlled by a series of RF beacons that broadcast the operating conditions on the infrastructure at relatively low bandwidth. Information transmitted would include bursts of data at about a 1 Hz update rate. Fine control of speed in close following conditions would be the responsibility of the vehicles using TBD.

Originally we believed that the power distribution system could also be modulated to provide communications as well. However, we believe that given the number of vehicles operating in a given area, the frequency of vehicles entering and exiting causing transients, and the the noise characteristics of the direct pickup mechanism would probably render broadcast modulation on the power conduit ineffective. Instead, we have postulated an RF-beacon mechanism similar to that of the concept in section 5.

7.1.3. Summary of Approach for Coordinating Behaviors

Coordination of behaviors among vehicles would be nearly completely autonomous and distributed. The only explicit coordination required is longitudinal spacing; lateral coordination is obviated by the use of dedicated tracks.

7.1.4. Special Acknowledgement

Credit for the genesis of this idea goes to John Kiljan of Colorado Department of Transportation. His perception of the problems of AHS implementation center on the following points:

- The focus for relieving urban congestion should be on the movement of people. Commercial freight vehicles are moderately efficient in terms of the energy expended per pound of freight moved. If a substantial portion of people moving traffic were taken off the existing highway infrastructure, the operating efficiency of the commercial freight traffic would increase substantially even if there were no developments in the CVO arena.

- Any good long-range solution must include a provision for reducing private, single-occupancy ridership. It is highly desirable to build an infrastructure that would work equally well with private and public means, but would provide the incentives for gradually and continually reducing the use of private vehicles.

- The basis for any major change in infrastructure or new infrastructure cannot be to make private transportation easier. The extensive use of private automobiles is generally perceived as the cause of urban freeway congestion.

- Environmental considerations will become more and more important in the next two decades. Any major expense must be directed at solutions that substantially improve the environmental impact of moving people, particularly in urban areas.

To address these concerns, Mr. Kiljan suggested the essentials of this concept, which we have refined as needed to carry out the evaluation within our conceptual framework. He also suggested the use of a vehicle design that was a hybrid of centrally-supplied power and on board storage (batteries or fuel cells). Under his concept, this would improve the operating radius of urban travel, even if only a portion of the energy needed to complete a trip was supplied by the infrastructure. We have omitted this aspect from the present section and our evaluation of the concept, but have included a discussion of the topic in the Concept Evaluation Document in section 5.1.1.

7.2. Distinguishing Characteristics

The single most distinguishing characteristic of this concept is the notion that public transit would share a dedicated infrastructure with private vehicles. The thought that lies behind this concept is that it would be initially justified on the basis of public transit. The problem with dedicated public transit from the general public's point of view is convenience. Generally, public transit vehicles do not go where most of the people want to go at the times they want to go there, especially during early phases of deployment when the coverage is limited. This is particularly a problem for business activity, where convenience of time translates directly into labor dollar costs. Also. it takes time for public authorities to develop the full infrastructure (routes and numbers of vehicles) required for full coverage. During this time, public interest can wane and consequently the sources of funding dry up.

Allowing private vehicles to share the medium mitigates these problems. The infrastructure would initially be developed on the corridors of highest density, and would branch out from there. Public transit vehicles would be built as the ridership demands, reducing the need for government subsidizing of system costs during the early phases of development. Further, the costs of development could be partially offset by use fees levied on private users. After a while (when the system is more fully developed) the coverage and route scheduling would be such that dramatic increases in public transit vehicle use would (hopefully) occur. Incentives could be developed, through pricing mechanisms, to encourage reduced use of the public transit infrastructure by private vehicles. In this way, ridership would be gradually transferred from private vehicle use to public transit use. However, during the long development interval, the convenience of private vehicles (in terms of coverage and schedule control) would still be available to the public. This concept allows for an optimal blend of public and private ridership on the same infrastructure, and the relative percentages between the two can change with time without having to modify the infrastructure. Moreover, the initial cost of the infrastructure could be justified based on the environmental benefits of electrically-powered vehicles.

A side effect of this concept is that it excludes large trucks from consideration. Improvements to commercial vehicle operations could continue on a parallel track, under the assumption that whatever CVO needs exist can be met on the existing highway infrastructure. However, benefits from this concept would accrue to CVO in that reduced congestion due to density and accidents on highways and arterials would reduce cost of operation on those roads.

7.2.1.1. On the Vehicle

Presence of vehicles ahead would be required for close vehicle following modes. Vehicles will also monitor the power pickup to smoothly transfer to internal power during lane change or power interruption.

7.2.1.2. In the Infrastructure

Infrastructure sensing is required to monitor number of vehicles, average current speed, and power demand or effects on voltage and current available.

7.2.2. Allocation of Control Functions

7.2.2.1. On the Vehicle

Steering, brake, and throttle control are entirely onboard each vehicle. Selection of lane, entry point, exit point are onboard the vehicle and at the operator's discretion.

Control of entry acceleration and exit deceleration profiles is the responsibility of the human operator.

7.2.2.2. In the Infrastructure

Selection of operating speed and spacing are in the infrastructure and based on sensed traffic flow conditions. There no actuation or control functions performed by the infrastructure other than the gate at each point of entry.

7.2.3. Allocation of Processing Functions

7.2.3.1. On the Vehicle

Control processing and sensing processing for determining the relative headway are on the vehicle. Vehicle route planning functions are also contained on the vehicle.

7.2.3.2. In the Infrastructure

Each highway segment is required to monitor traffic conditions and compute optimal speed and headway conditions. These data are to be broadcast to the vehicles operating along that segment. Adjacent segments will communicate to ensure that there are no large disparities in these operating conditions at the boundaries.

7.2.4. Allocation of Communications Functions

7.2.4.1. Vehicle to Vehicle

Vehicle-to-vehicle communications will be required to ensure safe operation at minimal headways. (See section TBD). Since platooning is ignored under this concept, no request-acknowledge sequence is required

Emergency stop beacons are required under this concept. Because the lanes are laterally restricted and vehicles cannot elect to depart from the lane except at designated points, the implication is that any vehicle executing a emergency in-lane stop maneuver presents a hazard to vehicles approaching from behind. Such beacons will use directional transmitting devices (RF antennas, IR, etc.) having sufficient range to allow approaching vehicles to safely come to a stop using no more 1.96 meters/second^2 (0.2 g). Table 2 below provides suggestive range values for a variety of speeds and reaction latencies.

Operating Speed (kph)	Reaction Latency *(Sec)*	Beacon Range (meters)
80	0.1	128
90	0.1	162
100	0.1	200
110	0.1	241
120	0.1	287
80	0.2	130
90	0.2	164
100	0.2	202
110	0.2	244
120	0.2	290
80	0.5	137
90	0.5	172
100	0.5	211
110	0.5	253
120	0.5	300

7.2.4.2. Vehicle to Infrastructure

At the point of entry, the infrastructure must provide encrypted entry location data. The vehicle is required to provide the configuration data and self-health built-in-test results as required.

The infrastructure is required to provide speed and headway set-points at one-second intervals.

At the point of exit, the vehicle must transmit the entry point data given to the vehicle on entry along with vehicle ID data. The infrastructure is required to record this data and pass it back to the central facility for billing.

7.3. Maneuver Requirements Satisfaction

7.3.1. Lane Tracking

Lane tracking is performed by each vehicle independently. All requirements for redundancy, safety, and performance fall to the vehicle.

7.3.2. Speed Maintenance Tracking

Speed tracking is allocated to the vehicle. The infrastructure selects the operating set point, and the vehicle is responsible for maintaining that speed as closely as conditions permit. However, if headway constraints dictate, speed will be reduced to that which does not cause collision. Headway maintenance functions take precedence over speed control functions.

Spacing regulation is allocated to the vehicle. The infrastructure selects the operating set point, and the vehicle is responsible for maintaining that headway as closely as conditions permit. However, speed constraints are an upper bound, and if that means that minimum headway is not sustainable unless speed constraints are violated, then speed constraints take precedence.

Headway regulation is in this concept not construed to mean platooning. The objective is to improve density by automatically maintaining close headway at normal operating speeds, but the concept of platoons (while not excluded) is not to be inferred from this description.

7.3.4. Lane Change (Nominal)

Lane change is to occur only at designated points along the highway. This is required under this concept because of the use of centrally-supplied power via direct pickup. Notionally, it is possible to design embedded pickup mechanisms that would permit unconstrained lane change, but our conceptual designs suggested that the cost and complexity would be greater, and the freedom to use a vehicle-side pickup mechanism was left in the design. Given that assumption, lane changes could only be made where there was a break in the mechanism.

7.3.5. Lane Change (Exceptional)

Exceptional lane changes would be precluded under this concept.

7.3.6. Vehicle Following (Nominal)

Under nominal operating conditions, vehicles would maintain following distance using low-resolution forward-looking radar. Vehicle speed and relative spacing are monitored on a continuous basis, and vehicle speed is controlled to maintain required spacing within given speed constraints. Speed limits and headway constraints are dictated by the system.

7.3.7. Vehicle Following (Exceptional)

As soon as an off-nominal condition is detected, following vehicles are expected to increase headway to safe distances. Since the guideway provides only occasional exit points, there is no provision under any condition for following vehicles that depart the lane of travel.

7.3.8. Emergency In-Lane Stop

Emergency in lane stop is accomplished via on-board control mechanisms as indicated by the c-stop beacon on the vehicle ahead or according to other 'TBD triggers or events. When an c-stop is executed, the c-stop beacon will signal to potential following vehicles without delay to allow them to behave appropriately.

7.3.9. Emergency Out-of-Lane Stop

Not permitted under this concept; lane changes are physically inhibited except at designated points along the highway.

Platoon operations are excluded from this concept by assumption. (Platooning is possible, but has been ignored for purposes of comparison with other concepts that permit it.)

7.3.11. Platoon Departure nominal)

Platoon operations are excluded from this concept by assumption. (Platooning is possible, but has been ignored for purposes of comparison with other concepts that permit it.)

7.3.12. Platoon Departure (Exceptional)

Platoon operations are excluded from this concept by assumption. (Platooning is possible, but has been ignored for purposes of comparison with other concepts that permit it.)

7.3.13. AHS Entry (Nominal)

Entry onto the AHS will occur at designated points only. Vehicles are expected to accelerate to the operating speed of the AHS prior to moving into the active lanes. Timing of the entry to merge into holes in the traffic will be under operator control. Once the vehicle is positioned in the active lane and engaged with the power supply and lateral control mechanism, automatic control will engage.

The intended point of exit must be prespecified at the point of entry and provided to the infrastructure. This data will be used to regulate power distribution and estimate traffic patterns throughout the system.

Entry points will be guarded by physical barriers that prevent entry of non-equipped vehicles. Since private vehicles are sharing the infrastructure with public transit vehicles, every precaution must be taken to ensure that only properly equipped and correctly functioning vehicles enter the AHS.

7.3.14. AHS Exit (Nominal)

AHS exit will occur at designated points only. Vehicles will depart and then decelerate. Departure and deceleration will be under operator control. The AHS equipped vehicle is expected to perform some form of operator readiness check. Failing that check, exit will be permitted.

7.3.15. AHS Entry Abort

Entry abort is not possible after the physical gate has allowed the vehicle to pass through. Since the merge process is under human control, the operator has the responsibility for

7.4. Required or Supporting Assumptions

7.5. Concept-related Issues

7.5.1. Tamper-Proof Power Use Metering

Because of the use of centrally-supplied power, a means of metering power draw during AHS operations that is tamper-proof is required to permit fair and accurate billing.

With vehicles entering and exiting the system in random fashion, centralized billing (offboard) is likely to be much more complex than a vehicle-borne system for measuring and reporting use. The problem here is that individuals could tamper with the equipment in such a way as to modify the reporting. Designs for detecting such tampering and prosecuting offenders is integral to the success of this concept.

A candidate implementation is to record on the vehicle the point of entry, and at the point of exit to report vehicle ID and point of entry. Billing for power use would be based on vehicle type and distance traveled, based on published rate tables. Cost of using the system would be billed on a monthly basis, much like present day utilities for building power. Entry would be denied at the point of entry to users delinquent in their payment for prior use.

The entry point, vehicle type, and vehicle ID data could be encoded in a date-specific fashion, with a daily changing public-key encryption schemes varying from day to day. This would make it nearly impossible to alter the data Vehicle ID data could be embedded in ROM at the time of manufacture to prevent inaccurate reporting.

7.5.2. Fines for Poor Maintenance

A disincentive for poor maintenance needs to be included in the system definition for AHS users under this concept to minimize the impact of failures on the general public.

The fundamental goal of this concept is improved people-moving capacity. Failures of private vehicles on the shared infrastructure have a potential impact on the good of the public at large. Ensuring that private operators perform the appropriate preventive maintenance could become a problem once private use becomes widespread.

A disincentive for poor upkeep would be to fine private users whose vehicle failures create congestion in the system. This is a radical concept in some regards, but the notion is that use of the AHS is a privilege, accepting the consequences of failure are an integral part of the user's agreement. Certain failures blowout due to cut tires, failures induced by the infrastructure) would be excluded.

Why is this required when there is no such provision in today's operating environment? After all, a failure is not necessarily the individuals fault, right? Public transit systems operate in one of two modes: they either operate on dedicated rights of way that the general public may not enter, or they operate on existing highways where they can generally circumvent problems created by private users. In the latter case simple vehicle failures are treated by pulling the failed vehicle onto the shoulder and the resulting traffic transients are usually short-lived. In an AHS system where there are a limited number of exit points and a single vehicle can bring an entire highway to a dead stop, there is potential for one individual to affect tens of thousands of commuters as well as the revenues of a public transit system. The consequences of failed vehicle causing a "system outage" *must* be directly felt by the individual responsible for the problem.

7.5.3. Weather Effects on Central Power Distribution System

The design of open-air direct connect power pickup mechanisms is very difficult in areas where there is significant snowfall or heavy rains.

Special attention will have to be paid to the design of the system to avoid shorting and leakage due to splashing water. In colder climates, problems due to icing conditions can physically damage the power pickup mechanisms.

7.5.4 System-Wide Power Requirements May be Prohibitive

The magnitude of power required for an entire urban area and the infrastructure it implies in power generation and distribution is quite substantial.

Let's examine two cases. Suppose in the first case there is a two-lane stretch of roadway that climbs through 100 vertical meters over a 4% grade (2.5 kilometer) segment. Supposed further that that segment has moderately high density traffic, say 10 trucks and 25 vehicles for each kilometer of each lane space. For this model, we use the drag model contained in the models documented by Prof. Iannou (3), converted to metric notation. The second case is a flat highway under similar circumstances.

The question is, how much energy in either case would be required to power traffic for each kilometer of travel? We presume for the sake of argument that a worst case (high density) flow is under consideration, since those conditions would dictate the Infrastructural requirements. These two cases could in a sense be considered bounding cases; actual power requirements are likely to fall in between the two.

Under these conditions, one could expect to have a requirement for almost 10 MW per kilometer of highway. The reader should note that we have used presumed efficiency factors. The power draw is inversely proportional to the efficiency factor. The reader should also note that this calculation is based on roughly 3100 vehicles/lane/hr. However, it should be noted that AHS researchers are planning toward densities of 4000-6000 vehicles per lane per hour, causing the power draw to scale proportionately. We also presume that lost energy due to accelerate/decelerate sequences for normal headway maintenance functions are included in the efficiency factors.

Table 3 on the next page demonstrates that calculation for a *2.5-km* segment of highway that averages a 4% grade. Table 4 on the page following provides the same set of calculations as modified for the case of the flat highway segment These two tables, as previously stated, could be taken to represent upper and lower bounds for a worst case design. Clearly, engineers would have to analyze the power requirement for each section of highway and sum the total requirements.

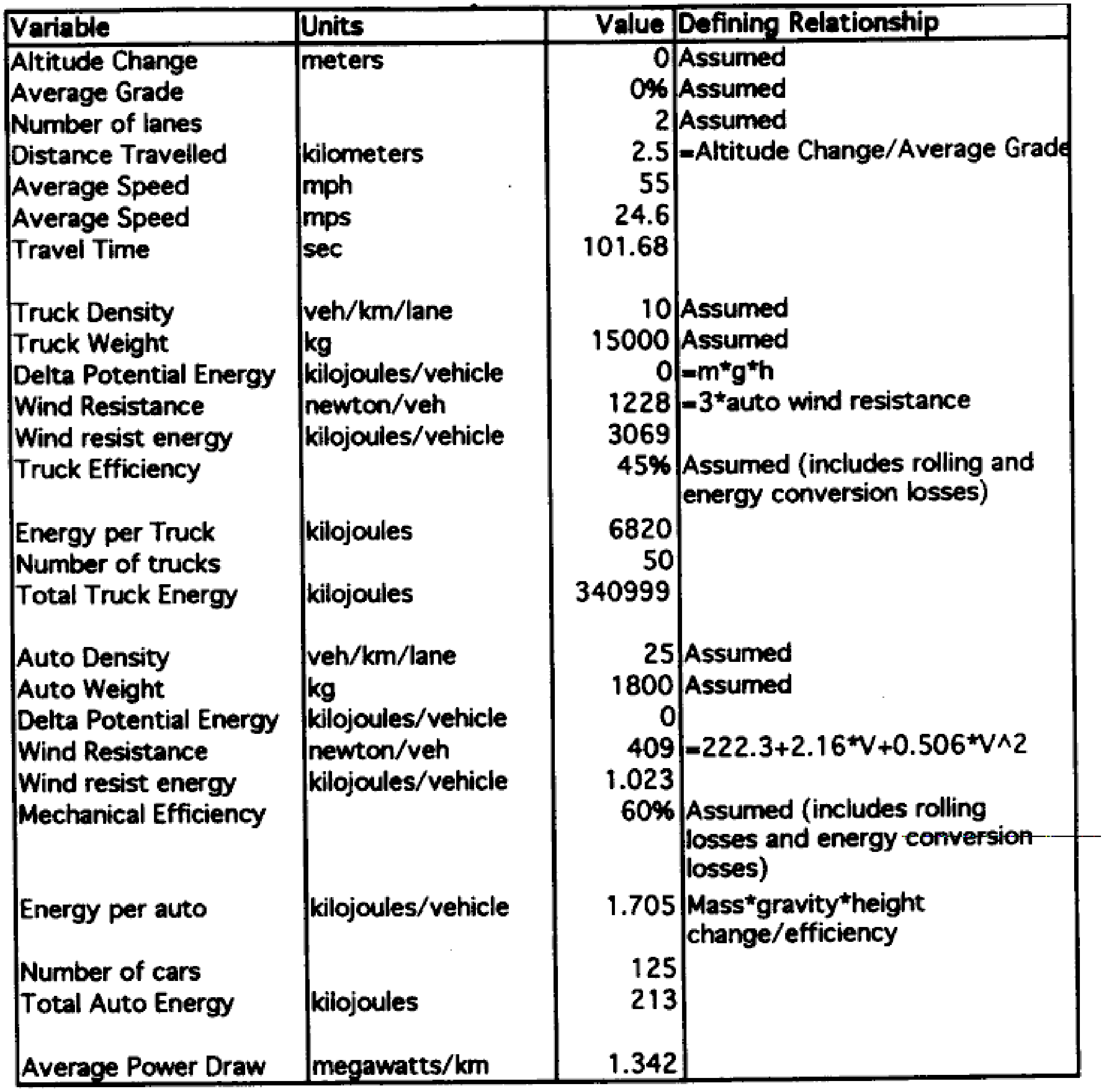
Suppose an average urban center were assumed to require (conservatively estimating) an average of 3MW for each kilometer under high-density conditions. If there were 250 miles of urban freeways and arterials in a service district, a power generation plant of 750 megawatts' capacity would be required.

Clearly these are very approximate ROM estimates. However, they point out that a substantial power generation and distribution capacity would be required if all the car and truck traffic currently on the highway were to be powered centrally. Obviously, not all vehicles will be transformed to use Infrastructural power all at once; initially the power requirement would be a small fraction of what is calculated above. But system designers must contemplate the final cost of the fully-implemented system.

Table 3. Power Required for Uphill 2.5km Segment

Variable	Units	Value	Defining Relationship
Altitude Change	meters	100	Assumed
Average Grade		4%	Assumed
Number of lanes		2	Assumed
Distance Travelled	kilometers	2.5	=Altitude Change/Average Grade
Average Speed	mph	55	
Average Speed	mps	24.6	
Travel Time	sec	101.68	
Avg Truck Density	veh/km/lane	10	Assumed
Avg Truck Weight	kg	15000	Assumed
Delta Potential Energy	kilojoules/vehicle	14704.5	=m*g*h
Wind Resistance	newton/veh	1228	=3*auto wind resistance
Wind resist energy	kilojoules/vehicle	3069	=wind resistance*distance
Truck Efficiency		45%	Assumed (includes rolling and energy conversion losses)
Energy per Truck	kilojoules	39497	
Number of trucks		50	
Total Truck Energy	kilojoules	1974832	
Avg Auto Density	veh/km/lane	25	Assumed
Avg Auto Weight	kg	1800	Assumed
Delta Potential Energy	kilojoules/vehicle	1765	
Wind Resistance	newton/veh	409	=222.3+2.16*V+0.506*V^2
Wind resist energy	kilojoules/vehicle	1.023	=wind resistance*distance
Mechanical Efficiency		60%	Assumed (includes rolling and energy conversion losses)
Energy per auto	kilojoules/vehicle	2943	Mass*gravity*height change/efficiency
Total Number of cars		125	Assumed
Total Auto Energy	kilojoules	367826	
Traffic Density	vehicles/lane/hr	3098	
Average Power Draw	megawatts/km	9.216	

Table 4. Power Required br Flat 2.5-km Seament



Variable	Units	Value	Defining Relationship
Altitude Change	meters	0	Assumed
Average Grade		0%	Assumed
Number of lanes		2	Assumed
Distance Travelled	kilometers	2.5	=Altitude Change/Average Grade
Average Speed	mph	55	
Average Speed	mps	24.6	
Travel Time	sec	101.68	
Truck Density	veh/km/lane	10	Assumed
Truck Weight	kg	15000	Assumed
Delta Potential Energy	kilojoules/vehicle	0	=m*g*h
Wind Resistance	newton/veh	1228	=3*auto wind resistance
Wind resist energy	kilojoules/vehicle	3069	
Truck Efficiency		45%	Assumed (includes rolling and energy conversion losses)
Energy per Truck	kilojoules	6820	
Number of trucks		50	
Total Truck Energy	kilojoules	340999	
Auto Density	veh/km/lane	25	Assumed
Auto Weight	kg	1800	Assumed
Delta Potential Energy	kilojoules/vehicle	0	
Wind Resistance	newton/veh	409	=222.3+2.16*V+0.506*V^2
Wind resist energy	kilojoules/vehicle	1.023	
Mechanical Efficiency		60%	Assumed (includes rolling losses and energy conversion losses)
Energy per auto	kilojoules/vehicle	1.705	Mass*gravity*height change/efficiency
Number of cars		125	
Total Auto Energy	kilojoules	213	
Average Power Draw	megawatts/km	1.342	

7.5.5. Emergency, Powered Lane Exit

Making a lane change under emergency conditions will mean that the vehicle will have to be able to exit the guideway at any point along the way. This, in turn, will require that power strips or contacts cannot impede lateral movement of the vehicle, at least in one direction..

Many have speculated on the benefits of roadway-powered vehicles because of the proven success and technological maturity of certain electric transit vehicles (e.g., Washington Metro, electric busses). However, there is a significant difference between transit vehicles operating on a dedicated guideway and a random mix of private, public, and commercial vehicles on a common use guideway. The latter case multiplies the types and severity of failure conditions. Variations in levels of maintenance, vehicle performance, reliability, and other' differences must be allowed for in the system design. We would argue that because of the large variety of vehicle types, purposes, and operators as well as the state of the art in detecting and reacting automatically to obstacles or incidents will mandate that fully automatic control prohibiting usurpation by the operator will be unacceptably safe.

If the operator (who has an undetermined level of training and awareness of the situation about him) is to usurp control, then there must be provision for him to have freedom to change the vehicle state to mitigate the problem he is reacting against, Having the ability only to change vehicle speed is unacceptable because of the frequency with which such events occur. One need only consider the huge impact of only one vehicle overheating and being unable to quickly remove itself from the Long Island Expressway during rush hour in the summertime.

Reacting to highway obstructions is an issue in the same vein. The current state of the art in sensors will not permit sensing of all types of obstructions that could damage a given vehicle at ranges sufficiently long to stop the vehicle. In dedicated guideway situations (such as the Washington Metro) this rarely happens. But in mixed traffic on an urban freeway, flotsam such as tire retreads that have been spun off or dropped cargo, while not an everyday occurrence, appears often enough to be something that *must* be allowed for. Most likely, this means the driver must be able to steer around the obstacle.

If the vehicle must be able leave the lane either momentarily or permanently, the power-supplying mechanism must not impede lateral movement of the vehicle, at least in one direction. This will mandate the use of a one-sided rail and restrict the system to no more than one AHS lane in the infrastructure, or it will require installation of flat plates for sliding contacts on the vehicle to draw power from

7.5.6. Catastrophic Power Loss -- Loss of Mobility Impact

Since the system is centrally powered, the effects of power loss to the system will be potentially catastrophic. At a minimum, all traffic will come to a halt unless sufficient fail-operational design elements and/or degraded mode operations are designed into the system.

All vehicles in the system are at least partially dependent on the power rail for motive force and lateral guidance. If power is lost, then either one of two conditions will ensue:

1) All vehicles have backup, internally supplied power and are capable of continuing to move after loss of power.

2) Those that do not will cause all movement to stop unless provision for passing is made in the design. Even so, the ensuing potential for collision and

The likelihood is that, under high density traffic conditions, the ensuing traffic jams will be momentous. Compared to individually powered vehicles (present day operations) where failed vehicles move to the side when they are disabled, this issue makes centrally-powered options unattractive.

Loss of power can come from several sources: power plant failure, distribution grid and switching failure, or disruption of the power distribution rail due to impact, accident, or environmental effects such as flooding.

The impact on system design of this issue is likely to be a high reliability requirement on the power infrastructure that may increase system cost. Analysis of existing comparable systems (electrically powered subways and bus systems) for reliability is needed. This analysis will be made more difficult by the fact that comparable Systems do not exist at such high power demand levels.

7.5.7. Catastrophic Power Loss -- Public Liability

The loss of power could lead to suddenly throwing the vehicle into an ~ manual operation mode, raising difficult liability questions. Fail-safe design may be difficult and/or expensive to achieve, but lack of a fail-safe operational state will operational liability problems for implementors.

If a sudden power loss forces a vehicle into an unsafe state of manual operation under tightly constrained operating conditions, does liability remain with the operator, fall on the vehicle designer, the power provider, or a combination of the above? Loss of centrally-supplied power will usually be sudden and complete, and recovery and fail-safe operation require that backup be provided by each individual vehicle to preclude loss of control.

The physical linkage to the power rail for guidance (if any) may mitigate this issue some, but compared to a flat-plate pickup mechanism, a side-rail pickup restricts vehicles' lane changing options to infrequent exchange points.

7.5.8. Frictional wear for direct electrical pickup

The wear associated with sliding contact electrical pickup under very high usage expected of the AHS may result in unacceptably high preventive maintenance requirements.

Transit systems that use direct pickup mechanisms operate for suitably long intervals before wear of the pickup device on the infrastructure needs to be replaced. In part, this is due to the fact that vehicles only occasionally pass any given point in the infrastructure. On the AHS, we anticipate that the number of contact passages per hour will be several orders of magnitude higher. For instance, if traffic densities of 4000 vehicles per hour are expected, that will also be the rate of contact passages past a given point. Compared to the Washington Metro, where the number of contact passages is a dozen or so trains pass per hour, multiplied by the number of contacts per train, the ratio is perhaps two orders of magnitude different.

Not only must designers address how frequently will contacts on the vehicles have to be replaced, but it also raises the concern for how frequently the Infrastructural elements will have to be replaced. Each time that occurs, how long that stretch of roadway will have to be out of service for each such preventive maintenance action? Will the public accept that frequency and duration of lane-mile outages (compared to today's highway system)? What will the recurring preventive maintenance costs be? Finally, will the frequency of related failures scale linearly with the increased traffic load compared to current transit experience, or might the occurrence of failures be an exponential function?

8. Conclusions and Recommendations

8.1. Issues Derived from System Identification

The process of defining system concepts has led to the identification of significant system issues even before engaging in the evaluation of those concepts. These issues are captured here to assure they art documented, and we intend to carry them through the evaluation process.

8.1.1. On the use of barriers to separate AHS lanes from non-AHS lanes

Some concepts call for the installation of Jersey barriers or other physical dividers to assure separation between the AHS and non-AHS vehicles and avoid encroachment accidents. Installing such barriers leads to the necessity to install fixed entry exit points at various intervals to permit migration to and from the AHS lanes. We have identified several issues with respect to such installations. This issue assumes that the AHS lanes will be taken out of existing right of way in urban freeway situations, and that the entry/exit points need occur at least as often as the freeway exits.

While the safety aspects of physically separating AHS and non-AHS traffic art compelling, the added complexity to design, construction operation, and maintenance of the highways is much greater than for a concept that reserves a lane for AHS for use without the separation.

8.1.1.1. Merging with AHS traffic requires acceleration lanes

Since it is likely that AHS lane traffic will be dense (after all, improving throughput at high density is one of the goals of the AHS), merging with on-going AHS traffic will require speed and position synchronization. The entering vehicle will have to have room to assume a position and develop the proper speed to merge into holes in the traffic. If density is high, then such holes may be scarce, requiring a place for the vehicle to wait and then accelerate into traffic. With barriers prohibiting moving into AHS lanes at any point, this mandates the construction of entry/acceleration lanes and conversely exit/deceleration lanes. These lanes must be built into the existing lane structure if we assume using existing rights of way for the AHS. A sample configuration is illustrated in Figure 16.

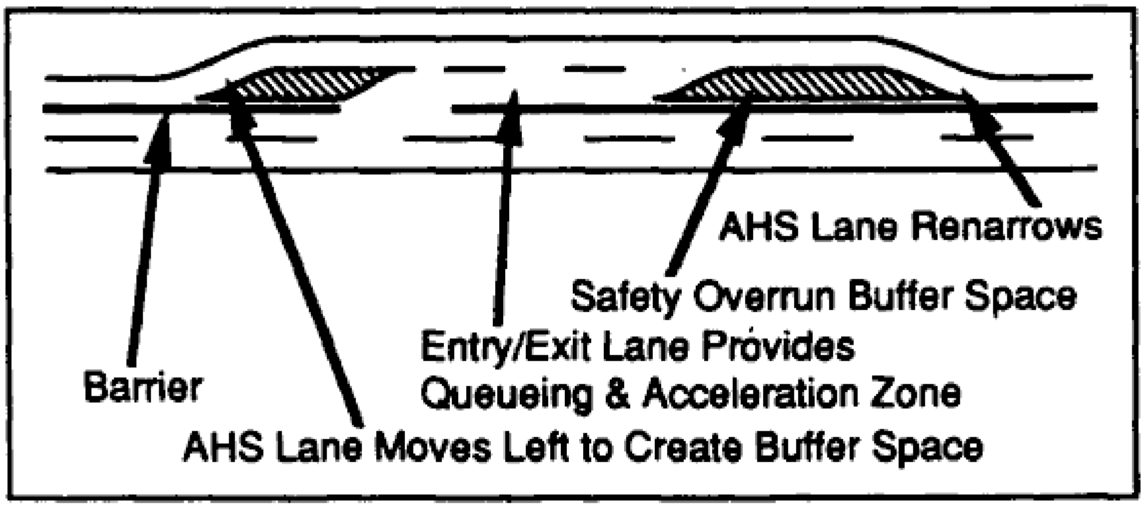


Figure 16. Sample Entry Lane Configuration with Barriers

Using this figure as a model, we have identified several significant problems:

8.1.1.1.1. Extra real estate required for entry/acceleration lanes

To create the buffer spaces needed for safety, and to allow for queuing of cars trying to merge into dense traffic, a dedicated entry/acceleration lane will be required. Without such a lane, the entering vehicle would have to be fully synchronized with AHS traffic while traveling in the non-AHS lanes prior to the entry point If AHS lanes are permitted to run at higher speeds, this will not be legally possible.

It can also be argued that a deceleration lane prior to the AHS barrier opening is needed for the case where the acceleration lane has stationary vehicles enqucued, further compounding the real estate requirements.

In many places, the space for these entry or exit zones may not exist, restricting access to a small number of points separated by greater distances than desirable. A three lane right of way requirement becomes a four lane requirement and possibly a five-lane requirement if the deceleration zone prior to entry is required.

The sum of the linear distance requirements for this zone includes the space needed for the lateral motion, the length of the safety buffer, the length of the acceleration lane, and the length of the overrun space. The combined total of these requirements is probably over a quarter mile. if there is one entry point between highway exits, and if those exits are spaced two miles apart, then *25%* of the highway length will be covered with these extra lanes.

8.1.1.1.2. Safety implications of barrier breaks

Each barrier break will have to be equipped with energy absorbing configurations to prevent fatalities from hitting the leading edge at high speed, increasing the construction and maintenance cost of the interchange.

8.1.1.1.3. Protocols needed to avoid non-AHS lane congestion at the entry points Rush hour traffic may cause backup in the entry/acceleration lane as vehicle desiring to enter wait for an opening. The spill~over into the non-AHS lanes could induce a slowdown there as well. This slowdown could be potentially dangerous in that it occurs in the "high speed lane" of the non-AHS traffic. Lane layout designs and regulations must be specified to avoid this problem.

8.1.1.2. Space must be allocated for failed vehicles

It is axiomatic that vehicles will fail and will become unable to move under their own power. When this occurs, there must be some place for the vehicle to coast to a stop. Assume the configuration of Figure 16 above. If physical barriers prevent moving to the right, and if there is no space next to the barrier in which to stop, then a median strip *must* be provided on the left for failed vehicles. If we assume that the extra lane width for the acceleration lane can come at a local usurpation of the needed shoulder space, then this argument suggests at the least that for n additional AHS lanes, (n+1) lane widths must be reserved.

8.1.2 String Stability for AHS at large

*String stability a phenomenon applicable *0 more than just the 'platooning' scenario.*

"String stability," as used here, refers to the effect characterized by relative motion in a sequence of loosely-coupled dynamic bodies. It can be observed by inducing a disturbance at the start of a sequence and observing the response of each member in the sequence as the disturbance propagates through the sequence. An unstable string (or sequence) will respond with a growing amplitude of disturbance, whereas a stable string will respond with a decreasing amplitude response. An example is a platoon of cars where the first vehicle tries to stop, the second vehicle experiences a delay and then tries to stop a little harder, the third vehicle experiences it's delay as well as the delay of the second vehicle and tries to stop still harder, etc.

Consider a sequence of vehicles, each with a common algorithm tracking the velocity and regulating the headway with respect to a lead vehicle. Assume further that accurate sensing is used to determine the actions of the leading vehicle. Simulation work with real vehicle and sensing/actuation models shows that the string of vehicles is not stable; a disturbance in one vehicle's velocity will give rise to increasing disturbances for vehicle further back in the string.

However, the phenomenon is not restricted to longitudinal control problems. Lateral control work to date has focused on the case where there is one AHS lane. Suppose there are a finite number of AHS lanes all containing dense traffic with no lateral barriers. Under this condition, lateral string stability may become a concern, as well. A lateral deviation where one vehicle begins to encroach on a neighboring lane will cause a collision avoidance system on the offended vehicle to drift away from the offending vehicle. As the offending vehicle detects and corrects, other nearby vehicles will detect the change in lateral motion and recover. However, the effect of finite reaction nine shown for the longitudinal motions will in this case cause the disturbance to grow as it propagates back through platoons of closely spaced vehicles.

One of the core issues is that slow, soft, low-bandwidth responses are needed for ride quality but sharp, high-bandwidth response needed for tight control is needed to avoid even low-energy collisions in closely spaced vehicle following. Our conclusion is that leading vehicle information may be a necessary condition proper performance on the AHS. However, analytical work is required in this arena.

Appendix A. One-Dimensional Stereo Sensor Resolution Derivation

A.1. Calculating Required Angular Resolution

To determine the required resolution for a stereo sensor pair, we begin with the range relationship for detecting range from two sensors offset by a fixed width *w* to a point emitter at a distance *r* ahead.

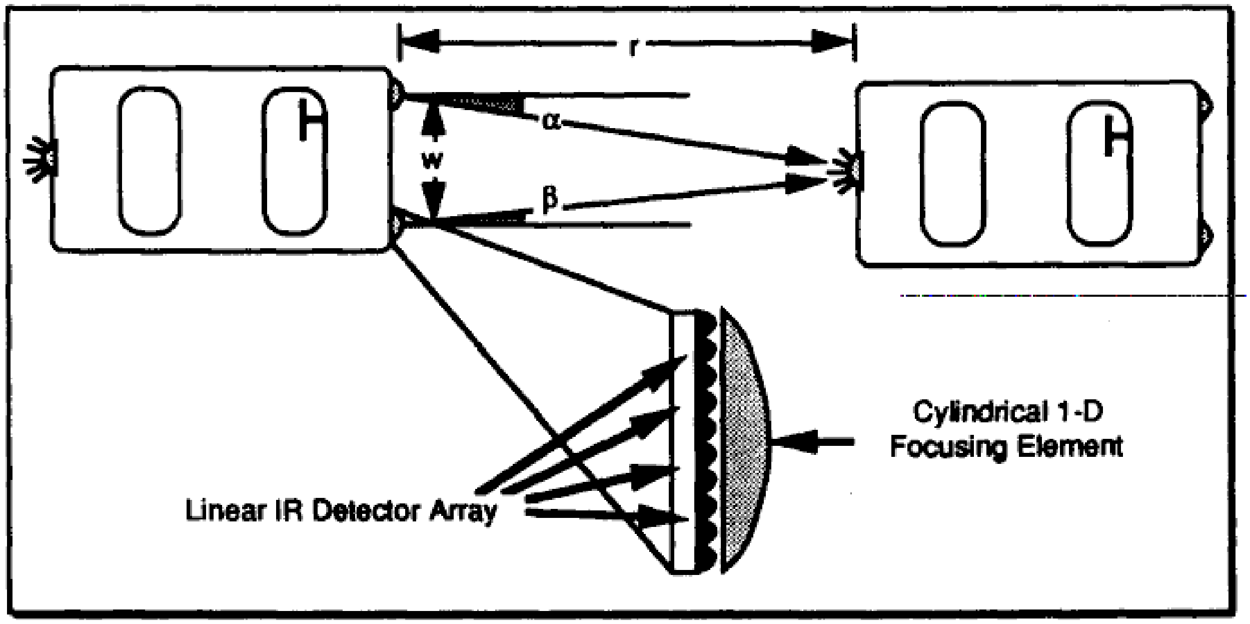


Figure 17. IR Sensor Configuration for Vehicle Following Capability

The sensors are presumed to be capable of discriminating the respective azimuthal angles ~ and ~ to that common point. The general range relationship is given by:

$$r = \frac{w}{\tan\alpha + \tan\beta} \qquad (1)$$

In the case where the two vehicles are laterally aligned, this can be simplified to:

$$r = \frac{w}{2\tan\alpha} \qquad (2)$$

Solving for α, we arrive at the relationship:

$$\alpha = \tan^{-1}\left(\frac{w}{2r}\right) \qquad (3)$$

Our goal is to determine the angular resolution required to be able to discriminate a range change of Δr at range *r*. To do so, we take the derivative of equation (3) with respect to range. Drawing from standard references on derivatives, the general form is:

$$\frac{\delta\left(\tan^{-1} u\right)}{\delta x} = \frac{1}{1+u^2}\frac{\delta u}{\delta x} \tag{4}$$

We start with a change of variables as follows:

$$u = \frac{w}{2r} \tag{5}$$

$$\frac{\delta u}{\delta r} = \frac{-w}{2r^2} \tag{6}$$

By substitution into (4) and solving for $\delta\alpha/\delta r$, we arrive at:

$$\frac{\delta \alpha}{\delta r} = \frac{-2w}{\left(4r^2 + w^2\right)} \tag{7}$$

Using this derivative, we calculate the angular change $\Delta\alpha$ due to change in range Δr at range r corresponds to an angular change $\Delta\alpha$ determined by the equation:

$$\Delta\alpha = \frac{2w\Delta r}{\left(4r^2 + w^2\right)} \tag{8}$$

This value $\Delta\alpha$ is the required angular resolution for a given level of range resolution.

A.2. Calculating Required Field of Regard

The field of regard is determined by the limiting look angles for the worst case in either direction. We assume for the sake of analysis that the maximum lateral deviation of the vehicle within the lane is required to be under one meter at long range and 0.25 meter at short range. We have further assumed AASHTO standard curves of 1950 foot radius for the highway case with nominal superelevation of the roadway. Given these parameters, the exterior angle (away from the vehicle's centerline) is limited by the long range case, including lateral offset due to road centerline curvature and lateral vehicle deviation from lane center, less the lateral offset from the sensor to the beacon location on the vehicle in front. We ignore the effect of offset of the beacon due to lead vehicle change in heading. This assumption is reasonable since the point of rotation is about the rear differential, and the moment arm from the pivot point to the beacon is likely to be relatively small. The relative heading differential is a also a small angle. In this case, the outward edge of the field of regard will be bounded by:

$$\alpha_{\min} = \tan^{-1}\left[\frac{\left(\frac{w}{2} - \left(\Delta y_{road\_curve} + \Delta y_{lateral\_deviation}\right)\right)}{r}\right] \qquad (9)$$

$$\Delta y_{road\_curve} = curve\_radius\left(1 - \cos\left(\sin^{-1}\left(\frac{r}{curve\_radius}\right)\right)\right) \qquad (10)$$

Figure 18 provides the relevant geometry for equations (9) and (10).

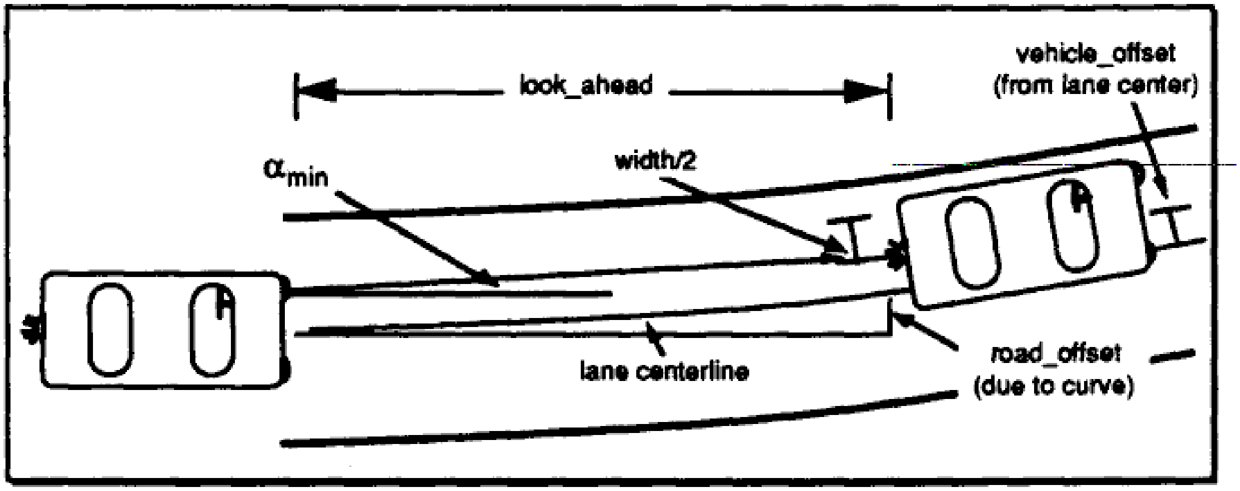


Figure 18. Geometry for Outbound Look Angle

The interior angle (toward the vehicle's centerline), is bounded by the look-angle required to track the maximum deviation at the closest range. At two meter spacing, road curvature is of no consequence, and the relationship for the inward looking maximum angle is given by:

$$\alpha_{\max} = \tan^{-1}\left(\frac{\frac{w}{2} + lateral\_offset}{least\_range}\right) \qquad (11)$$

The field of regard is the difference:

$$\alpha_{FOR} = \alpha_{\max} - \alpha_{\min} \qquad (12)$$

Naturally, these results are symmetric for both left and right sensors.

A.3. Determining Required Resolution and Close Range Sensitivity

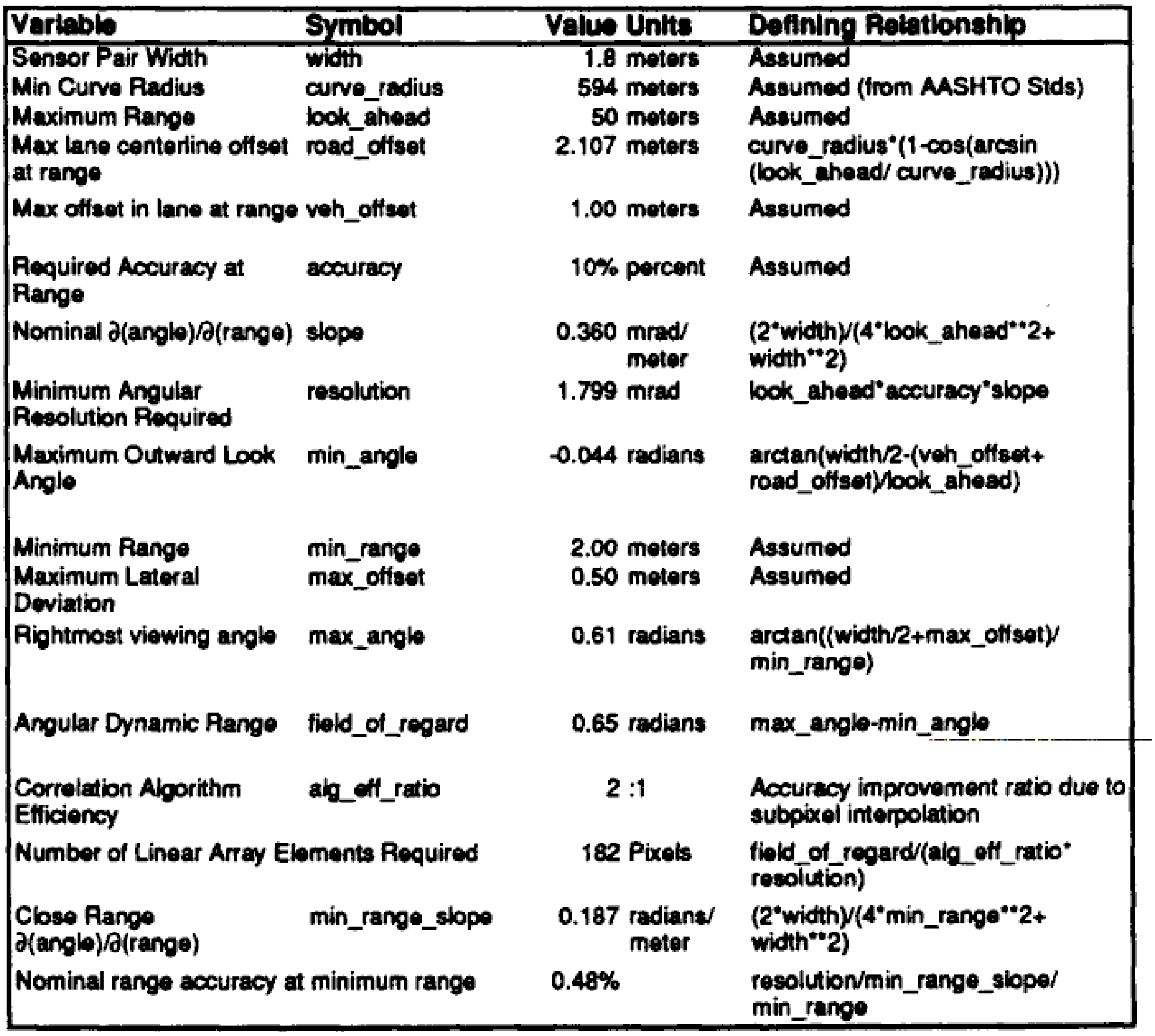
Knowing the angular resolution required to sense at the long range (Equation 8) and the angles required to cover the full range of operation needed (Equation 12), the number of detector elements required is a simple ratio of the two. However, there is one factor that needs to be applied. Current state of the art stereo processing techniques employ subpixel interpolation. This technique tends to improve the resolution by a factor of two to three times above that of more straightforward approaches. This, in turn, reduces the number of pixels actually required to achieve a given level of resolution. Since this technique has not been applied to one-dimensional stereo computations and we do not today know the actual improvement expected, we have taken the more conservative 2x figure.

Finally, the sensor's range sensitivity at close range as a percentage of the sensed distance can be calculated by applying the inverse of equation (7) and dividing by r:

$$sensitivity = \frac{\left(4r^2 + w^2\right)\Delta\alpha}{-2wr} \times 100 \tag{13}$$

where we substitute the minimum range value for *r* and the sensor resolution for a. Applied as a ratio of the operating range. Table 5 on the next page provides a sample set of calculations using presumed operating parameters as noted in the table on the following page.

Table 5. Stereo Resolution for Nominal System Design Parameters



Variable	Symbol	Value	Units	Defining Relationship
Sensor Pair Width	width	1.8	meters	Assumed
Min Curve Radius	curve_radius	594	meters	Assumed (from AASHTO Stds)
Maximum Range	look_ahead	50	meters	Assumed
Max lane centerline offset at range	road_offset	2.107	meters	curve_radius*(1-cos(arcsin (look_ahead/ curve_radius)))
Max offset in lane at range	veh_offset	1.00	meters	Assumed
Required Accuracy at Range	accuracy	10%	percent	Assumed
Nominal ∂(angle)/∂(range)	slope	0.360	mrad/ meter	(2*width)/(4*look_ahead**2+ width**2)
Minimum Angular Resolution Required	resolution	1.799	mrad	look_ahead*accuracy*slope
Maximum Outward Look Angle	min_angle	-0.044	radians	arctan(width/2-(veh_offset+ road_offset)/look_ahead)
Minimum Range	min_range	2.00	meters	Assumed
Maximum Lateral Deviation	max_offset	0.50	meters	Assumed
Rightmost viewing angle	max_angle	0.61	radians	arctan((width/2+max_offset)/ min_range)
Angular Dynamic Range	field_of_regard	0.65	radians	max_angle-min_angle
Correlation Algorithm Efficiency	alg_eff_ratio	2	:1	Accuracy improvement ratio due to subpixel interpolation
Number of Linear Array Elements Required		182	Pixels	field_of_regard/(alg_eff_ratio* resolution)
Close Range ∂(angle)/∂(range)	min_range_slope	0.187	radians/ meter	(2*width)/(4*min_range**2+ width**2)
Nominal range accuracy at minimum range		0.48%		resolution/min_range_slope/ min_range

The important conclusion to draw from this analysis is not the particular resolution calculated, since it is subject to various assumptions and requirements that may change as the concept is refined. Rather, it is that the resolution and field of regard required is well within the realm of feasibility of the sensor technology, from the standpoints of device fabrication and signal processing requirements.

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Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Task D: Lateral-Longitudinal Control Analysis

Volume IV: AHS System Concept Evaluation Document

US Department of Transportation
Federal Highway Administration
Publication No. FHWA-RD-95-051
November 1995

FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (SPA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The SPA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations
Research
and Development

NOTICE

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List of Abbreviations and Acronyms

AHS	Automated Highway System
FUR	Forward Looking Infrared
LIDAR	Laser Imaging Detection and Ranging
LLCS	**Lateral/Longitudinal** Control Study
MDFRD	Maneuver Definition and Functional Requirements Document
MMWR	Millimeter Wave Radar
mps	meters per second
mph	miles per hour
psa	**Precurser** Systems Analysis
RSC	Representative System Configuration
SCDD	System Concepts Definition Document
SCED	System Concept Evaluation Document
TBD	To Be Determined

AHS System Concept Evaluation Document

1. Introduction

1.1. Purpose of the Document

This is the third of three technical documents produced wider the AHS Precursor Systems Analysis contract tided "Lateral-Longitudinal Control Study", a one-year systems analysis of conceptual alternatives for the Automated Highway System (AHS). It was developed under contract to the US Department of Transportation, contract number DIFH61-93-C(X)198.
This *AHS System Concept Evaluation Document* (SCED) presents and summarizes the results of the evaluation of concepts defined in the *AHS System Concept Definition Document* (STDD) according to the requirements and evaluation criteria defined in the *AHS Manesiver Definition* and *Functional Requirements Document* (MDFRD). It also refers to technologies described in the *Sensor Taxonomy Description Document* (STDD) as source material for the evaluation process. The overall process we used in deriving the evaluation is presented in the Section 1.2 below.

1.2. Analysis Approach

This section provides an overview of our analysis process and how this document fits in that process. Figure 1 on the next page illustrates the overall process. The boxes represent tasks, and the document icons represent the products of these tasks. The numbers enclosed in the various ellipses indicate the Statement of Work task corresponding to each box.

The first task was to develop a taxonomy of maneuvers as independent of the system concepts as possible. This taxonomy provided the outline structure for capturing the functional requirements, and evaluation criteria from tasks two and three. The products of three tasks were captured in the *AHS Maneuver Definition and Functional Requirements Document (MDFRD).*

The next task was to develop and refine our system concepts, and describe them in a clear enough way to permit meaningful evaluation and comparison of the concepts. This was done by first roughly describing each concept, and then showing how it filled the functional requirements outlined in the MDFRD. The product of that effort is provided in this document, the *AHS System Concept Definition Document* (STDD).

Concurrently with the above efforts, we undertook an effort to describe all the enabling technologies in a sensor taxonomy. The result was the *Sensor Taxonomy Descnption Document* (STDD). It classifies all the relevant sensor types and describes the basic technology, provides an assessment of each of the enabling technologies, and in some cases projects where the technology is going and what issues surround the use of that particular technology. In it we also collected all the information we were able to in a reasonably short interval from our archives, from a brief literature review, and from various sensor vendors with whom we are in frequent contact.

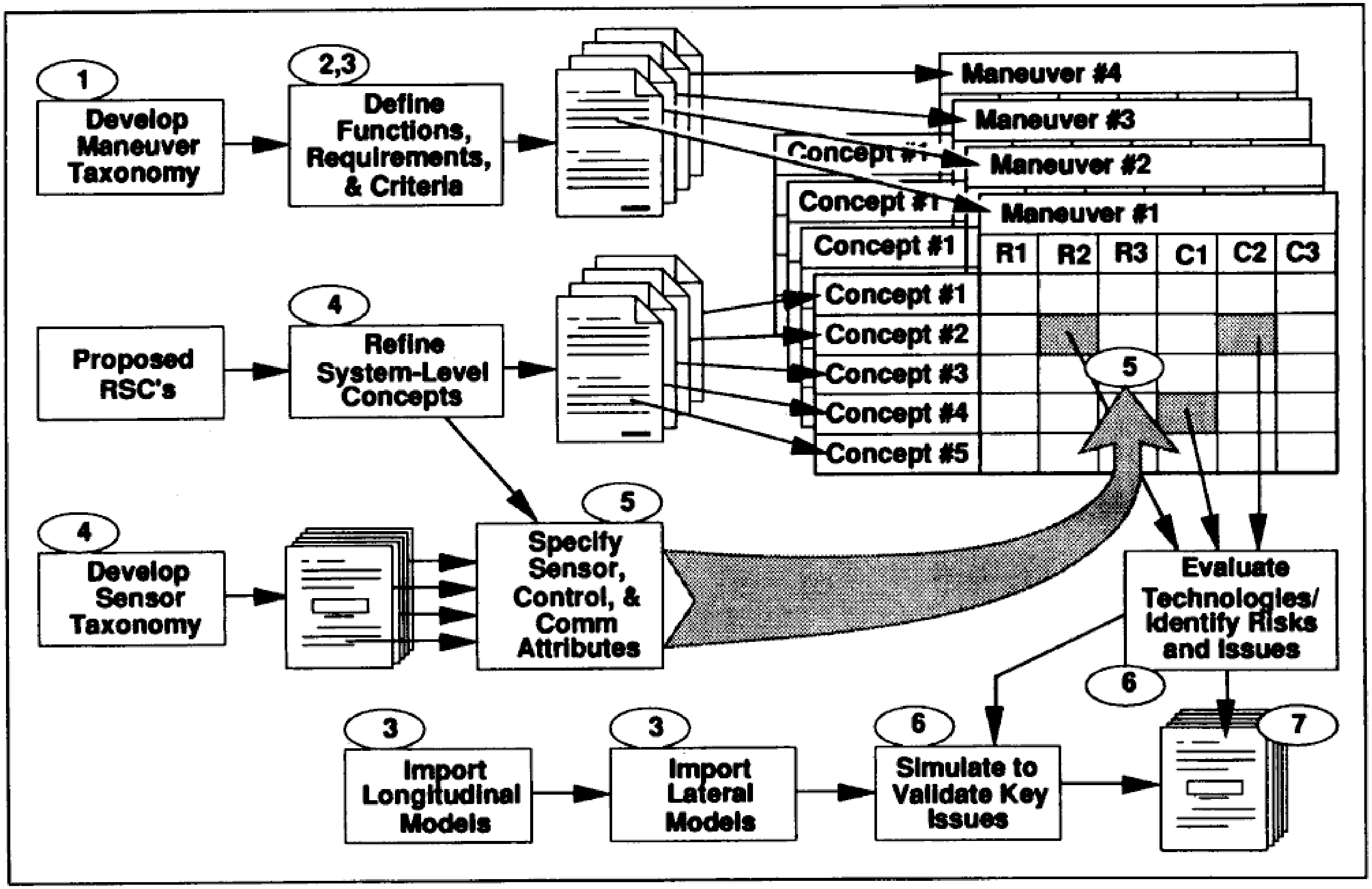


Figure 1. Lateral/Longitudinal control study approach

The purpose of the STDD is to provide a technical foundation for the evaluation portion of this effort described below. From that document we draw an assessment of the sensor attributes needed to satisfy each concept. Since sensor technology is in many cases the dominant limitation on overall approaches, this mechanism for capturing, cataloging, and sharing data on sensor technologies may be particularly useful to the anticipated AHS Consortium.

The last step was to apply the evaluation criteria defined in the MDFRD to the concepts described in the SCDD and assess the merit of each of those candidate concepts. The primary objective was to capture along the way the issues surrounding implementation of an AHS and provide a first-look assessment at the broad merits of each of the candidates. This evaluation is recorded in the *AHS System Concept Evaluation Document* (SCED).

The series of matrices in the upper right of the diagram represent the heart of this program: the evaluation of system concept. The planes of this three-dimensional matrix are each captured as one Microsoft Excel spreadsheet Each plane corresponds to one of the maneuvers defined in the MDFRD. The rows of the matrices are the various concepts defined in the SCDD and referred to by the corresponding paragraph number in the SCDD. The individual columns are divided into requirements and evaluation criteria, referred to by paragraph number in the MDFRD. Requirements are developed in the paragraph describing each maneuver. Evaluation criteria are separately defined in section 8 of the MDFRD. Because of this extensive use of index references, the reader *must* understand the contents of the MDFRD and the SCDD in order to comprehend these sheets.

The method of rating concepts has two steps. The first step is to evaluate its ability to meet each requirement on a scale of (0=fails, l=low probability, 2=likely, 3=definitely meets requirements). This evaluation is accumulated into a "confidence rating" on that concept's ability to meet the full set of requirements. After the concept has passed the requirements gate, the second step is to evaluate it in terms of the evaluation criteria outlined in section eight of the MDFRD. The individual figures of merit are then combined using a weighted summation. The weight selection and their justifications are outlined in Section 9 that document, and the individual concepts are evaluated on an integer scale of 0 to 9,9 being the highest (best) score.

The spreadsheets provide several additional useful ways to collect and organize the results of this evaluation. Behind each cell of the spreadsheet is a set of notes for what factors contributed most to that evaluation datum. These notes are intended to provide the basis for qualitative summarization and identification of issues arising out of this study. The union of these issues will be discussed in our final report. In addition, the comparison sheets provide a means of developing graphical depiction’s of the evaluation.

Some concepts require quantitative analysis to provide the basis for evaluation. The simulation environment we have developed provides the necessary tools for this analysis as reported in section 4. These models were executed on various test scenarios to provide the needed quantitative data. A set of test cases were be defined and executed to examine the identified issues quantitatively. Unfortunately, this program did not have the time or scope of effort to simulate all aspects of all concepts, so due diligence was applied to the selection of particular conditions and concepts to be simulated.

The overall evaluation can only be relied upon to identify clear winners and losers in a broad sense, and to ascertain significant risks and issues with each. It is important to note that there are too many unknowns at this time to definitively establish both the weights and the specific evaluation numbers. There is therefore a large margin of uncertainty surrounding the resultant numerical evaluations. Instead, they are intended only to provide insight into which concepts are strongest and merit further consideration, which are weakest and may be dismissed. It is important to view the numerical results as "fuzzy indicators", not as a tool for absolute ordinal rankings.

These evaluations are by no means final. It is our expectation that the weights and evaluations are subject to some change as concepts are further refined or as new technologies become available. It is for precisely that reason that the spreadsheet formalism has been chosen; it provides a simple way to perform various sensitivity analyses. For instance, if the Federal Highway Administration chooses a different weighting scheme of importance factors for the evaluation criteria, or if new requirements are inserted, the comparisons could change dramatically. Various scenarios can be evaluated easily with this approach.

Due to scope limitations, our evaluation cannot be all-inclusive. There are a number of concepts being developed under the various SPA contracts which this contract will not have time to evaluate. When the results of all these contracts are available, it will be important for the consortium to be able to compare and contrast each project's results in a consistent manner. A common formalism is required to accomplish that comparison meaningfully. As new concepts are developed, they can easily be added to the structure we have outlined. It is our hope that the Federal Highway Administration or the anticipated AHS Consortium will be able to apply this technique to a complete comparison of all the candidate concepts.

1.3. Evaluating Requirements Satisfaction and Criteria Ratings

To be able to meaningfully compare system concepts, a way is needed to bring all the concepts into a common representation. We have elected to employ a two-step evaluation process. The first step is evaluation against system requirements. Requirements are those conditions a system *must* meet in order to be viable. Methodical evaluation at this level is needed to winnow out concepts having no chance of successful implementation before significant resources are expended in their development. The second step is evaluation against a set of criteria or figures of merit. These criteria are evaluation categories where some concepts may be superior to others, but there is no clear dividing line between succeeding and failing. The purpose of this step is to develop a relative ranking among the candidates concepts. The following sections describe our method for executing these two steps in more detail.

1.3.1. Evaluating Concepts' Requirements Satisfaction

Most requirements are binary; a system concept meets them or it fails. However, a passing or falling assessment is in many cases dependent upon specific implementation, the details of which have not been elaborated at this stage of development Therefore, we have elected to rate each concept against each requirement on a *likelihood* scale. In some cases, meeting a requirement is a virtual certainty or a near-impossibility. In other cases, we can only speculate on the probability that a concept can or cannot meet a requirement within reasonable design and cost constraints.

Quantifiable requirements consist of a metric, a threshold value, and the existence of one or more means to test the requirement If the system concept exceeds the threshold value, then it falls to meet the requirement. At this stage of AHS definition, there is no agreement upon the selection of metrics. One expectation from this study is that ensuing discussion will center on the definition of the metrics and not upon the specific values contained herein. A discussion of values implies that the metrics themselves have been accepted.

Each requirement in this document describes how the competing concepts are to be evaluated against it. For instance, consider the following candidate requirement and its associated evaluation method:

> Requirement 3.2.1.2: The 3-sigma deviation for lateral positioning with respect to the lane center shall be no greater than 18 inches.
>
> Evaluation Method: Each concept will be assessed in terms one of the enumerated values in the set (0=fails requirement, 1=meets requirement).

If no evaluation method is explicitly provided, the default description is assumed to be as follows:

> Each concept will be assessed in terms of its ability to meet each of the stated requirements, being assigned one of the enumerated values in the set (0= not possible, 1 = possible but unlikely, 2= likely, 3 - certain).

1.3.2. Combining Requirements Evaluations

Having evaluated individual concepts against individual requirements, we next apply a method for combining the individual ratings. Combination of requirements is on an unweighted scale, since there is no assessment of the relative importance of requirements. The resulting value represents the evaluators' aggregate confidence that a given concept will meet all requirements. This combining method establishes a confidence number in the range [0,1].

Each maneuver section describes the function for combining requirements evaluated by other than the default method. If a method other than the default described below is used, the maneuver must explicitly establish the combining method, or state that no reasonable method can be specified.

When all the requirements use the default evaluation criteria, the following combining function will be used:

$$C(j) = \sqrt[n]{\prod_{i=1}^{n} R_{i,j}} \quad \text{where:}$$

$C(j)$ is the confidence rating for concept j $[0 \le C(j) \le 1]$
$R_{i,j}$ is the rating on requirement number i for concept j
n represents the number of requirements in that maneuver

The equation above is a geometric average of the individual evaluations. If any ~ has a 0 rating (meaning it is not possible for that configuration to meet that requirement), then that configuration receives an overall "0" combined rating, since failing any mandatory rating constitutes failure in the aggregate. This function evenly weights all requirements, and is somewhat skewed toward lower values; that is, to be highly rated, a concept must rate highly in all areas; a single low rating will have a stronger downward effect on the rating than would be true with an arithmetic average.

One might argue that not all requirements should be evenly weighted, or that the assessment of "probability of meeting requirements" is inappropriate, but in the end some means for performing aggregate comparisons of concepts has to be established. This sort of combining functions is a functions method for deriving a confidence number for a given configuration's ability to meet all requirements. A given configuration's ability to meet all requirements cannot be definitively established without detailed design verification. Design verification, in turn, presumes the existence of detailed designs. Because of the absence of detailed design alternatives, we employ this tradeoff approach.

1.3.3. Evaluating Concepts' Figures of Merit

Having completed the assessment against the requirements, the next step is to evaluate the concepts against the figures of merit. The major difference between criteria and requirements is that requirements are (or should be) non-negotiable; the system passes or fails. On the other hand, figures of merit are measures of goodness against which the merit of the system can be assessed. Each system is given a numerical rating for each figure of merit. The scores are then combined through a weighted summation process. The selection of weights represents the relative importance attached to each criteria. The result of the summation represents the aggregate merit of each concept.

In this evaluation, each of the system evaluation criteria will be assessed in the context of each of the maneuvers. This approach allows for the possibility that an implementation might, for instance, be particularly safe for lane changing but have serious safety concerns with respect to emergency platoon disengaging. The values to be assigned to each criterion are set on a scale normalized on the range [0,9]. The meaning attached to each scale depends on the particular criterion being assessed. Section 8 of this document describes the rating system for each criterion.

1.3.4. Combining Figures of Merit

Having rated each concept against each criterion, the evaluator is confronted by a large array of values from which some significance must be drawn. Reducing this volume of data to a manageable result requires a method of combining ratings. This evaluation uses a simple linear weighted sum:

$$E(j) = \frac{\sum_{i=1}^{n} \left(W_i * M_{i,j} \right)}{\sum_{i=1}^{n} W_i} \quad \text{where:}$$

$E(j)$ is the weighted evaluation for the jth concept
W_i is the weight factor for the ith criterion
$M_{i,j}$ is the measure of effectiveness rating for jth concept against the ith criterion
n is the number of weight factors

This combining scheme establishes a rating for each maneuver for each concept, but does not attempt to aggregate concepts' scores across maneuvers for an overall score. Our belief was that merging information to that extent went beyond simplifying results to the point of hiding information.

This document also establishes a nominal set of weight values in the range [0,9]. The range itself has no inherent meaning; it merely provides enough discrimination to distinguish the different criteria without attempting finer granularity than truly has meaning. For each criterion listed in section 8, we have selected a nominal weight value. These are presented in Section 9 with the associated justification for the particular selection.

1.3.5. Notes on Methodolgy Implementation and Limitations

It is important for the reader to bear in mind that this process depends upon judgment and opinion. The individual rating scores are subjectively defined, and the weights by which they are combined with the others are also subjectively established. However, the structure created by this process is well suited for what-if analysis. To accommodate multiple weight sets, we have chosen to implement the evaluations M a series of spreadsheets using the Microsoft Excel (version 4.0) application. Excel contains a feature called the "Scenario Manager" permits a user to establish multiple parameter sets as scenarios and perform evaluations for each scenario. This feature, if applied to the combining weights described above, could be used by future system designers to quickly assess the impact on candidate systems' merit as the criteria change. For instance, if safety were to be heavily weighted compared to robustness at night, one evaluation will result, if on the other hand, the ability to operate at night were rated equally with safety, a different result would occur. Both these cases can be maintained as separate scenarios. This evaluation does not perform multiple weighting scenarios, but our hope is that this structure will be used by those performing trade analyses in the future.

Since this evaluation process is not deterministic but instead is judgment-based, it is equally important to remember that the precision of the results is low. A combined rating of 0.84 cannot be considered as substantially different from one of *0.75*. There are also no clear thresholds nor dividing lines among scores. However, gross differences in score can be taken to be indicative of a general tendency of one concept to have superiority over another within the context of the weight set. This approach serves as a useful broad discriminator for directing more detailed analyses and evaluations.

1.4. Underlying Evaluation Assumptions

1.4.1. Heavily Loaded Highway

The evaluation of the merits of the various candidates in this study have assumed that the highway is loaded with dense traffic. Evaluation of concepts under light loading at this point did not seem to be worthwhile because it was not the most stressing case. One might argue that under lightly loaded conditions, the prime benefit of a good AHS will be fewer single-vehicle accidents, but that efficiency, environmental impact, and multiple-car collision rates (particularly rear-end collisions) would not be substantially affected by the automation. However, we have proceeded on the assumption that alleviation of "everyday" conditions, such as congestion, is a prime motivator for developing an AHS, and that safety is a benefit at the outcome end of the process.

This assumption also implies that urban freeway situations are the focus of attention. Rural highways are not likely to be loaded heavily much of the time, unless one includes under "rural" stretches of intercity interstate highways such as 1-95 between New York and Philadelphia. The benefits, risks, and issues identified in this study are to varying degrees applicable to rural highways, but our presumption was that improving intracity freeway travel will be the most beneficial place to apply AHS technology and thereby alleviate problems of congestion, pollution, and safety.

2. Requirements Satisfaction Evaluation

When we began defining the evaluation process, we identified a hierarchy of maneuvers required of vehicles on the AHS regardless of implementation strategy. This process led us to define requirements in a bottom-up fashion to assure we had sufficiently broad and complete coverage. This hierarchy is described in Section 1 of the MDFRD.

However, when we began evaluation of the various concepts, we soon discovered that there was little discriminating the concepts at the lower levels of the hierarchy. Specifically, the bottom two levels (level 0 and level 1 in figure 1 on page 13 of the MDFRD) are so primitive that there was no reason to formalize and document the requirements satisfaction and evaluation criteria at those levels. Consequently, we have elected to carry out the intended evaluation at level 2 and up.

For example, section 3.2 of the MDFRD describes the lateral control maneuver under the "Primitive Level Maneuvers" section. Upon reviewing the requirements for this maneuver, we deduced that one of two conditions existed:

1) The requirements were so important to fundamental feasibility that they were built into each of the concepts from the start There was no point in performing evaluation any further since there was no discrimination value that could be derived from the evaluation.
2) The requirements were stated in a non-quantifiable way, such that their satisfaction could not be evaluated without further definition of the requirement, the concept, or both. These requirements were captured in the documentation in the hope that they would provide the AHS consortium with a starting point for further refinement, but they were not carried into the evaluation of the concepts.

The evaluations that follow are referenced by the section number in the MDFRD. Each table represents one maneuver. The rows represent the concepts under evaluation, and the columns represent the likelihood of requirements satisfaction as described in the MDFRD.

In performing an assessment of whether a given concept is likely to meet a given requirement, it is important to constrain the evaluation to *reasonable cost* and *design complexity* limitations. Almost any concept, given enough design freedom and no cost constraints, can meet the stated requirements. To make the evaluations more meaningful, we have used engineering judgment in limiting the scope to likely implementations on private automobiles, under the assumption that passenger auto implementations are likely to provide the most demanding cost, power, and weight limitations.

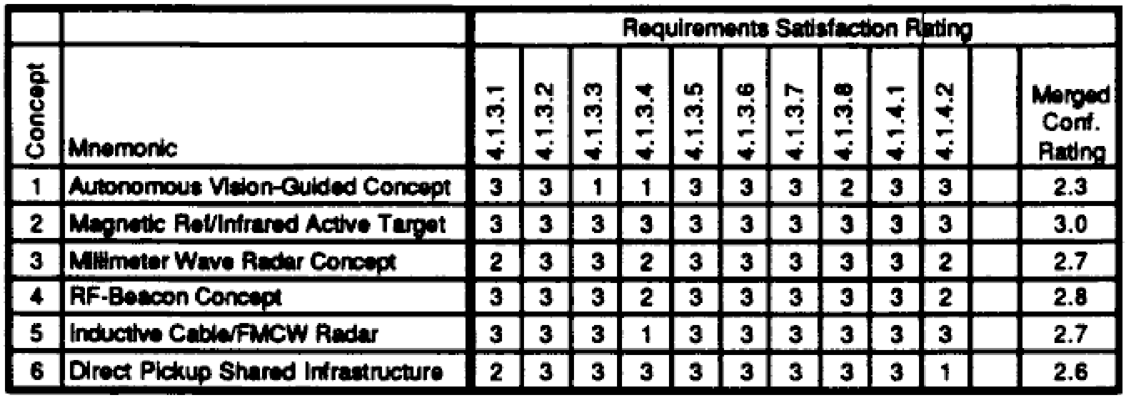
In each of the evaluation spreadsheets, notes have been attached to justify any rating below "3." These notes have been indexed according to the requirement number and the concept number.

2.1. Vehicle-Level Maneuvers (Level 2)

This section provides the evaluations of each concept for each maneuvering requirement in tabular form. Associated with each table is a series of notes (in the originating spreadsheet file) that explain selected rating values as they relate to some of the issues uncovered during the evaluation process. Each cell in the table is referenced by the maneuver requirement followed by the concept number. For instance, the rating value for the second concept against the nth requirement is indexed as n.n.n.n-2. The requirements themselves are indexed according to the paragraph in the MDFRD.

Table 1 provides the rating developed for the lane tracking maneuver. This maneuver, and all maneuvers that are designated nominal, assesses each concept when there are no incidents to deal with. However, as the reader will see, this does not preclude consideration of system failure modes.

Table 1. Evaluation of Nominal Lane Tracking



		Requirements Satisfaction Rating											
Concept	Mnemonic	4.1.3.1	4.1.3.2	4.1.3.3	4.1.3.4	4.1.3.5	4.1.3.6	4.1.3.7	4.1.3.8	4.1.4.1	4.1.4.2		Merged Conf. Rating
1	Autonomous Vision-Guided Concept	3	3	1	1	3	3	3	2	3	3		2.3
2	Magnetic Ref/Infrared Active Target	3	3	3	3	3	3	3	3	3	3		3.0
3	Millimeter Wave Radar Concept	2	3	3	2	3	3	3	3	3	2		2.7
4	RF-Beacon Concept	3	3	3	2	3	3	3	3	3	2		2.8
5	Inductive Cable/FMCW Radar	3	3	3	1	3	3	3	3	3	3		2.7
6	Direct Pickup Shared Infrastructure	2	3	3	3	3	3	3	3	3	1		2.6

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

The low rating for 4.1 .3.~1 is based on current system performance. One of the problems most of the implementations to date have experienced are the coupled effects of sample rate (typically 5-15 Hz) and steering quantization. These are manifested as a tendency to wander laterally within the lane boundaries. There are ways to reduce this problem, including higher sampling rates, lower-bandwidth compensation to reduce responsiveness and effectively "both" steering commands, and smaller quantization intervals in the steering chain. However, each of these fixes complicates the design, increases cost. In the context of consumer-grade devices and current technology, the near-term prospects are not encouraging.

One of the key concerns in this evaluation section was the ability of the system to maintain safe operation under failures (requirement 4.1.3.4). The type of failure that was the most damaging to that system's performance was the case considered. For the autonomous vision-guided concept, that failure was a loss of the video input signal somewhere between the camera and the processor, including image capture and digitization, camera failure, covering of the lens or viewing window by foreign material, damage to optics from stones or flying debris, and similar occurrences. The expense of duplicating the sensor channel with sufficiently different placement or other physical attributes to avoid duplication of the failure may be prohibitive for consumer applications using current technology. Loss of steering control as a result would be unacceptable. for the inductively powered vehicle, the problem was loss of infrastructure power and the simultaneous loss of control for all vehicles on the highway. For this evaluation, we have ignored the presence of dissimilar redundancy (use of an entirely different control concept as a backup). The safety implications of such an event on this concept are daunting, compared to other concepts.

The rating value 4.1 .4.2~ is because this concept uses an electrical pickup infrastructure element that precludes lane changeovers except where the intrastructural support is explicitly provided, limiting the options for maneuvering under either automatic or manual control. This requirement is a conditional requirement, however, and would be dropped in the presence of a concept utilizing dedicated, barrier-bounded lanes.

2.1.2 Nominal Speed Maintenance Evaluation

Speed control is almost independent of AHS implementation or architecture. Rather, it is a function of design particulars on the vehicle itself. Cruise control technology, as it exists today, appears to be sufficient to meet AHS requirements, though tighter tolerances on Speed variations may be required. The notable exception is concept 5, which relies on synchronous vehicle speeds, and for which speed control is not an issue.

No evaluation is required here, so the table is omitted.

2.1.3. Emergency ID-Lane Stop

From an actuation standpoint, emergency stopping in the lane is almost independent of lateral-longitudinal control approach or AHS architecture. Almost any automation scheme will (or at least should) have actuation designs capable of full authority braking action. The differentiation between concepts lies mainly in the ability to sense the conditions requiring execution of this maneuver.

Table 2. Evaluation of Emergency In-Lane Stop

		Requirements Satisfaction Rating											
Concept	Mnemonic	4.3.3.1	4.3.3.2	4.3.3.3	4.3.3.4	4.3.3.5	4.3.3.6	4.3.4.1	4.3.4.2				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	3	2	1	2	1	1	2	2				1.6
2	Magnetic Ref/Infrared Active Target	3	1	2	3	3	1	1	1				1.6
3	Millimeter Wave Radar Concept	3	2	2	3	3	2	2	2				2.3
4	RF-Beacon Concept	3	2	1	3	2	2	1	1				1.7
5	Inductive Cable/FMCW Radar	3	2	2	3	3	2	2	2				2.3
6	Direct Pickup Shared Infrastructure	3	1	3	3	2	2	2	2				2.1

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

The primary difference among the concepts evaluated here lies in the ability to detect obstacles of such sire and relative position such that an emergency maneuver is required and can be initiated in time. We have based the evaluation of the concepts primarily on this differentiation. It is important to note that each of the concepts could be modified to provide lacking detection capability, but we have chosen to evaluate the concepts as they were defined. It is equally important to note that the evaluation is based on the assumption that the requirements listed in ~4 of the MDFRD are truly requirements; one could argue that some of the requirements could be deleted.

Concepts 3 and 5 rate the highest because they possess self-contained active sensors that are most likely to provide the ability to sense obstacles. We judge that most other deployment concepts will likely need one of these options unless the requirement to respond to the presence of obstacles is ignored. Concept 6 rates nearly as high because the physical constraints on the infrastructure reduce the likelihood of intrusion of objects other than vehicles that belong in the roadway.

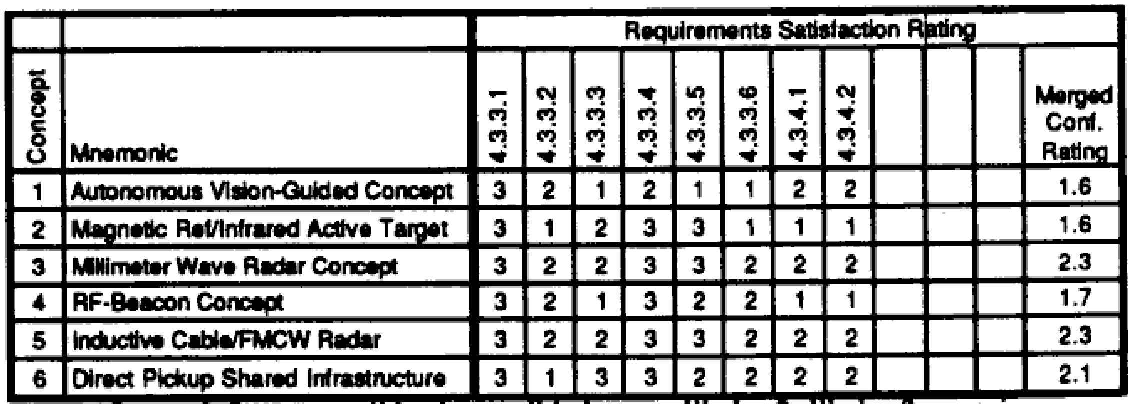
However, we note that it will take very few multivehicle collisions on the automated highway to cause the public to lose confidence in highway automation. Systems in which humans are passengers typically constrain designers to develop systems *significantly better than the* human *control functions they replace.* Typically, human error (failure to see and react to an obstacle) is much more acceptable to the general public as an explanation for accidents than a comparable system-level inability (failure to sense the obstacle). If circumstances highlight the inability of a system to avoid property damage, attributing that deficiency to the fact that the situation is outside the bounds of the system design is not generally a publicly acceptable explanation, even if the human could have performed no better. As a general judgment, we believe that if permitting operators to remove their attention from the highway situation involves a significant risk of an avoidable collision, then the general public acceptance for such a concept is going to be low. Careful attention to human factors that limit the tendency of operators to divert their attention from the highway situation will mitigate this problem.

2.2. Interaction Level Maneuvers (Level 3)

2.2.1. Norminal Spacing Regulation

This maneuver provides little discrimination among the various concepts. The one significantly low rating is in cell 5.1.3.34, due primarily to the fact that centralized control of all vehicles in a segment in a real-time environment will require very high-bandwidth, low-latency communication to assure sufficiently high update rate for each vehicle in the control segment to dynamically adjust speed for maintaining headway. That high-bandwidth link will have cost implications for not only the infrastructure but for each vehicle as well. For this function, a distributed approach (functionality located on each vehicle) is likely to be much more cost-effective.

Table 3. Nominal Spacing Regulation Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	4.3.3.1	4.3.3.2	4.3.3.3	4.3.3.4	4.3.3.5	4.3.3.6	4.3.4.1	4.3.4.2				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	3	2	1	2	1	1	2	2				1.6
2	Magnetic Ref/Infrared Active Target	3	1	2	3	3	1	1	1				1.6
3	Millimeter Wave Radar Concept	3	2	2	3	3	2	2	2				2.3
4	RF-Beacon Concept	3	2	1	3	2	2	1	1				1.7
5	Inductive Cable/FMCW Radar	3	2	2	3	3	2	2	2				2.3
6	Direct Pickup Shared Infrastructure	3	1	3	3	2	2	2	2				2.1

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

The RF-beacon concept will be quickly overcome by the bandwidth requirements in providing all the vehicles within a given control segment with all the information on all vehicles nearby with velocity and relative position and position rate data In support of this argument, consider the following thumbnail assessment of communications requirements. Suppose that every vehicle in a 0.5-km segment communicates its state data to and receives a velocity command from the infrastructure twice a second to maintain smooth, collision-free spacing control. Suppose moderately dense traffic such that vehicles (cars) are spaced one for every 10 meters of roadway. Table 4 on the next page summarizes the bandwidth required for each segment The table assumes that each vehicle will transmit and receive a total of twenty bytes of information per control cycle and that all vehicles in the segment must be communicated with each cycle.

Current state of the art networked radio communications suggests that a reasonable bandwidth for the RF equivalent of an Ethernet-type data packet communications scheme is on the order of 2-10 *KB/sec.* The system referred to here is the Hazeltine Packet Switched Radio, developed for military applications under ARPA sponsorship. This type of communications will be required because of the dynamic real-time control nature of the task, and the bi-directional communications involved (as compared to unidirectional communications such as AM broadcast highway advisory radio). The numbers in the table suggests that the bandwidth requirement is more than that.

Table 4. Communication Bandwidth Estimate for Beacon Concept

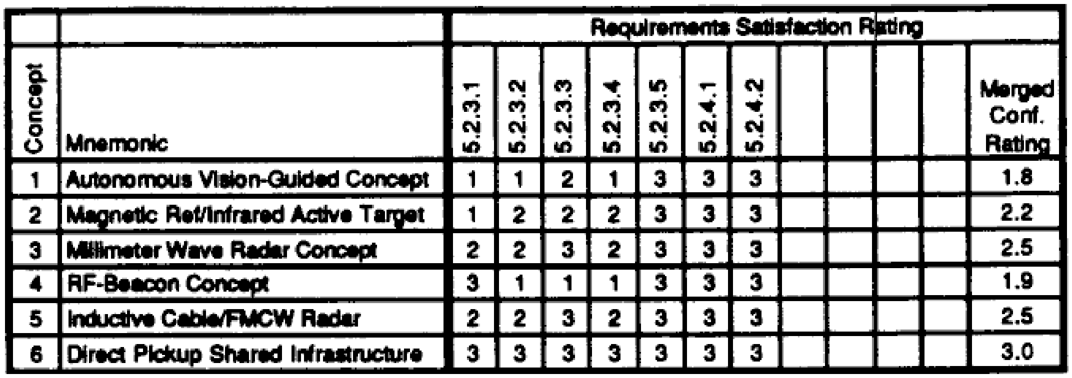
	Units	Value
Vehicle/Message ID	Bytes	4
Data effective time	Bytes	4
Vehicle position	Bytes	8
Vehicle absolute velocity	Bytes	1
Vehicle Operating Mode I Status	Bytes	1
Velocity command to vehicle	Bytes	1
Misc data	Bytes	1
Data Volume per vehicle msg	Bytes	20
Required update rate	*Hz*	2
Bandwidth required per vehicle	bytes/sec	40
Number of lanes		6
Segment Length	km	0.5
Avg Veh-to-veh distance	meters	10
Vehicles per segment		300
Total Bandwidth for all vehicles	bytes/sec	12000

Further, this table is most likely a best-case scenario for several reasons. First, packet messaging generally has several bytes of overhead that has not been considered here. Second, the table assumes full-duplex communications in the same 2-byte packet, but in reality RF communications will only be half-duplex. Incoming state information and outgoing command information has to be split into separate messages. Since one packet is formed for the outgoing data and one is formed for the incoming data, message overhead is increased. Third, the system has to be sized for the worst-case scenario, and this assumes lighter than maximum vehicle density. if platooning is used to increase highway throughput, there could be more vehicles per kilometer of highway, and therefore more vehicles in each segment to be controlled. Fourth, the control update rate of 2 Hz may also be inadequate in close following situations, as will be seen from the simulation study later in this year.

2.2.2. Nominal Lane Change

This maneuver provides the capability of performing controlled lane changes under nominal (no incident) circumstances. Doing so in high traffic density conditions requires omnidirectional determination of spacing with respect to the vehicle performing the maneuver. This evaluation was dominated by the issues surrounding maintaining safe clearances and guaranteeing no collisions in absence of failures. This maneuver only considers individual vehicle maneuvers, multiple vehicle lane changes are considered under MDFRD §5.5, "Nominal Vehicle Following".

The two concepts most dramatically affected by the problem of omnidirectional sensing are the vision-guided approach and the RF-beacon concept. Vision-guided omnidirectional sensing is not feasible because of the bandwidth and processing limitations associated with multiple (three or more) simultaneous image processing requirements. Multiple cameras are likely to be affordable, but complete processing on all the images is not, unless a breakthrough in integrated devices containing both camas and image processing functions is achieved.



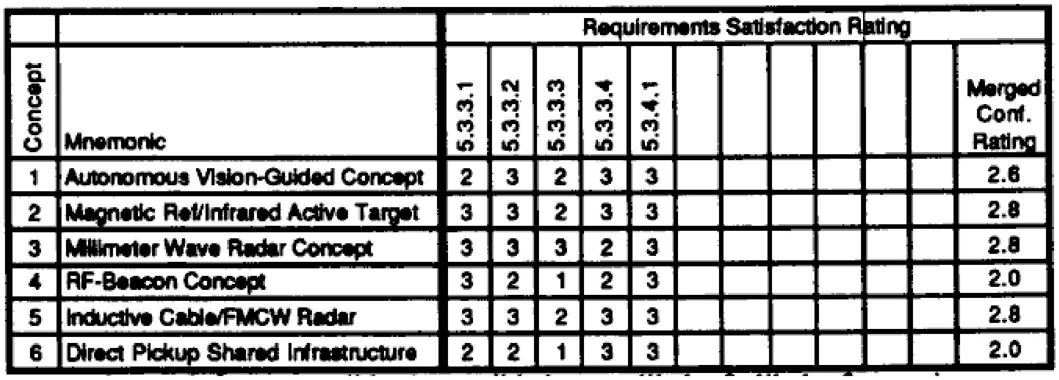
		Requirements Satisfaction Rating											
Concept	Mnemonic	5.2.3.1	5.2.3.2	5.2.3.3	5.2.3.4	5.2.3.5	5.2.4.1	5.2.4.2					Merged Conf. Rating
1	Autonomous Vision-Guided Concept	1	1	2	1	3	3	3					1.8
2	Magnetic Ref/Infrared Active Target	1	2	2	2	3	3	3					2.2
3	Millimeter Wave Radar Concept	2	2	3	2	3	3	3					2.5
4	RF-Beacon Concept	3	1	1	1	3	3	3					1.9
5	Inductive Cable/FMCW Radar	2	2	3	2	3	3	3					2.5
6	Direct Pickup Shared Infrastructure	3	3	3	3	3	3	3					3.0

Table 5. Nominal Lane Change Evaluation

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

As noted in §2.2.1 above, the RF-beacon concept will be quickly overcome by the bandwidth requirements in providing all the vehicles within a given control segment with all the information needed for accurate, robust control.

2.2.3. Nominal Vehicle Following



		Requirements Satisfaction Rating											
Concept	Mnemonic	5.3.3.1	5.3.3.2	5.3.3.3	5.3.3.4	5.3.4.1							Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	3	2	3	3							2.6
2	Magnetic Ref/Infrared Active Target	3	3	2	3	3							2.8
3	Millimeter Wave Radar Concept	3	3	3	2	3							2.8
4	RF-Beacon Concept	3	2	1	2	3							2.0
5	Inductive Cable/FMCW Radar	3	3	2	3	3							2.8
6	Direct Pickup Shared Infrastructure	2	2	1	3	3							2.0

Table 6. Nominal Vehicle Following Evaluation

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

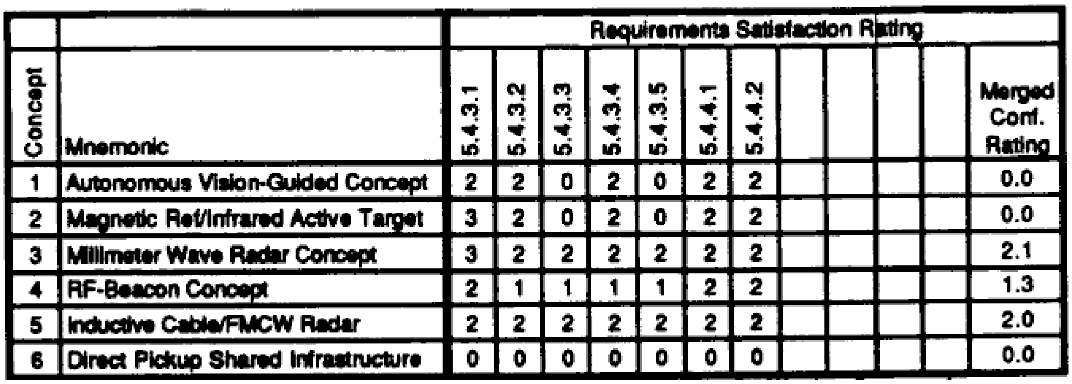
The first three requirements of this maneuver reference those of the maneuver in section 5.1, therefore the ratings should be (and are) identical.

2.2.4. Emergency Lane Change

This table is perhaps of questionable value, since the validity of automatically performing a lane change under emergency conditions is itself a questionable prospect. We have included the table, but recognize that its contribution to the overall evaluation of concepts is suspect.

Like some of the previous evaluations, the absence of rearward sensing can be mitigated through communication or development of a hybrid concept. The zero ratings on this table merely indicated the need to provide such hybrid concepts, though scope of this study did not permit iteration on conceptual designs. Also, active self-contained sensing concepts provided the strongest potential for meeting this maneuver's requirements.

Table 7. Emergency Lane Change Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	5.4.3.1	5.4.3.2	5.4.3.3	5.4.3.4	5.4.3.5	5.4.4.1	5.4.4.2					Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	2	0	2	0	2	2					0.0
2	Magnetic Ref/Infrared Active Target	3	2	0	2	0	2	2					0.0
3	Millimeter Wave Radar Concept	3	2	2	2	2	2	2					2.1
4	RF-Beacon Concept	2	1	1	1	1	2	2					1.3
5	Inductive Cable/FMCW Radar	2	2	2	2	2	2	2					2.0
6	Direct Pickup Shared Infrastructure	0	0	0	0	0	0	0					0.0

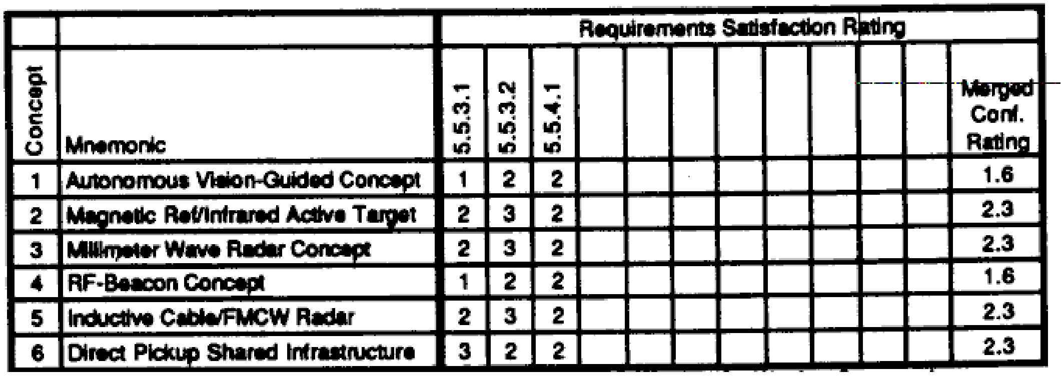
Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

The last concept requires a restricted, dedicated lane which cannot be entered or exited except at dedicated transition points. Therefore, this maneuver is not possible to perform One might argue that it should not be a factor in the evaluation of that concept, but the counter to that argument is that restricted access to and from these lanes increase the possibility of multiple vehicle pile-ups. For this reason, we have kept the zero rating.

2.2.5. Emergency Vehicle Following

Like the emergency lane change maneuver above, the emergency vehicle following maneuver is of questionable value. The premise is that forward-looking sensors are obscured in close vehicle following situations, and if an obstacle is detected and can be avoided by partially or fully leaving the lane of travel to avoid it, then vehicles immediately following will have to mimic the maneuver because insufficient time will remain once the lead vehicle is sufficiently out of the way to no longer obstruct the following vehicle's sensors. The assumption is the intentional lane departure would be communicated and that following vehicles would know that the departure is purposeful and not due to failure.

Table 8. Emergency Vehicle Following Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	5.5.3.1	5.5.3.2	5.5.4.1									Merged Conf. Rating
1	Autonomous Vision-Guided Concept	1	2	2									1.6
2	Magnetic Ref/Infrared Active Target	2	3	2									2.3
3	Millimeter Wave Radar Concept	2	3	2									2.3
4	RF-Beacon Concept	1	2	2									1.6
5	Inductive Cable/FMCW Radar	2	3	2									2.3
6	Direct Pickup Shared Infrastructure	3	2	2									2.3

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

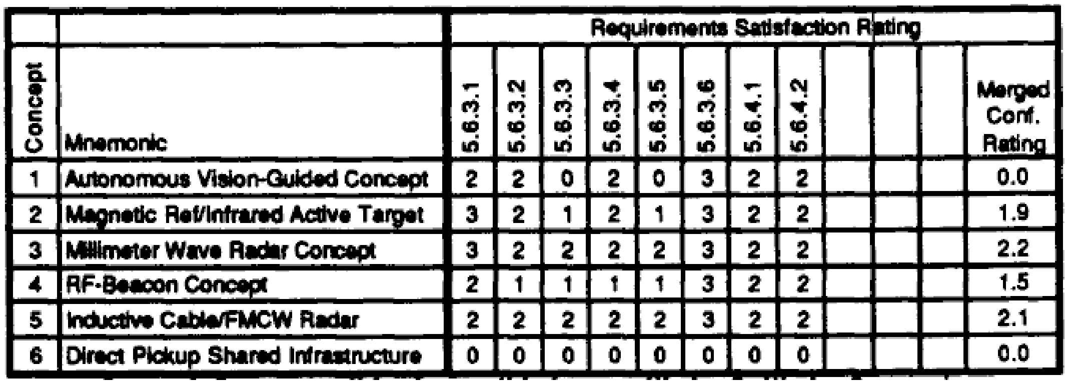
Given the questionable nature of this maneuver, we nonetheless find that the vision-guided and the centralized control concepts have the most difficulty meeting the requirement because of the extremely low latencies required to safely react, especially under close vehicle following conditions where reaction times must be very short.

Unlike the previous section, wherein the last concept received all zeros, this evaluation resulted in non-zero values for the sixth concept because the maneuver calls for doing whatever the vehicle in front did, and we must presume that the vehicle in front performed a permissible and feasible maneuver. Therefore, there is no prohibition in this context, and zeros were unwarranted.

2.2.6. Emergency Out of Lane Stop

Out-of-lane stops may in many cases be the most advantageous means of avoiding fatalities. Staying in lane in the presence of fast approaching obstacles guarantees collision if you can't stop in time. On the other hand, departing the lane leads to a reduced probability of corrosion, but does not completely eliminate the possibility. The possibility of colliding with vehicles in neighboring lanes or losing control due to sudden control input under reduced traction conditions is still present, but the severity of impact in such cases is likely to be less than that of hitting a stationary object.

Table 9. Emergency Out-of-lane Stop Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	5.6.3.1	5.6.3.2	5.6.3.3	5.6.3.4	5.6.3.5	5.6.3.6	5.6.4.1	5.6.4.2				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	2	0	2	0	3	2	2				0.0
2	Magnetic Ref/Infrared Active Target	3	2	1	2	1	3	2	2				1.9
3	Millimeter Wave Radar Concept	3	2	2	2	2	3	2	2				2.2
4	RF-Beacon Concept	2	1	1	1	1	3	2	2				1.5
5	Inductive Cable/FMCW Radar	2	2	2	2	2	3	2	2				2.1
6	Direct Pickup Shared Infrastructure	0	0	0	0	0	0	0	0				0.0

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

Once again, the active self-contained sensing concepts provided the greatest likelihood of satisfactory performance.

The argument detailed in §2.2.4 with respect to the sixth concept applies here as well

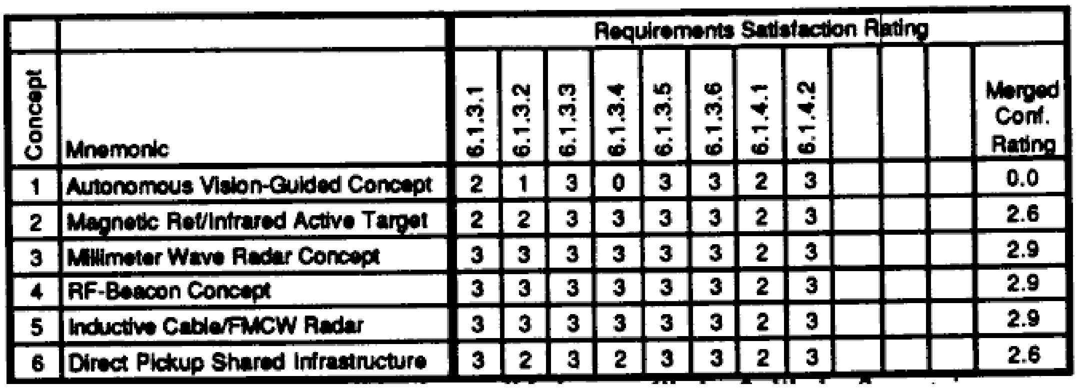
2.3. Platoon Level Maneuvers (Level 4)

This level of maneuvers is the first level at which intentional coordination among the vehicles on the AHS emerges. One of the key issues that emerged is the importance of the ability to provide *some* level of communication for purposes of coordination. Only one of our concepts, as originally defined, explicitly excluded such communication, and the evaluations reflect that fact However, the reader should note that the study method was to avoid redefining any of the concepts to correct any original deficiencies, but rather to let those deficiencies stand and be flagged by the ratings.

2.3.1. Platoon Merge

As stated in the introduction to this section, the lack of communications (explicitly excluded) in the autonomous vehicle concept resulted in its receiving a zero rating. Concepts that are totally independent of coordination communications will have difficulty in meeting all AHS requirements in general. There are several reasons for this. The first is that some simulations have shown that if close following is to be successfully achieved, state communication is required to reduce reaction latency or else platoons will experience increasing errors toward the rear of a platoon under transient conditions. Another is that to avoid the appearance of failures, intent must be communicated when changing states or modes.

Table 10. Platoon Merge Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	6.1.3.1	6.1.3.2	6.1.3.3	6.1.3.4	6.1.3.5	6.1.3.6	6.1.4.1	6.1.4.2				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	1	3	0	3	3	2	3				0.0
2	Magnetic Ref/Infrared Active Target	2	2	3	3	3	3	2	3				2.6
3	Millimeter Wave Radar Concept	3	3	3	3	3	3	2	3				2.9
4	RF-Beacon Concept	3	3	3	3	3	3	2	3				2.9
5	Inductive Cable/FMCW Radar	3	3	3	3	3	3	2	3				2.9
6	Direct Pickup Shared Infrastructure	3	2	3	2	3	3	2	3				2.6

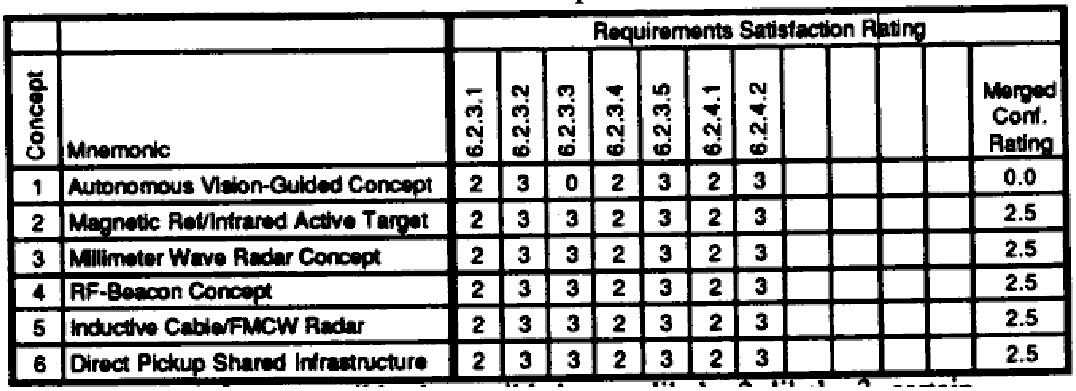
Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

We could have easily revisited the definition to include such low-bandwidth, point-to-point communications and mitigated this problem, but the conditions of the study were such that we held the concept definitions constant. Iterations to correct such deficiencies of individual concept are the subject of follow-on trade studies. Other than the issue of lack of communications, and given the assumptions surrounding this maneuver, very little distinguished concepts from one another in this maneuver.

2.3.2. Nominal Platoon Departure

As the reader can see, this maneuver provided little discriminating power among the concepts, other than the completely autonomous concept fails in requirement 6.2.3.3 due to the lack of communications.

Table 11. Nominal Platoon Departure Evaluation



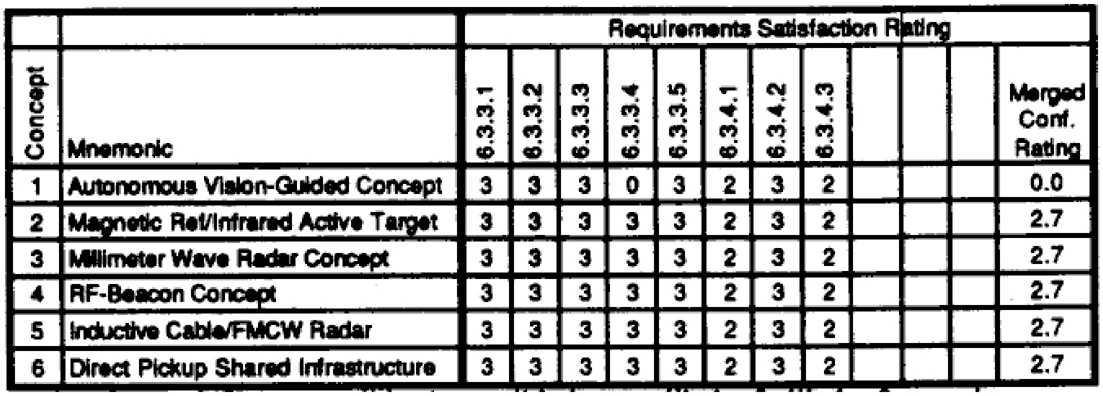
		Requirements Satisfaction Rating											
Concept	Mnemonic	6.2.3.1	6.2.3.2	6.2.3.3	6.2.3.4	6.2.3.5	6.2.4.1	6.2.4.2					Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	3	0	2	3	2	3					0.0
2	Magnetic Ref/Infrared Active Target	2	3	3	2	3	2	3					2.5
3	Millimeter Wave Radar Concept	2	3	3	2	3	2	3					2.5
4	RF-Beacon Concept	2	3	3	2	3	2	3					2.5
5	Inductive Cable/FMCW Radar	2	3	3	2	3	2	3					2.5
6	Direct Pickup Shared Infrastructure	2	3	3	2	3	2	3					2.5

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

2.3.3 Emergency Platoon Departure

As in the previous section, there was no difference among the concepts other than the obvious problem created by the lack of communications in the first concept, as can be seen in table 12 below.

Table 12. Emergency Platoon Departure Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	6.3.3.1	6.3.3.2	6.3.3.3	6.3.3.4	6.3.3.5	6.3.4.1	6.3.4.2	6.3.4.3				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	3	3	3	0	3	2	3	2				0.0
2	Magnetic Ref/Infrared Active Target	3	3	3	3	3	2	3	2				2.7
3	Millimeter Wave Radar Concept	3	3	3	3	3	2	3	2				2.7
4	RF-Beacon Concept	3	3	3	3	3	2	3	2				2.7
5	Inductive Cable/FMCW Radar	3	3	3	3	3	2	3	2				2.7
6	Direct Pickup Shared Infrastructure	3	3	3	3	3	2	3	2				2.7

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

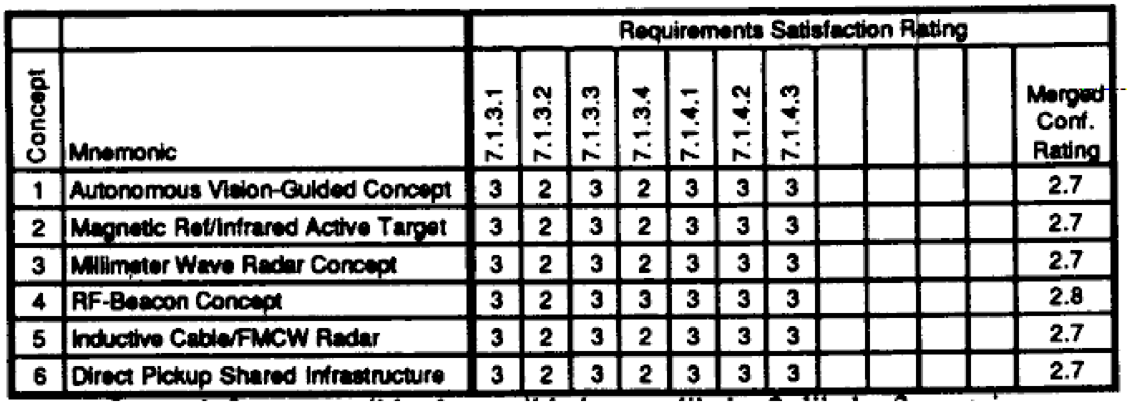
2.4. System Level Maneuvers (Level 5)

These maneuvers define the major mode transitions. Previous maneuver levels addressed nominal operations and handling of incidents both as individual vehicles and as coordinated units. This level, by contrast, focuses on the major changes that occur as vehicles enter and leave the system at large. As it turns out, at this high a level, there is very little that discriminates among the system concepts (at least from the perspective of lateral and longitudinal control), primarily because of the lack of depth in the definition of the system concepts.

2.4.1. Nominal AHS Entrance

Table 13 shows the evaluation for the AHS Entrance maneuver. This rating provided only slight variation among the concepts.

Table 13. Nominal AHS Entrance Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	7.1.3.1	7.1.3.2	7.1.3.3	7.1.3.4	7.1.4.1	7.1.4.2	7.1.4.3					Merged Conf. Rating
1	Autonomous Vision-Guided Concept	3	2	3	2	3	3	3					2.7
2	Magnetic Ref/Infrared Active Target	3	2	3	2	3	3	3					2.7
3	Millimeter Wave Radar Concept	3	2	3	2	3	3	3					2.7
4	RF-Beacon Concept	3	2	3	3	3	3	3					2.8
5	Inductive Cable/FMCW Radar	3	2	3	2	3	3	3					2.7
6	Direct Pickup Shared Infrastructure	3	2	3	2	3	3	3					2.7

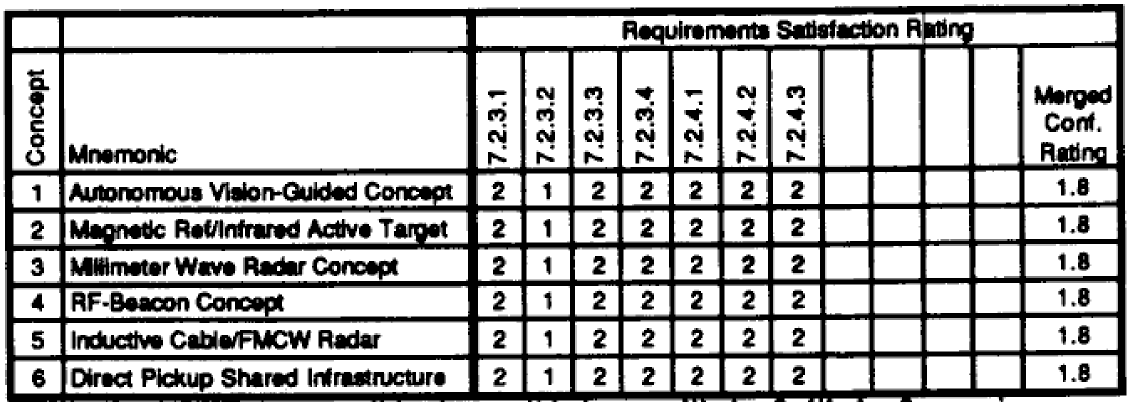
Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

We conclude that more definition in all the concepts is required if there is to be better discrimination among the concepts.

2.4.2 Nominal AHS Exit

Table 14 shows the evaluation for the AHS Entrance maneuver. This evaluation yielded no variation among the concepts. Once again, at this high level of abstraction, it is extremely difficult to assess the systems' ability or inability to meet certain requirements, and the requirements themselves need further refinement

Table 14. Nominal Exit Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	7.2.3.1	7.2.3.2	7.2.3.3	7.2.3.4	7.2.4.1	7.2.4.2	7.2.4.3					Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	1	2	2	2	2	2					1.8
2	Magnetic Ref/Infrared Active Target	2	1	2	2	2	2	2					1.8
3	Millimeter Wave Radar Concept	2	1	2	2	2	2	2					1.8
4	RF-Beacon Concept	2	1	2	2	2	2	2					1.8
5	Inductive Cable/FMCW Radar	2	1	2	2	2	2	2					1.8
6	Direct Pickup Shared Infrastructure	2	1	2	2	2	2	2					1.8

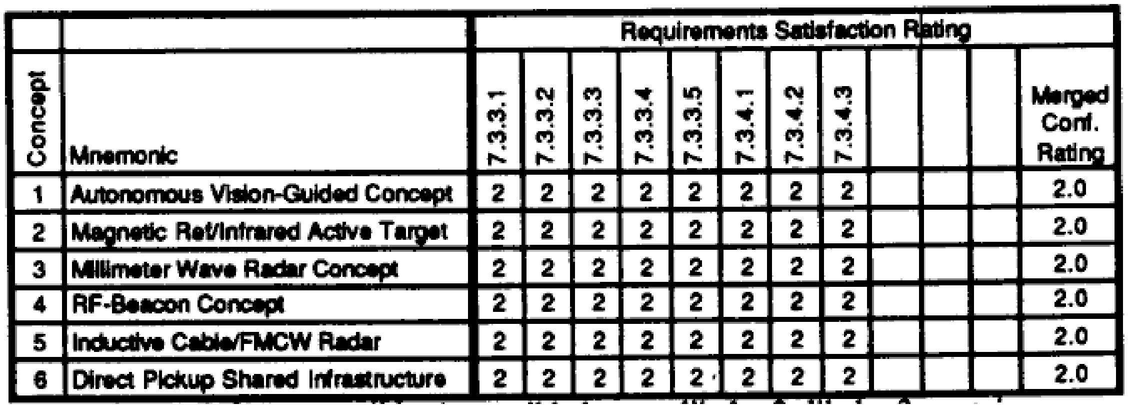
Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

None of the concepts provided any specific implementation for operator certification, but the issues surrounding the concept of ensuring the operator is ready to take over manual control seem much more difficult than the issues of requirement 7.1.3.2 for releasing control to the automatic modes.

2.4.3. Emergency Entry About

This maneuver also provided no discrimination among concepts. At this high level of abstraction, it is extremely difficult to assess the systems' ability or inability to meet certain requirements, and the requirements themselves need further refinement.

Table 15. Emergency Entry Abort Evaluation



		Requirements Satisfaction Rating											
Concept	Mnemonic	7.3.3.1	7.3.3.2	7.3.3.3	7.3.3.4	7.3.3.5	7.3.4.1	7.3.4.2	7.3.4.3				Merged Conf. Rating
1	Autonomous Vision-Guided Concept	2	2	2	2	2	2	2	2				2.0
2	Magnetic Ref/Infrared Active Target	2	2	2	2	2	2	2	2				2.0
3	Millimeter Wave Radar Concept	2	2	2	2	2	2	2	2				2.0
4	RF-Beacon Concept	2	2	2	2	2	2	2	2				2.0
5	Inductive Cable/FMCW Radar	2	2	2	2	2	2	2	2				2.0
6	Direct Pickup Shared Infrastructure	2	2	2	2	2	2	2	2				2.0

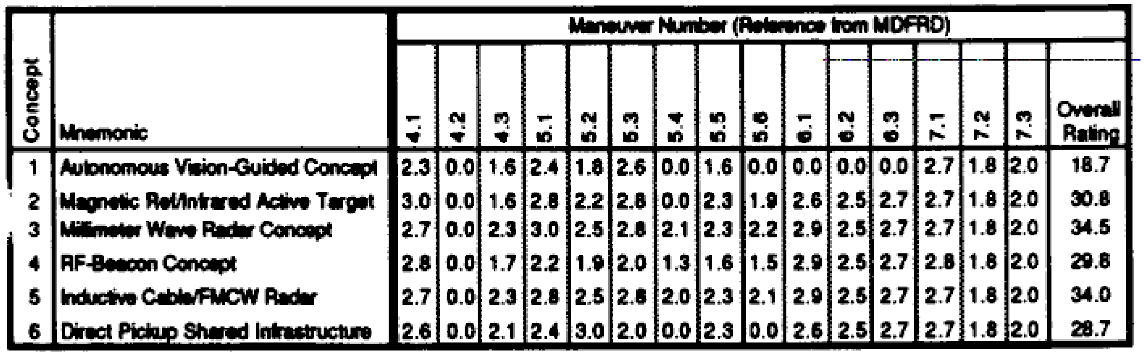
Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

2.5. Summary of Maneuver Requirements Evaluations

Table 16 below summarizes all the individual evaluations above. In this table, the merged confidence ratings of each of the previous tables (rightmost column) have been made individual entries. In each row, these have been summed for an overall score. However, the overall score is at best a very coarse goodness indicator, since there are many assumptions about how configurations did or did not meet requirements. The authors anticipate that these evaluations are merely the first of several iterations. Each of the concepts rated could be redefined to meet additional requirements and bring up their respective scores. Each of the requirements must be evaluated as to its true applicability and whether it is a firm or "soft" requirement.

It must be remembered that this is the initial step in a multi-stage process, so definitive conclusions are inappropriate to draw at this point. The results of table 16 will be revisited later in this document after the evaluation of section 3 is completed, so the reader is cautioned to defer judgment until that point. The highest score possible on any one entry is 3.0, and the highest overall sum for a given concept is 45 (given the current maneuver set; specifying additional maneuvers changes the number of columns).

Table 16. Concept Requirements Evaluation Summary



Concept	Mnemonic	Maneuver Number (Reference from MDFRD)															
		4.1	4.2	4.3	5.1	5.2	5.3	5.4	5.5	5.6	6.1	6.2	6.3	7.1	7.2	7.3	Overall Rating
1	Autonomous Vision-Guided Concept	2.3	0.0	1.6	2.4	1.8	2.6	0.0	1.6	0.0	0.0	0.0	0.0	2.7	1.8	2.0	18.7
2	Magnetic Ref/Infrared Active Target	3.0	0.0	1.6	2.8	2.2	2.8	0.0	2.3	1.9	2.6	2.5	2.7	2.7	1.8	2.0	30.8
3	Millimeter Wave Radar Concept	2.7	0.0	2.3	3.0	2.5	2.8	2.1	2.3	2.2	2.9	2.5	2.7	2.7	1.8	2.0	34.5
4	RF-Beacon Concept	2.8	0.0	1.7	2.2	1.9	2.0	1.3	1.6	1.5	2.9	2.5	2.7	2.8	1.8	2.0	29.8
5	Inductive Cable/FMCW Radar	2.7	0.0	2.3	2.8	2.5	2.8	2.0	2.3	2.1	2.9	2.5	2.7	2.7	1.8	2.0	34.0
6	Direct Pickup Shared Infrastructure	2.6	0.0	2.1	2.4	3.0	2.0	0.0	2.3	0.0	2.6	2.5	2.7	2.7	1.8	2.0	28.7

Legend: 0=not possible, 1=possible but not likely, 2=likely, 3=certain

What conclusions may be drawn from this evaluation? The first is that in terms of the likelihood of satisfying requirements, there appear to be four logical groupings. The highest band contains concepts three and five. The second band contains concepts two, four. The third band contains concept six, and the lowest contains concept one. As stated above, the numerical values are of low precision, and differences of tenths of a point are meaningless. Second, concept ratings are highly dependent on the definition of the concept A simple addition of intervehicle communication to the first concept would have substantially increased its rating in terms of requirements satisfaction. At this point in the study, we do not see any single attribute other than communication coming to the fore in terms of importance.

2.6. Additional Maneuvers for the Maneuver Taxonomy

During the course of the evaluation, some candidate maneuvers were uncovered that could have been added to the taxonomy, but to avoid continuously growing scope in the study we elected to avoid adding them to the evaluation.

2.6.1. In-Lane Slowing Exception

Under certain exceptional conditions, continued operation in the nominal mode is either unsafe or may lead to emergency conditions, yet an emergency in-lane stop is an inadvisable or excessive reaction. In such cases, an "In-Line Slowing Exception" maneuver is called for, defined as a slowing to create spacing or additional reaction time under exceptional conditions such as sudden fog that reduces sensor effectiveness. Execution of this maneuver may cause congestion to occur and should be avoided if at all possible, but in cases where continued motion does not violate safety constraints such a maneuver can keep traffic flowing in a reduced capacity mode until conditions warrant resumption of fully nominal operation.

To provide for gradual degradation, varying levels of slowing exceptions could be defined. A candidate set would include slowing by 5, 10, and 15 mps for levels I, fl, and m respectively.

An example of a situation in which this response is appropriate was uncovered during the evaluation of the "Nominal Spacing Regulation" maneuver (MDFRD, §5.1). Suppose for some reason the controller senses loss of headway and normal operational limits are exceeded such that a minor collision is unavoidable. Without a well-defined slowing exception maneuver, there are two choices:

- Take whatever control action is required (such as application of brakes), and expect that vehicles behind will react accordingly.

- Execute an "[n-lane Emergency Stop" or "Emergency lane Change" maneuver to avoid impact.

While the second choice is excessive and will lead to unnecessarily interrupting traffic flow, the first reaction leads to unconstrained activity requiring more robust (and hence more complex and expensive), systems design. A defined maneuver places limits on behaviors allowable and permits more specific design of the sensing and control processes, either on the vehicle or in the infrastructure, which in turn increases safety and robustness in the system.

3. Concept Merit Evaluation Approach

3.1. Summary of Evaluation Criteria

Ranking and comparing a set of system concepts across many dimensions of evaluation criteria can quickly become an intractable problem if there is too little structure and simplifying assumptions are not employed. In the present study, we have identified three dimensions of evaluation: each concept is evaluated against each maneuver requirement and against each measure of performance or effectiveness. Unless one structures the evaluation, it will be difficult to aggregate individual results and make meaningful comparisons.

The next step in the overall process is to determine the list of criteria to be used in evaluating the system. This is perhaps the most crucial step, because it establishes the "rules" for the evaluation. The outline of this section provides the criteria we have elected to consider. Table 26 on page 32 provides the list at a glance. By no means should the list be regarded as all-inclusive. Rather, it represents a list of the criteria we believed were genuine to the experience base we brought to the task. Our hope is that others would extend this list within the structure we have set up, providing a broader, more comprehensive evaluation.

To make this process tractable, a simplified scheme of evaluations is required. We have elected to establish a integer scale for each criterion in the inclusive range [0,9]. This scale provides enough granularity to discriminate moderately finely, without forcing the evaluator to inappropriate levels of precision. Single-digit numbers also make the presentation of the evaluation easier to read in a spreadsheet form.

Having established the scale, the next step is to define how an evaluator determines the rating value for the concept being evaluated. In the sections that follow, we provide the definition of how this [0,9] scale is applied to each criterion, and finally the selection of the weight set for the relative importance of all criteria In most cases, we have selected what we believe is a rational set of weights and tried to justify them at a high level. However, we fully expect that both the definition of the scales and the selection of combining weights will be iterated many times before the final selection is made.

3.1.1. Cost

3.1.1.1. Per Vehicle Costs

3.1.1.1.1. Drive-Away Cost

Initial purchase costs (or drive-away costs) for a suitably-equipped vehicle will have a profound impact on the feasibility of any system. There is a strong negative correlation between the added cost to the car-buying public and the ultimate success of any concept.

We believe that Figure 2 on the following page typifies that relationship.

To apply this chart, the rating is chosen picking the point representing the upper bound on projected system cost, and taking the rating value corresponding to that value. This approach results in a somewhat conservative rating. To estimate cost bounds, the evaluator may assume technology enhancements that may reduce system cost in the future. As a rule of thumb, limiting future cost estimates to a 10-year horizon is a good idea, since projecting technology beyond that point is difficult at best. In any event, the estimate is admittedly a highly subjective one, subject to assumptions and justifications of the evaluator.

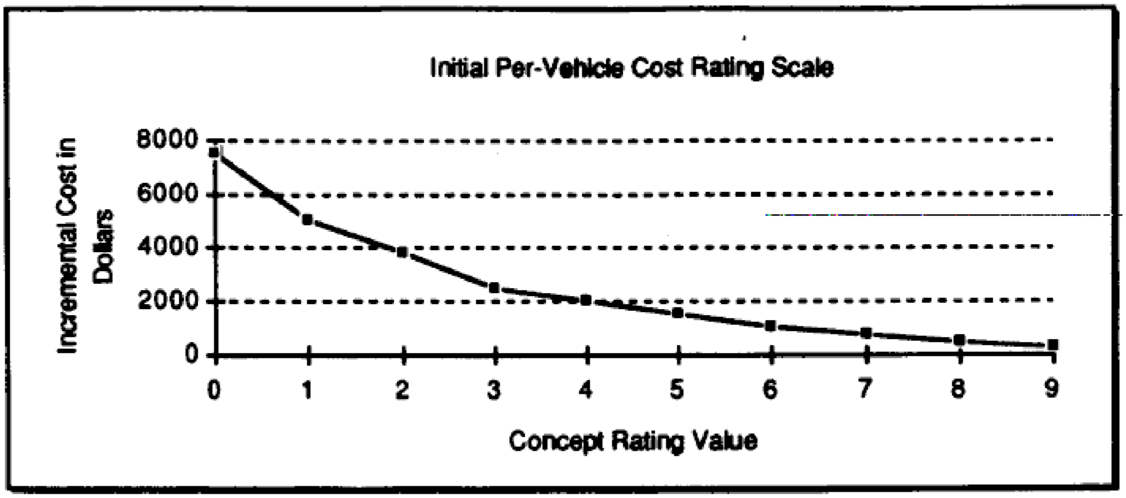


Figure 2. Per Vehicle Drive-Away Cost Rating Scale

The basis for choosing this scale is the argument that the number of people willing to purchase AHS capability will vary somewhat logarithmically. We assume that a reasonable fraction of the driving public will accept $2000 per vehicle in 1995 dollars, assuming the performance improvements can be shown. By comparison, a limited number of buyers have indicated a willingness to purchase GPS gear for fishing boats at a price of several thousand dollars. The cost versus market penetration curve for personal computers follows a similar curve. Certainly, a more accurate version of this graph requires significant market analysis. There may be some initial work along these lines of which we are unaware, but we have assumed this relationship for the purposes of performing the evaluation.

3.1.1.1.2. Recurring Cost

Recurring costs for the individual vehicle include a variety of ongoing expense items, depending on the concept. The categories of recurring vehicle cost are:

- Energy cost to operate the system compared to gasoline powered internal combustion.
- Costs for repair and periodic calibration, preventative maintenance, or replacement.

- Costs for periodic inspection by motor vehicle authorities.
- Registration and use fees resulting from public costs for operating the system.

These obviously cannot be projected with any accuracy. Evaluation is based on a subjective comparison to current recurring costs for operation and maintenance of ordinary private automobiles, according to the following Table 17 on the following page.

3~1.1.2 Infrastructure Costs

3.1.1.2.1. Initial Installation Cost

Interstate highway costs vary widely depending on right of way, number of exits and bridges and other factors, but $1M/mile is a rough median figure. Since representative concepts vary from creating new highways to dedicating existing lanes to leaving all infrastructure as is and using full autonomy, the are a wide variety of cost types. Some of the more obvious ones are:

Table 17. Recurring Per-Vehicle Cost Comparison

Rating	Meaning
0	Prohibitively costly
1	Considerably more costly
2	Noticeably more costly
3	Somewhat -C- costly
4	Slightly more costly
5	Comparable to current costs
6	Slightly less costly
7	Somewhat less costly
8	Noticeably less costly
9	Considerably less costly

- Construction of new highway lanes or ramps.
- Modification of existing lanes (such as transforming three current lanes to four narrow AHS lane.
- Adding instrumentation at regular intervals, such as placing radar corner reflectors every 20 feet.
- Adding new instrumentation, such as surveillance sensors at irregular intervals.

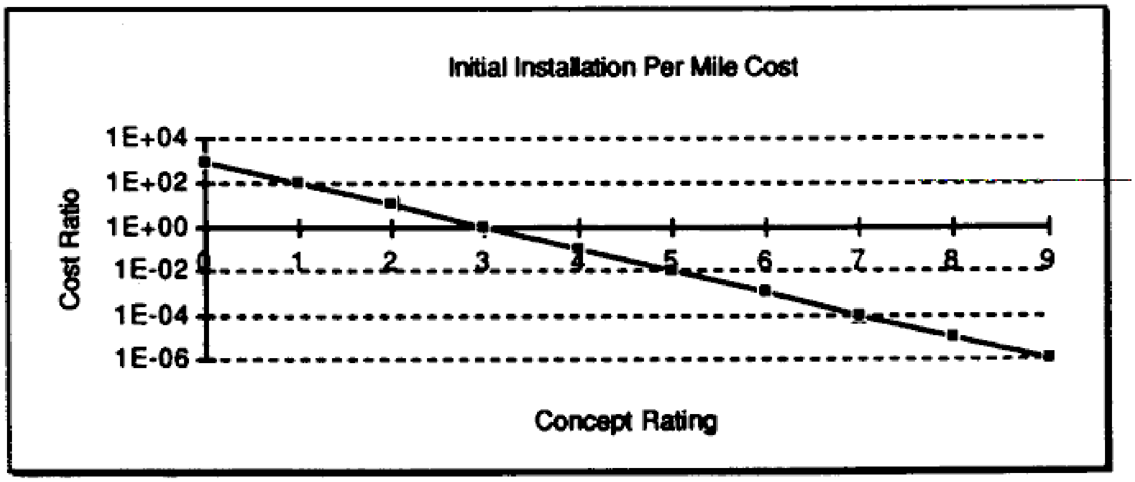


Figure 3. Rating for Infrastructure Initial Installation Cost

Initial installation cost ratings will be based on a cost ratio calculated as the anticipated cost per mile of the required infrastructure improvements compared to current construction costs per mile. We chose as the midpoint for this scale a 1% increase in the cost per mile for new roads, or 1% of the original cost per mile for improvements to existing highway. Note that if the cost for infrastructure approaches the cost of new road (a ratio of 1:1), this rating scale is well below the midpoint. According to this scale, we would anticipate that no concept will rate lower than "2", because concepts costing more than 10 times the current construction costs will probably never be proposed. The best score is reserved for concepts costing up to a few dollars per mile, which we considered to be insignificant.

3.1.1.2.2 Recurring Infrastructure Costs

Includes costs of maintenance and upkeep, personnel costs, and other associated annual costs. These costs are too difficult to judge at this level of detail, but they should not be ignored.

3.1.2. Safety

3.1.2.1. Personnel Injury Risk

Risk to personnel is perhaps the single most important evaluation criteria Not only is the human consideration of major significance, but the liability risk in a legal sense will ultimately be a major driver in the decision of how to deploy an AHS system.

Evaluating the risk to the individual drivers and passengers of various concepts for lateral and longitudinal control can be reduced to the likelihood of collision at moderate to high relative rates of closure. Studies by the PATH program suggest, for instance, that close vehicle following reduces risk of injury because of the lower relative collision speeds.

Table 18. Personnel Risk Rating Scale

Rating	Meaning
0	Prohibitively risky
1	Considerably more risky
2	Noticeably more risky
3	Somewhat more risky
4	Slightly more risky
5	Comparable to current risk
6	Slightly less risky
7	Somewhat less risky
8	Noticeably less risky
9	Considerably less risky

Another form of personnel safety risk is the risk to individuals on foot on or near the AHS. The primary source of such risk is from exposed power sources (if any) from which vehicles draw. An example of this might be a concept wherein vehicles draw power from radiated microwaves. If individuals near the infrastructure could be irradiated in this manner, there is a high risk of encountering personnel safety problems.

We know of no way to perform this evaluation other than subjectively. We based the evaluation an assessment of the risk relative to current risk of operating cars on urban freeways. Hopefully, other Precursor Systems Analysis contracts will provide additional definitive evaluation criteria The following table describes the rating scale we have used for this study.

3.1.2.2. Equipment Damage Risk

As in section 3.1.2.1., we know of no way to perform this evaluation other than subjectively. We based the evaluation an assessment of the risk relative to current risk of operating cars on urban freeways. The following table describes the rating scale we have used for this study.

Table 19. Equipment Risk Rating Scale

Rating	Meaning
0	Prohibitively risky
1	Considerably more risky
2	Noticeably more risky
3	Somewhat more risky
4	Slightly more risky
5	Comparable to current risk
6	Slightly less risky
7	Somewhat less risky
8	Noticeably less risky
9	Considerably less risky

3.1.3. Robustness with Respect to Environmental Conditions

There are a variety of environmental factors that can grossly affect system performance, depending on the concept involved. For instance, IR-based systems will experience significant degradation in the presence of roadway mist Video based systems will have difficulty at night Control concepts dependent on active devices built into the roadway will experience outages due to failure and vandalism. Susceptibility to these factors are an important measure of a concept's validity and merit.

Rating concepts in terms of these effects and merging the results in a consistent manner is difficult at best However, we have attempted such evaluations as indicators of overall importance on the system merit.

3~1~3.1. Obscurants

Different system concepts will be susceptible to interference from atmospheric obscurants. Rain, snow, dust, haze will all impact imaging sensors in particular, with different obscurants being more of a problem in some frequency domains than others. For instance, infrared will be more affected by moisture than millimeter wave. Fog and dust will be particular problems for video cameras. Obscurants tend to be a problem only under exceptional conditions, and therefore need not be weighted as heavily as night operations. However, they can become a problem in a sudden way, and to the extent that they interfere with safe operations, even for a few seconds, they become a significant part of the design trade space.

Table 20. Obscurants Susceptibility Rating Scale

Rating	Meaning
1	Obscurants likely to render system inoperable
3	Obscurants a significant problem under certain circumstances.
5	Obscurants may be a challenge
7	Moderate but acceptable degradation is possible
9	Obscurants are of no consequence

3.1.3.2. Night Operations

When we began analyzing and comparing candidate rating criteria, our first reaction was to place a much lower emphasis on the importance of night operations, under the presumption that most commercial and private traffic operated during the day. Our thinking was that if night was a problem initially, but a capability that could be added later, that would be an acceptable state of affairs. We soon realized. however, that rush hour traffic occurs in darkness every day during the winter month, if the goal of the AHS is to significantly improve system efficiency during high traffic periods, then ability to operate throughout the year to improve rush hour traffic conditions was an important capability. In terms of impact on the system cost and the readiness of the technology, this is an important figure of merit.

The problems of operating at night are most pronounced when the primary form of sensing is video or infrared. Loss of contrast, reversal of contrast, and interference from other sources of energy (oncoming headlights, engine heat, lightning flash) are the primary effects. Table 21 defines the evaluation scale for night operations.

Table 21. Night Operations Rating Scale

Rating	Meaning
1	Night operations not achievable
3	Night operations will most likely not be achievable for some time.
5	Night operations a significant but solvable problem
7	Some loss of capability will occur at Night
9	Night operations no different from daylight operations.

3.1.3.3. Interference

Interference can come from many sources, and is mostly a problem for various types of sensors and communications. While electromagnetic interference can affect processors or actuators, these forms of interference are usually solved by good engineering. For instance, pulse-width modulated electromechanical actuators will interfere with many RF communications, but can be controlled by placement of components, shielding, and filtering.

Table 22 defines the rating scale used for these effects.

Table 22. Interference Rating Scale

Rating	Meaning
1	Interference likely to be an intractable problem
3	Interference is likely to be a major challenge to solve.
5	Interference is a significant problem but methods to overcome it are conceivable
7	Some loss of capability will occur due to interference or modest cost designs can overcome it.
9	Interference will not be a problem

Forms of interference we considered in our ratings include the following:

- other vehicles in the vicinity with similar active sensing modes,
- oncoming headlights or other illuminating sources (such as lightning, streetlights)
- obstructions to line of sight
- high-power transmitters nearby emanating harmonics
- acoustic noise sources

3.1.3.4. Susceptibility to Damage or Component Impairment

Physical damage can be the result of corrosion, weather effects, vandalism, or collision. Impairment can be the result of loss of power or out-of-calibration conditions. if a concept is particularly susceptible to any of these effects, it can have significant impact on the viability of that concept For instance, a concept requiring an exposed cable lying on the road surface is likely to be damaged by traffic very quickly, and so is an unworkable concept. if loss of an infrastructral component such as a transponder or a reflector due to vandalism or collision damage, then that concept may not be practicable. Table 23 defines the rating scale for these effects.

Table 23. Damage Susceptibility Rating Scale

Rating	Meaning
1	Loss due to failure, collision damage, vandalism will likely cause a significant safety problem or shut down operation until repairs can be effected.
3	Damage or impairment forms will likely cause serious interruption of service.
5	Damage or impairment forms will degrade highway
7	Damage or impairment modes will require modest reliability engineering.
9	System has little susceptibility to damage or impairment

3.1.4. Timeline for Implementation

This figure of merit rates a system's timeline for implementation. If a concept requires significant development time before the first operational use can occur, then it rates low in this figure of merit. If a concept cannot be turned on in a limited mode now and later improved upon, it rates lower than one that can be gradually phased in over a long interval. For instance, vehicle-intensive, fully autonomous capabilities by definition require little to no infrastructure improvement. Such concepts would receive a more favorable rating than ones requiring considerable time and expense in the infrastructure before the first use can occur.

We believe this to be an important element of the evaluation. Concepts that cannot be phased in over time will have trouble maintaining advocacy long enough to see implementation through. Concepts that allow for partial capability with a benefit that fits the cost now, and continued evolution to the final configuration will meet with much greater public and Congressional approval.

This figure of merit is very subjective in its application. Table 24 defines the scale we have applied.

Table 24. Implementation Timeline Rating Scale

Rating	Meaning
1	Full-up implementation of all components is required prior to Full use OR technology is immature and implementation is not likely for many years.
3	A road map for phased implementation is difficult to envision and initial capability is not likely within 15 years
5	A road map for phased implementation is conceivable and initial capability is possible within 10 years but full capability will take 1~20 years longer.
7	A road map for phased implementation is conceivable and initial capability is possible within 10 years and full capability is not more than 20 years away.
9	An incremental implementation road map is intuitively obvious AND initial capability is likely within 5-10 years and full capability is likely within 15 years.

3.1.5. Likelihood of User Acceptance

User acceptance has on two significant components. Short-term acceptance is based primarily on the public perception of early prototype demonstrations and the success of various pilot projects. This term is important because poor early user acceptance could result in loss of Congressional advocacy, which could delay or stall deployment of an AHS. long term acceptance is based more on experience indicating a positive cost~beneflt ratio (both as individual purchasers and as a taxpaying class), market forces, and speed with which the system reaches technological maturity.

Both these terms are important in their own right. However, there is no objective measure we can identify for separately evaluating them or separately weighting them. Therefore, we have assigned the following scale:

Table 25. User Acceptance Rating Scale

Rating	Meaning
1	User acceptance not likely before the 22nd century
3	User acceptance is questionable
5	User acceptance not a serious issue
7	User acceptance is likely
9	Concept will meet with universal acclaim instantaneously

3.1.6. Other Inestimable Terms

This section describes the evaluation terms we considered but had to preclude from our evaluation scheme due to time constraints. Doubtless there are others that we have yet to uncover or others will point out, and we will continue to use this section as a collection point for these thoughts until they become firm enough to incorporate in one of the sections above.

3.1.6.1 Design Impact

Our initial approach included rating each concept according to its impact on design of elements of the AHS, outside of first-order cost considerations. There are many ways in which design impact can be felt. Highway and vehicle design might be significantly altered to the point where existing engineering training would be obsolete. Vehicle design or dynamics might be significantly different to the point of requiring driver training. Completely new materials might have to be developed specifically for this application. Training required for maintenance crews to perform calibration and periodic maintenance might be considerably more involved. All of these items are outside the scope of the cost measures cited above. Evaluating these impacts seemed initially to be an important part of the trade.

However, we found that, at this stage of system definition and evaluation, we were unable to derive a meaningful way to assess these figures of merit. We believe they will have to be assessed at some point in the future prior to selection of the final AHS configuration, but at this level of study they are not primary effects, and we have chosen to ignore them for the present.

3.1.6.2. Throughput Benefits

In any trade study, evaluation of the projected benefit should be weighed against the cost of the various options. For the AHS, the primary benefits include such things as speed, throughput or capacity increase, safety improvement, pollution reduction, energy efficiency, and so forth. Many of these are terms for which quantitative metrics can be established. At this point in the study, we can only point out that simulation is required to project these measures, but that the scope of the current contract does not permit carrying out the needed modeling and simulation. Some of this is already being done at other locations, and we will attempt to incorporate those results into the measures above where practicable. The remainder we will document in the list below for the anticipated AHS consortium to incorporate into its task plans.

- Improvement in average speed
- Improvement in highway capacity
- Estimated reduction in fuel usage Estimated reduction in emissions
- Estimated reduction in collisions per vehicle-mile

3.1.6.2. Timeline for Repair

Depending on the implementation and the types of failures possible, there will be distinct differences in the amount of time required to restore a failed system to operating condition. For instance, after an accident, the vision-guided AHS approach recovers by removing the failed vehicle from the highway and proceeding. However, after an accident in which the infrastructure is damaged, the direct pickup approach will require significant ~ time to restore the electrical pickup mechanism. That time will affect when the AHS is returned to service (the duration of the outage).

3.2. Evaluation Criteria Weights

To accomplish a meaningful comparison and avoid undue bias, the various criteria must be assigned a relative weight Table 26 below lists the criteria described above and assigns their relative weights. Weights are assigned on an integer range of [0,9], inclusive. The column labeled "Justification" provides a high-level reason behind each particular assignment.

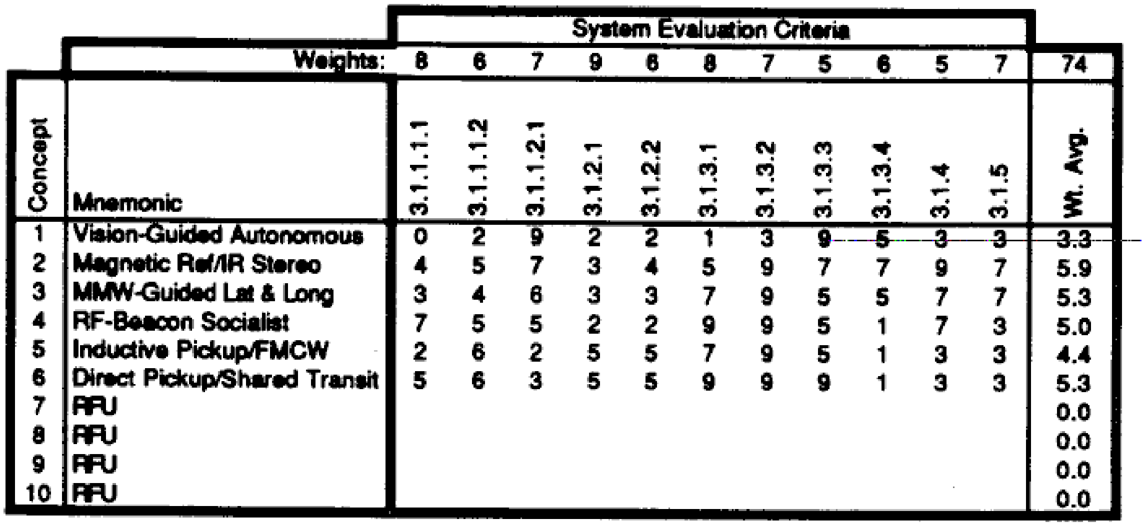
Table 26. Evaluation Criteria Weight Set

Index	Criterion Name	Weight	Justification
3.1.1.1.1.	Drive-away cost	8	Behind the risk of personal injury, this is probably the most important factor.
3.1.1.1.2.	Vehicle recurring cost	6	The public is somewhat less sensitive to this cost term than it is to the drive-away costs.
3.1.1.2.1.	Initial installation cost	7	The public is somewhat less sensitive to this cost term than it is to the drive-away costs.
3.1.2.1.	Personnel injury risk	9	Probably the single most important factor, since this will be the basis for the most serious tort litigation problems.
3.1.2.2.	Equipment damage risk	6	Somewhat less important than personal injury; we believe that the public will accept some risk to cars and infrastructure for the perceived benefits, as long as that risk doesn't translate into obviously higher accident rates.
3.1.3.1.	Robustness/ obscurants	8	Rain is a significant problem throughout much of the country for much of the year. Systems must be able to operate in up to moderate rainfall. However, system breakdown under heavy rain (several inches per hour) is probably acceptable, since heavy rain seriously degrades travel currently. Snow is a considerably less common problem on a nationwide scale. Some reduction, or even reversion to manual control in snow, is probably acceptable.
3.1.3.2.	Robustness/ nighttime	7	More important than snow, but slightly less than driving in rain. Most driving is done in the daytime. Good nighttime implementation is something that could be introduced later without killing the concept.
3.1.3.3.	Susceptibility to interference	5	Fairly important; there is continual increasing demand on the EM spectrum from a wide variety of need areas. Active sensing and sources of illumination are likely to cause problems for some concepts. These effects can frequently be engineered out of the system.
3.1.3.4.	Susceptibility to Damage & Impairment	6	Mostly felt as a cost, this item is also important from the standpoint of how dependent is the system on equipment that vandals or out of control vehicles could reach.
3.1.4.	Implementation Timeline	5	As noted in the text, this is important, but relative to feasibility on a technical level, it is not a significant trade weight.
3.1.5	User acceptance likelihood	7	A moderately important factor, but one which can be heavily influenced by demonstrators and human factors engineering.

3.3. System Evaluation

The final step in the evaluation is to apply the criteria to each of the concepts and score them according to the weights defined in the previous segment. This has been done and the results are presented in Table 27:

Table 27. System Evaluation Spread



		System Evaluation Criteria											
	Weights:	8	6	7	9	6	8	7	5	6	5	7	74
Concept	Mnemonic	3.1.1.1.1	3.1.1.1.2	3.1.1.2.1	3.1.2.1	3.1.2.2	3.1.3.1	3.1.3.2	3.1.3.3	3.1.3.4	3.1.4	3.1.5	Wt. Avg.
1	Vision-Guided Autonomous	0	2	9	2	2	1	3	9	5	3	3	3.3
2	Magnetic Ref/IR Stereo	4	5	7	3	4	5	9	7	7	9	7	5.9
3	MMW-Guided Lat & Long	3	4	6	3	3	7	9	5	5	7	7	5.3
4	RF-Beacon Socialist	7	5	5	2	2	9	9	5	1	7	3	5.0
5	Inductive Pickup/FMCW	2	6	2	5	5	7	9	5	1	3	3	4.4
6	Direct Pickup/Shared Transit	5	6	3	5	5	9	9	9	1	3	3	5.3
7	RFU												0.0
8	RFU												0.0
9	RFU												0.0
10	RFU												0.0

It is important to note that the evaluation is purely from a lateral-longitudinal control perspective. Those more concerned with environmental impact, legal and societal issues, human factors, or other perspectives would likely choose other criteria and other weight sets.

Even within the limited domain of lateral-longitudinal control, it is important to note that this is a judgment-driven process. There is no completely objective way to perform such an evaluation. One may argue with the selection of criteria, the scales along which the criteria are evaluated, the weight factors, the particular scores assigned to each concept for each criterion, and even the combining process. There is plenty of room for results to vary widely. The table above is our first cut at such an evaluation, and we have tried here to justify the results. We fully acknowledge that others may derive different but equally or perhaps even more valid results.

3.4. Individual Concept Strengths and Weaknesses

In addition to trying to derive a comparison between the various concepts on some sort of numerical scale, it is important to assess of how the concepts stack up against one another. The sections that follow provide an assessment of the strengths and weaknesses of each of the concepts, with an emphasis on those areas that distinguish one concept from another.

3.4.1. Autonomous Vision-Guided Concept

3.4.1.1. Significant strengths

- Very little requirement is placed on the infrastructure. As a consequence, initial implementation costs are low and the potential for phased implementation is quite high.

- Because of the potential for phased implementation, the chicken-and-egg problem of requiring significant market penetration before substantial public funds are invested can be averted.

- There are no active sensors, and therefore the risk is low of incurring implementation difficulties due to interference when there are many vehicles crowded into a small operating area.

- Decentralized control and energy supply limits liability risk of public agencies and governments; burden for safety and maintenance rests primarily with the individual operator.

3.4.1.2. Significant weaknesses

- Individual vehicle costs are likely to be high unless there are substantial breakthroughs before implementation. This gives rise to the risk of appearing to design a system that disenfranchises the poor because they will not have the ability to pay for the capability.

- The state of the art is such that systems of this type all have problems with robustness with respect to effects of lighting, obscurants (snow, rain, fog), and damage to the system's optics. Safety of such systems will be a significant issue.

- Public acceptance of a system that only works under ideal conditions will be low. Public patience for the systems to be developed that work under all operating conditions will be just as low.

- In general, eliminating sources of latency is more difficult for image-processing based approaches than for other concepts such as radar and magnetometers. Changing from a base update rate of 15 *Hz* to 30 or even 60 *Hz* dramatically increases the bandwidth required of the data channels between sensor and image processing equipment. Image processing algorithm latencies can be improved by parallelization, but this leads to more expensive computing hardware. As a rule, means of improving such systems' thoughput require greater system cost, complexity, and lower reliability.

- Implementation timeline may be much longer than for some of the other concepts because of the current state of the art and the concomitant robustness issues.

3.4.2. Magnetic Reference with Infrared Range Detection

3.4.2.l. Significant Strengths

- This concept is relatively insensitive to environmental conditional. Lateral control is likely to be unaffected by rain, snow, day/night conditions. Longitudinal control may be affected by rain, but the signal-noise ratios achievable with an active cooperating target and the relatively short ranges probably will make for very robust performance.

- Implementation in the near term is quite possible.

- Infrastructure costs are quite low. Insertion of the magnetic reference markers is the only significant infrastructure modification required.

- Phased implementation is quite possible.

- Public acceptance can be developed over time by gradually inserting new capabilities and permitting the public at large to become accustomed to one level of performance before moving to the next plateau.

3.4.2.2. Significant weaknesses

- None identified.

3.4.3. Radar-Guided Semiautonomous Concept

3.4.2.1. Special note about millimeter waves

- Atmospheric attenuation effects are an important consideration for millimeter wave systems. Water absorbs energy at the rate of about 2 db/km in the 22 GHz region, oxygen absorbs energy at the rate of about 20 db/km at 60 GHZ and 2db/km at 118 GHz, and various other factors create energy-absorbing resonances at 183 GHz and *325 GHz.* For this reason, millimeter applications to date have concentrated on 35 GHz and 94 GHz, where the absorption bands are at relative minima. Another relative minimum occurs around 140 Hz, but we know of no serious attempt at present to develop production-grade devices that operate at these frequencies. Superimposed on this attenuation in clear air is the influence of rain. At a moderate rate of 5 mm/hr, rain will attenuate at about 1-5 db/km, depending on droplet size12.

However, millimeter wave radar applications to date have operated at frequencies that minimize atmospheric attenuation because they have mainly been developed for airborne applications with greater operating ranges (5-50 km) and attenuation is a serious problem. For close-range highway applications, this constraint will not be quite so serious, and other non-optimal frequency assignments could be employed.

3.4.3.2. Significant strengths

- Millimeter wave frequencies are currently not heavily burdened by existing applications and frequency assignments, and are less likely than microwave frequencies to have allocation conflicts.

- Suitable devices for transmitting and receiving millimeter wave energy are emerging because of work over the last decade in the military domain. The cost of producing such devices is likely to fall dramatically over the next decade, particularly at the lower power levels required for highway applications

- The small wavelength compared to microwave radar provides greater range resolution, which may be particularly important for close following. The real requirement for range resolution is not known and some simulation work will be needed to see if the use of millimeter wave radar will provide significant performance benefits.

  Doppler sensitivity is also higher, providing more accurate velocity measurement. Skolnik notes that "the large Doppler frequencies at millimeter wavelengths, however, can sometimes result in the echo signal being outside the receiver bandwidth, which complicates the receiver design." 12 This is less of a concern for vehicular applications, where the relative velocities, and hence the amount of Doppler shift, is much lower than for airborne radar applications.

- Greater bandwidth available provides more opportunity for encoding radar pulses with identifying information without significantly reducing signal to noise ratios. This may be important because with thousands of vehicles on the highway, it will be important to distinguish one's own energy from other emitters' energy.

- For a given antenna gain beam width), millimeter antennae can be much smaller. This is a double-edged sword for airborne applications because reducing antenna size also reduces the area over which echo energy can be received. However, for close-range automotive applications, this is less likely to be a concern. The physical design problems associated with multiple sensors of narrow beam width located around the vehicle are dramatically lower than for comparable sensor systems in the microwave region.

- Avoiding the typical application bands and using operating frequencies with higher atmospheric attenuation can be used to advantage. Since the ranges of interest are small (approximately 0.2 km), atmospheric attenuation can be a significant advantage in reducing or eliminating mutual interference from other users on the highway.

3.4.3.3 Significant weaknesses

- Device technology is an emerging technology, and there is far less experience with robust, reliable designs in the millimeter domain. This will, of course, be less of a concern over time, but near-term implementation at reasonable cost factors is an issue.

Dependence on barriers or other infrastructure elements at the lateral position reference makes the lateral control system highly susceptible to interruptions, obscuration by other vehicles, and backscatter effects than for lane-relative sensing concepts. This may lead to the desire to place barriers on both sides of each lane, which in turn limits the flexibility for vehicles to change lanes.

3.4.4. RF Beacon Triangulation *I* Socialist Architecture

3.4.4.1. Significant strengths

- The vehicle equipment complement is relatively inexpensive compared to other sensing techniques.

- Problems associated with calibration and position accuracy are dramatically reduced compared to autonomous GPS position data because the position is calculated with respect to static, surveyed positions of the transmitters.

- Robustness with respect to environmental conditions (day/night, rain, snow, etc.) is not likely to be a problem.

- Because the primary sensing is passive on the part of the vehicles (though the infrastructure is active), mutual interference problems are limited to vehicle-vehicle and vehicle-infrastructure communications.

- Synchronous speed control reduces the variation in vehicle speeds that leads to congestion. It also has the potential of operating at greater energy efficiency and lower rates of emissions, since variations in speed have a high energy cost

- Depending on the specific architecture, the potential is high for mitigating reliability concerns through beacon redundancy. if operating ranges and spacing intervals are such that a given vehicle can utilize six or more beacons simultaneously, the problems of failures in the beacons and obscuration by other vehicles may be obviated.

3.4.4.2. Significant weakness

- Because of the use of centralized control, the system is much more susceptible to power loss and failure due to accidents or even vandalism than a more distributed, autonomous control approach.

- Operating speeds are more tightly controlled because of the synchronous operation. While analysis may show that synchronous operation can enhance highway throughput, a more subjective question remains of user acceptance by a driving public used to some degree of autonomy. Being constrained to operate in a pre-defined "time-space slot" may be more frustrating to operators, particularly if the highway is not operating near capacity and there is maneuvering room but the system constrains speed and location anyway.

- Because of the dependence on the centralized control within each segment, there is greater risk of collision and personal injury in the event of a failure of the beacon infrastructure, which affects *all* vehicles in the vicinity. Without some backup form of lateral sensing control, the risk of sudden, unwanted disturbances may be unacceptable.

- Recurring maintenance costs could be a problem for the beacon infrastructure. These will be subject to environmental effects, vandalism, and ordinary degradation over time. Calibration will be very important for these devices, particularly if their emissions are phased according to their distance from nearby transmitters.

3.4.5. Inductive Drive with FMCW Radar

3.4.5.1. Significant strengths

- Use of central power for locomotion has strong potential for emissions and noise reduction if the problems of power distribution, transfer, and reliability can be solved.

- Synchronization is managed by field rate in the linear motor. It is a natural consequence of how the energy is transferred and requires no additional command and control structure. Operating at less than synchronous speeds is possible but should be avoided as it leads to inefficiency and heat transfer issues.

- The system could be designed such that the motive force needed does not come entirely from the infrastructure. Since vehicles must have independent means of locomotion for non-AHS travel, the possibility exists for using the infrastructure to augment the motive force available from internal means instead of providing the total force required. This approach has the benefit of softening the design requirements on the infrastructure as well as on the vehicle. In addition, the AHS would be the way that vehicle could extend their range compared to non-AHS travel, since only part of the energy needed to travel needs to be stored on the vehicle.

3.4.5.2. Significant cant weaknesses

- Vehicle equipment may be heavy and bulky, significantly compounding vehicle design to cost problems. For private passenger vehicles, the extra weight also means a higher energy penalty (on a percentage basis) than would be true for transit vehicles.
- Vehicles would be required to be hybrid designs. The need to operate in non-AHS environments leads to a requirement for internal combustion locomotion or battery powered electric drive in addition to the linear motor component.
- Vertical clearance tolerances are likely to be a critical, if not over-constraining, design factor.
- The system is highly sensitive to failure of the central power production and distribution network. Power failure would in essence shut down the highway.
- Using the magnetic field as a means of determining lateral position is not as attractive as first thought Without good sensitivity to lateral position, lateral ride quality will be difficult to achieve and vehicles not positioned at the point of optimal field strength will experience dramatically reduced motive force from the linear motor. This suggests that some other means of determining lateral position would be required.
- Magnetic attractive forces will require a very stiff suspension, which complicates the designer's problems in providing sufficiently smooth ride quality. If the guideway is designed to sufficiently small tolerances, this problem is mitigated. An associated problem is that of a physical and mechanical design that works to tight tolerances on the AHS and yet operates on today's highways at the same time.
- The presence of strong magnetic fields required for locomotion lead to the likelihood of "collecting" flotsam (such as vehicle body parts) that is magnetic in nature.

3.4.6. Direct Pickup Shared Transit

3.4.6.1. Significant strengths

- There is considerable experience with power distribution, transfer, and control from transit applications of this technology
- Use of central power for locomotion has strong potential for emissions and noise reduction if the problems of power distribution, transfer, and reliability can be

solved.

- Acquiring approval for funding may be easier because public funding for transit infrastructure could be enhanced by the public perception that a mixed-mode public-private transit system would be more flexible than a dedicated light rail, for instance.

- A plan for phased implementation might be easier to envision because the costs of infrastructure improvements could be justified on the basis of building corridors in the areas of highest need first and providing incentives for travel in the public transit mode. Phased implementation, in this context, refers not to gradually increasing capability but gradually greater areas of coverage.

3.4.6.2. Significant weaknesses

- The system is highly sensitive to failure of the central power production and distribution network. Power failure would in essence shut down the highway.

- Vehicle equipment may be heavy and bulky, significantly compounding vehicle design to cost problems. For private passenger vehicles, the extra weight also means a higher energy penalty (on a percentage basis) than would be true for transit vehicles.

- Vehicles would be required to be hybrid designs. The need to operate in non-AHS environments leads to a requirement for internal combustion locomotion or battery powered electric drive in addition to the linear motor components.

- The issues of frictional wear under extremely high use rates compared to similar designs for transit systems is an unknown at this time. We suspect that the rate of wear will be unacceptably high for an AHS simply because of the traffic load. Transit systems currently in use are "lightly loaded" in the sense of infrastructure occupancy and the number of times per hour that a contact passes a given point on the rail.

- Modifying existing highway infrastructure to install this concept would be difficult and expensive, if not impossible. On the other hand, for some of the areas of greatest need, the biggest problem is cost of acquiring right-of-way, and any concept that requires new right of way will compare very unfavorably with concepts that make existing highway more effective.

4. Simulation Results

As stated in section 1.2, part of our approach was to validate some of our analyses through the use of simulation, Once again, the reader should note that the scope of this study was to determine longitudinal/lateral control issues. Toward that end, we developed a longitudinal and lateral vehicle model in the MatLab simulation environment based on vehicle model data developed at USC by Petros Iannou and his associates(5). MatLab was selected because it is a widely available tool and it provides an environment in which such models can be very quickly and accurately implemented. Those models will be provided to the FHWA in as-is condition at the close of the study, and it is our hope that others will be able to use these models and extend and adapt them to their own work. For that purpose, AHS researchers may acquire the models by contacting FHWA.

During the course of definition of maneuver requirements and system concepts, we identified some concerns about the influence of sensor and control sample rate, sensor quantization intervals, and vehicle control bandwidth that lent themselves well to a limited simulation effort. Sensing for all vehicle states was assumed to be the ideal case. Since the test cases involving multiple vehicles, the models were extended by adding five vehicles in series coupled by headway sensors and a simple control feedback scheme to control throttle based on Speed and sensed headway. In addition, a feedback from each vehicle to the vehicle following was provided to emulate a communications link to demonstrate the benefits of communicated speed information during platooning.

Section 4.1 below defines the longitudinal model, section 4.2 defines the lateral model, section 4.3 details our model initialization strategy, section 4.4 describes the test cases we selected and the strategy behind that selection, and section 4.5 provides the conclusions we drew from analyzing and comparing the test run outputs. Appendix B provides the actual time history data for all twenty-four test cases.

4.1. Simulation Definition

4.1.1. Longitudinal Components

The top level block diagram, called the system longitudinal vehicle model, is provided in Figure 4. The longitudinal model components are broken into the following groupings:

Detail Area	Section
Throttle and Intake Manifold	4.1.1.1
Cornbustion process	4.1.1.2
Engine Dynamics	4.1.1.3
Torque Converter	4.1.1.4
Transmission	4.1.1.5
Vehicle Longitudinal Dynamics	4.1.1.6

System longitudinal dynamics model inputs include:
1) throttle position and
2) brake force.

System longitudinal dynamics model outputs include:
1) V - vehicle longitudinal velocity,
2) n - net engine torque,
3) n-engine speed, and
4) A - vehicle longitudinal acceleration.

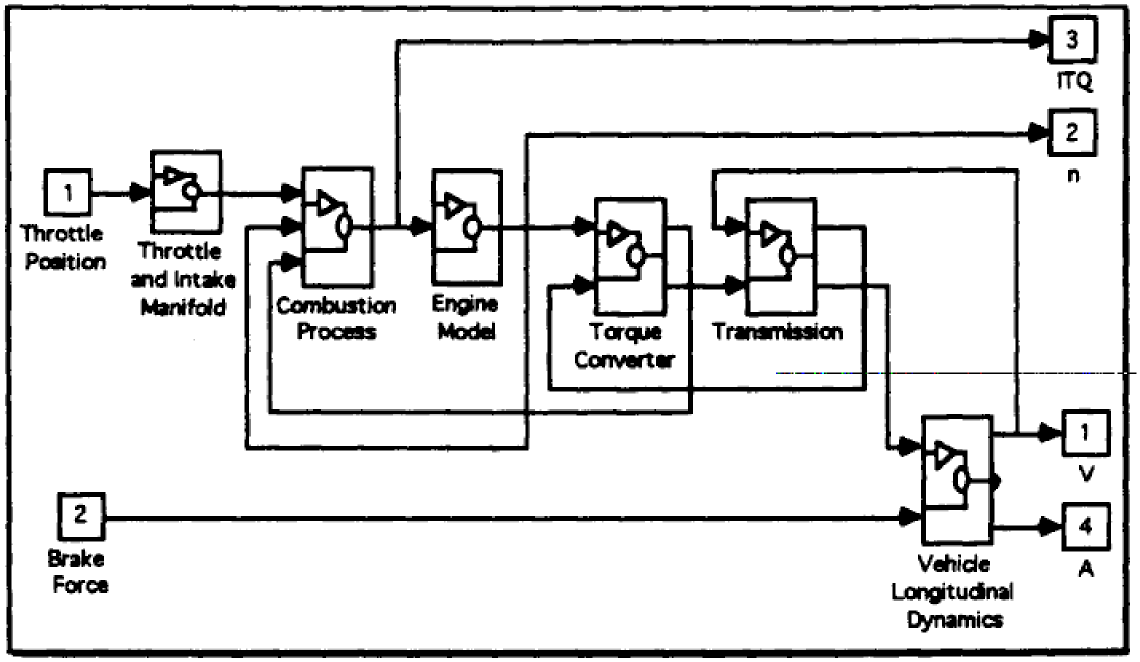


Figure 4. System Longitudinal Block Diagram

4.1.1.1. Throttle and Intake Manifold Components

The throttle and intake manifold components consist of a limiter, to restrict the range of possible angles between fully closed and fully open throttle positions, and a table look-up of the air mass-density in the intake manifold, based upon the throttle angle. These components are illustrated in Figure 5. The executable code for the look-up is provided in Appendix A.1.

There are no initialization requirements for the throttle and intake manifold components, since there are no states to initialize in this component However, the throttle position - which has been allocated to the throttle actuator model - does require initialization for proper operation, as discussed in section 4.

Throttle and intake manifold inputs include:
1) throttle position.

Throttle and intake manifold outputs include:

1) MDAIR~out - the Mass density of the air in the intake manifold (1).

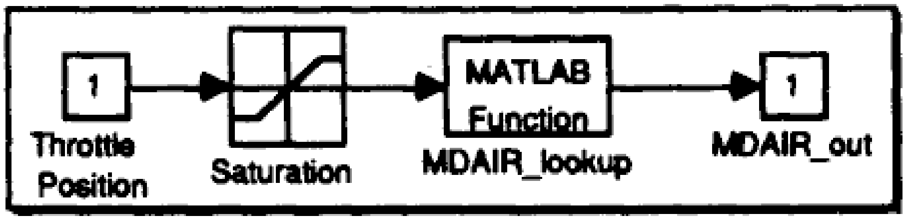


Figure 5. Throttle and Intake Manifold Block Diagram

4.1.1.2. Combustion Process Component

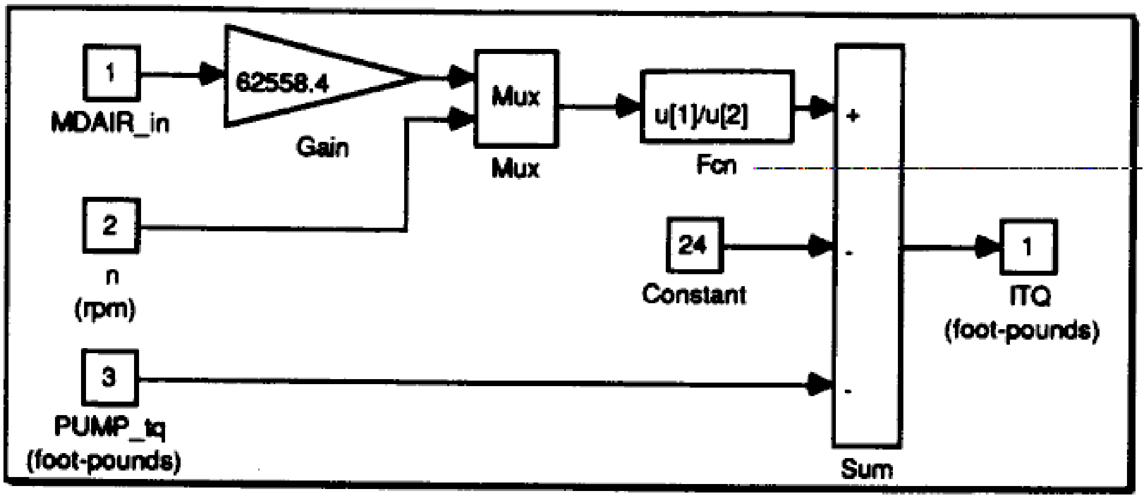


Figure 6. Combustion Process Block Diagram

There are no initialization requirements for the combustion process component. The combustion process inputs include:

1) MDAIR_in - the Mass density of the air in the intake manifold,
2) n-the engine speed, and
3) PUMP~tq - the feedback torque from the torque converter.

The combustion process outputs include:

1) ITQ - the net engine torque (1).

4.1.1.3. Engine Dynamics Component

The engine dynamics, described in (5), amount to implementation of a scale factor and a time constant These components are illustrated in Figure 7. Numerous implementations are possible for this equation form. The one shown here was chosen for ease of initialization.

Initialization of the engine dynamics component requires initialization of the engine speed integrator. Initialization will be discussed in section 4.

Engine dynamics inputs include:

1) n- the net engine torque

Engine dynamics outputs include:

1) n-engine speed.

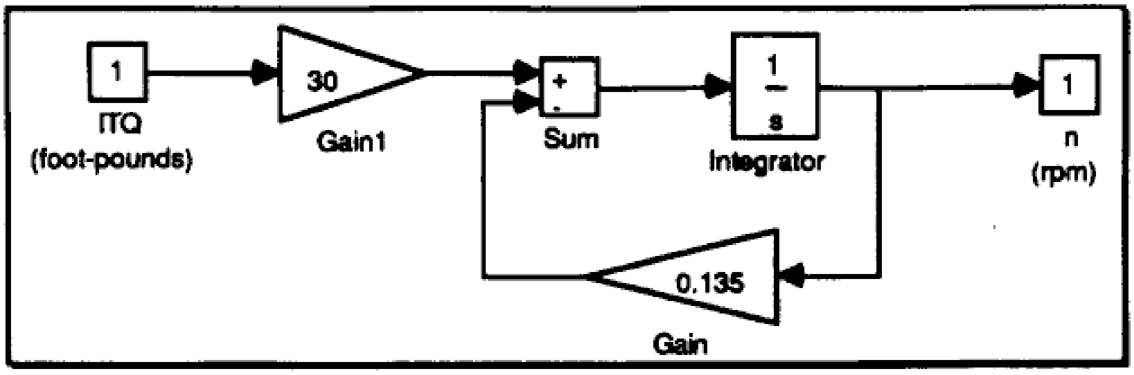


Figure 7. Engine Dynamics Block Diagram

4.1.1.4. Torque Converter Component

The torque converter ,reference Figures 8,9, and 10, transforms the differential speed between the engine and the transmission into both a drive torque for the transmission and a retarding torque for loading the engine.

There are no initialization requirements for the torque converter component. Torque

converter inputs include:

1) n - the engine speed, and
2) n_turbine - the turbine speed.

Torque converter outputs include:

1) tau~pump - the feedback torque from the torque converter to the engine, and
2) tau_turbine - the drive torque from the torque converter to the transmission.

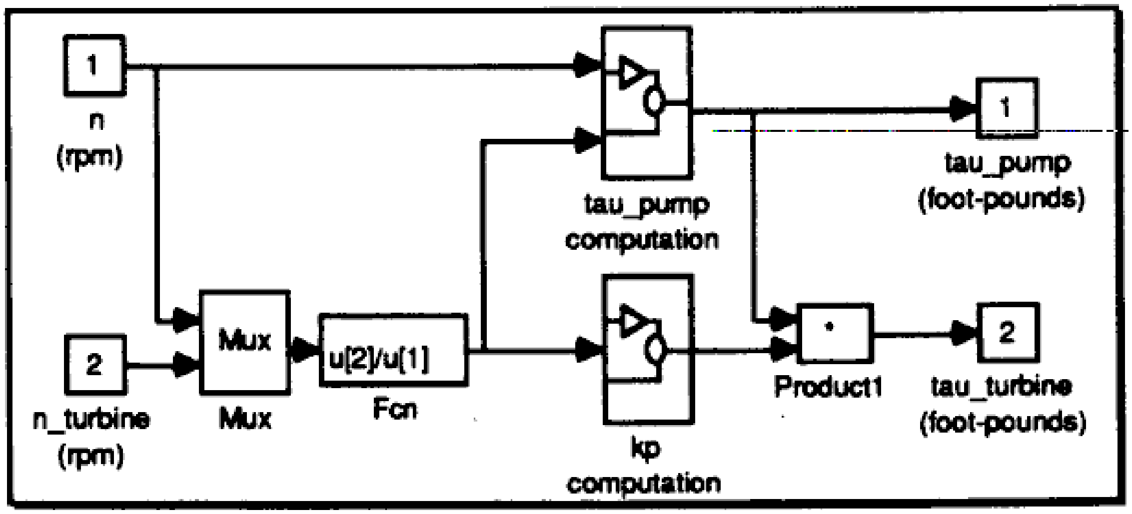


Figure 8. Torque Converter Block Diagram

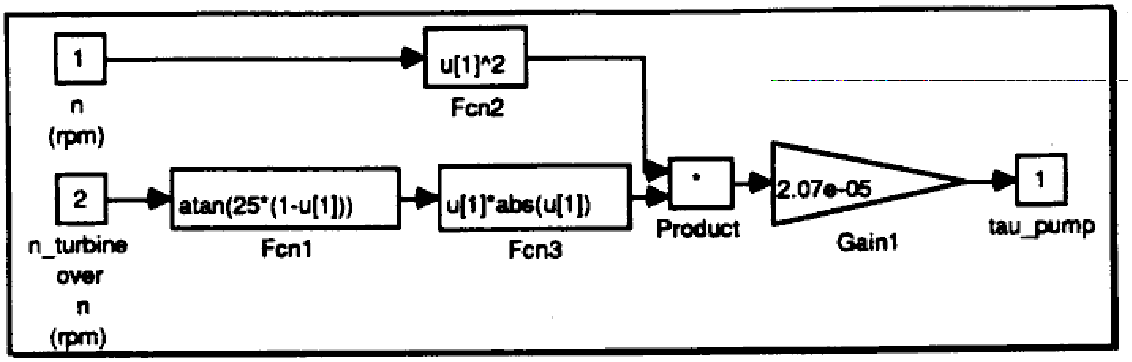


Figure 9. tau~pump computation Block Diagram

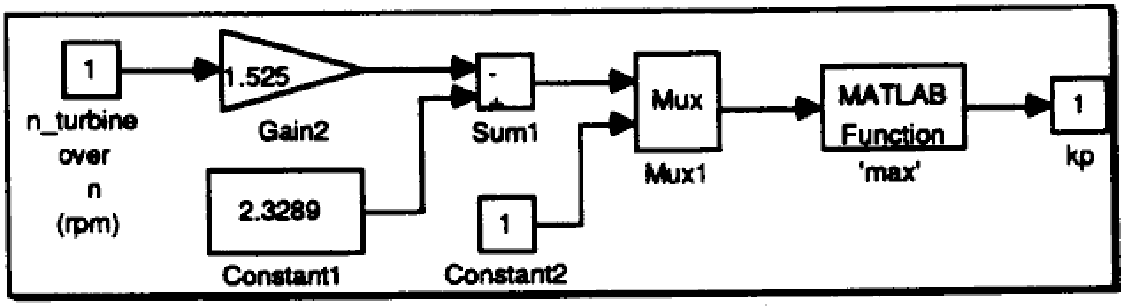


Figure 10. kp computation Block Diagram

4.1.1.5. Transmission Component

The transmission , reference Figure 11, provides a classic gear reduction function. In this case, linear velocity at the transmission output, is converted into angular velocity, at the transmission input, and rotational torque, at the transmission input, is converted into linear drive force, at the transmission output Implementation of the lookup table, required to define kv, can be found in Appendix A.2

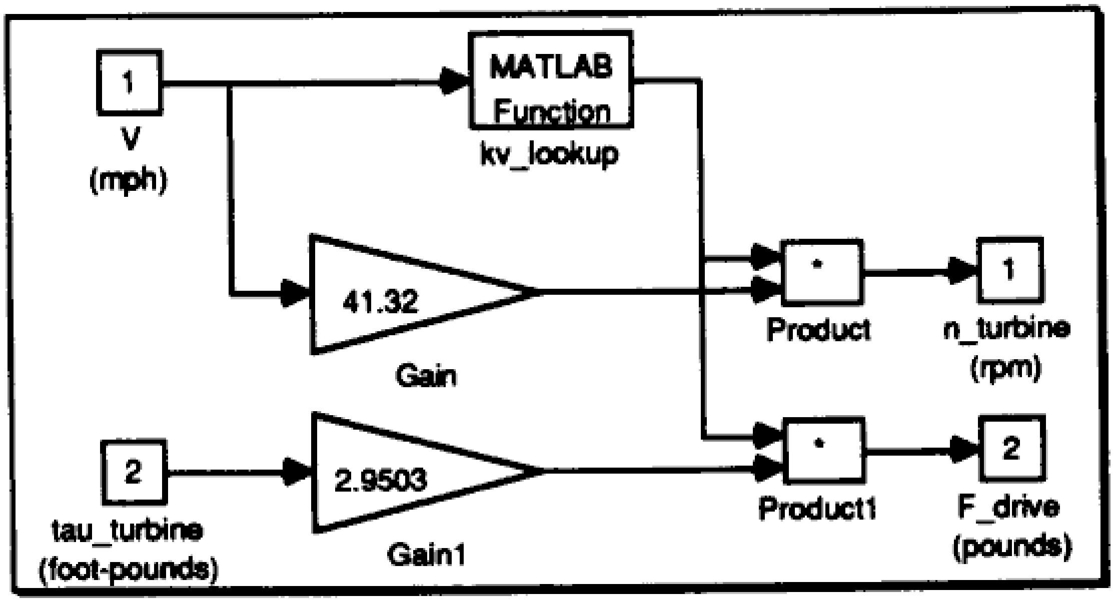


Figure 11. Transmission Diagram

There are no initialization requirements for the transmission. Transmission inputs

include:

1) V - the vehicle speed, and
2) tau_turbine - the drive torque from the torque converter to the transmission.

Transmission outputs include:

1) n_turbine - the turbine speed, and
2) F_drive - the linear driving force (2).

4.11.6. Vehicle Longitudinal Dynamics Component

The vehicle longitudinal dynamics model in figure 12 computes the net force applied to the longitudinal axis of the vehicle, which is then used to compute the vehicle acceleration. The vehicle acceleration is integrated to form the vehicle velocity. The forces acting upon the longitudinal motion are the drive force, the brake force, and the aerodynamic resistance force. The brake dynamics model in figure 13 provides a mechanical pole. The resistance force computation in figure 14 provides a non-linear force as a function of vehicle velocity.

Initialization of the vehicle longitudinal dynamics component requires initialization of the velocity integrator, as well as the brake dynamics integrator. The later is assumed to be zero for highway conditions, i.e. the brake is assumed to be released. Initialization of the former will be discussed in section 4.

At the vehicle dynamics level there are two inputs;

1) VF_drive - the linear driving force, and
2) Fb_cmd - the brake force command assumed to be at the input to the master cylinder,

and three outputs;

1) V - the vehicle speed
2) F_resist - the vehicle 'aerodynamics drag force, and
3) A - the vehicle longitudinal acceleration.

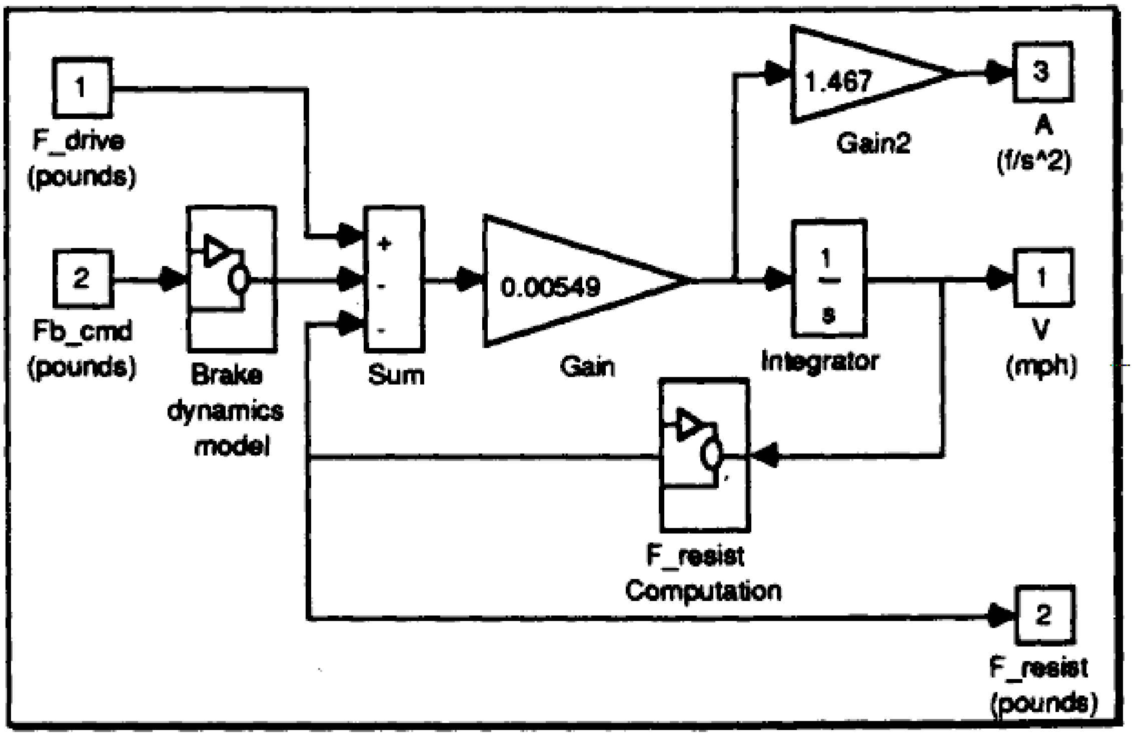


Figure 12. Vehicle Longitudinal Block Diagram

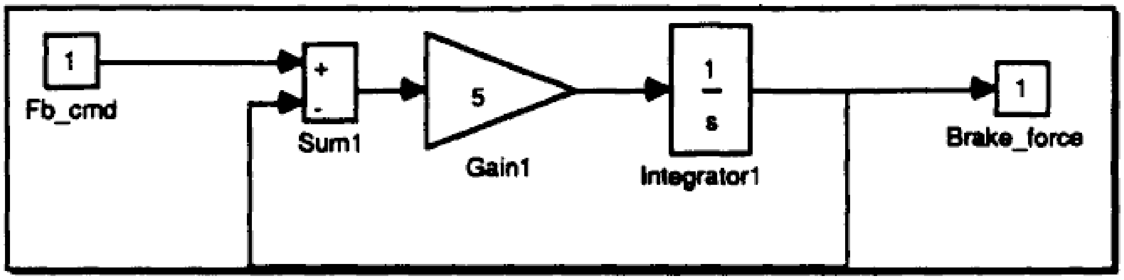


Figure 13. Brake Dynamics Model Block Diagram

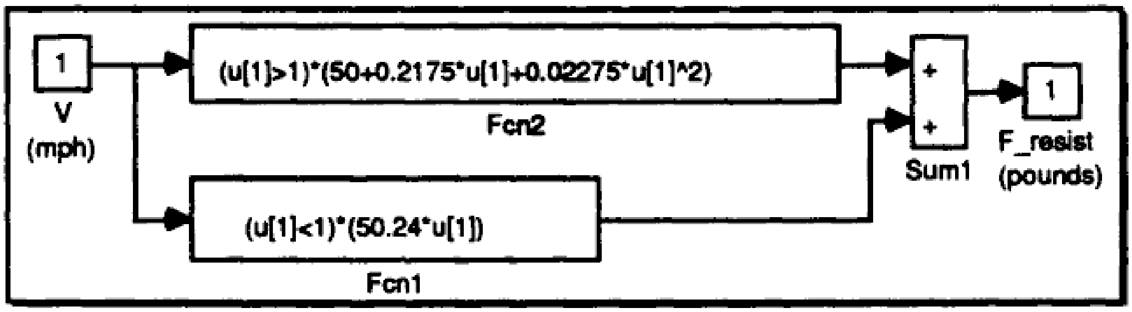


Figure 14. Resistance Force Computation Block Diagram

4.1.2. Lateral Components

The top level block diagram of the system lateral model is provided in Figure 15. The vehicle lateral components are broken *into* the following groupings:

Detail Area	Section
V_hat Computations	4.1.2.1
Beta Computations	4.1.2.2
Psi Computations	4.1.2.3

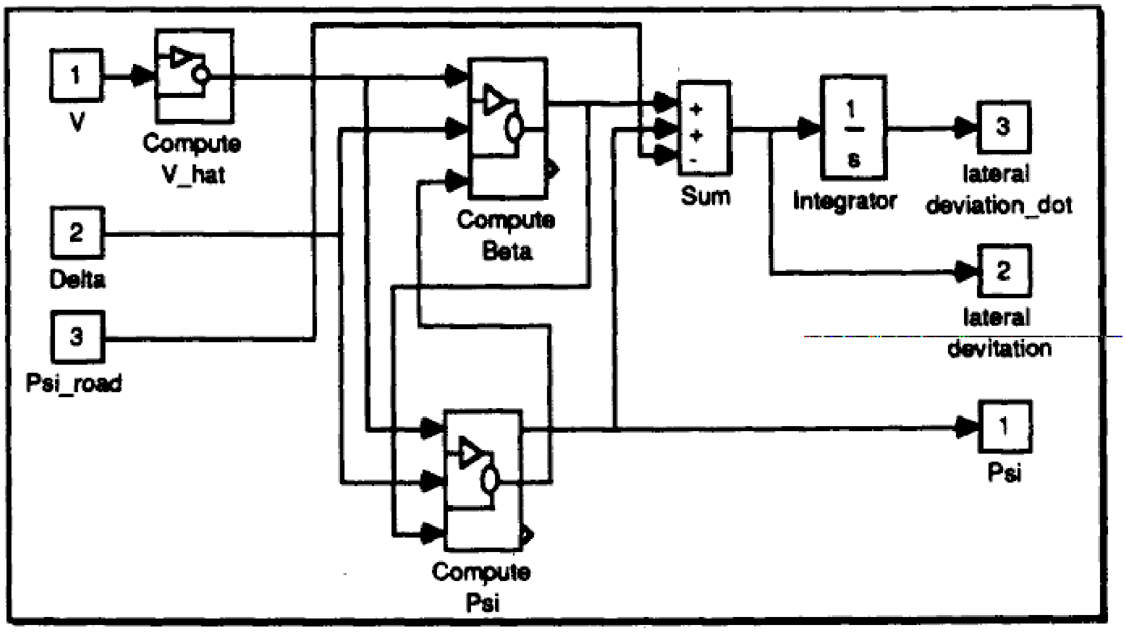


Figure 15. System Lateral Block Diagram

System lateral inputs include:

1) V - vehicle longitudinal velocity,
2) Delta - vehicle steering angle, and
3) Psi_road - the roadway heading.

System lateral outputs include:

1) Psi - the vehicle heading,
2) lateral deviation, and
3) lateral deviation rate.

4.1.2.1. V hat Components

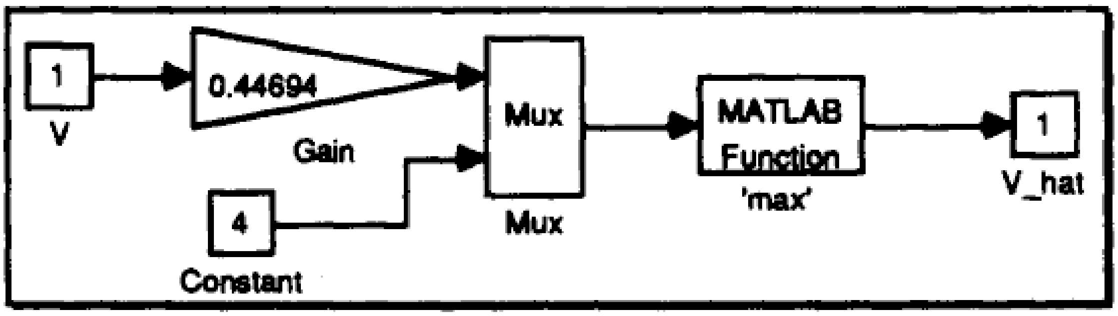


Figure 16. V_hat Computations Block Diagram

4.1.2.2. Beta Computations Block

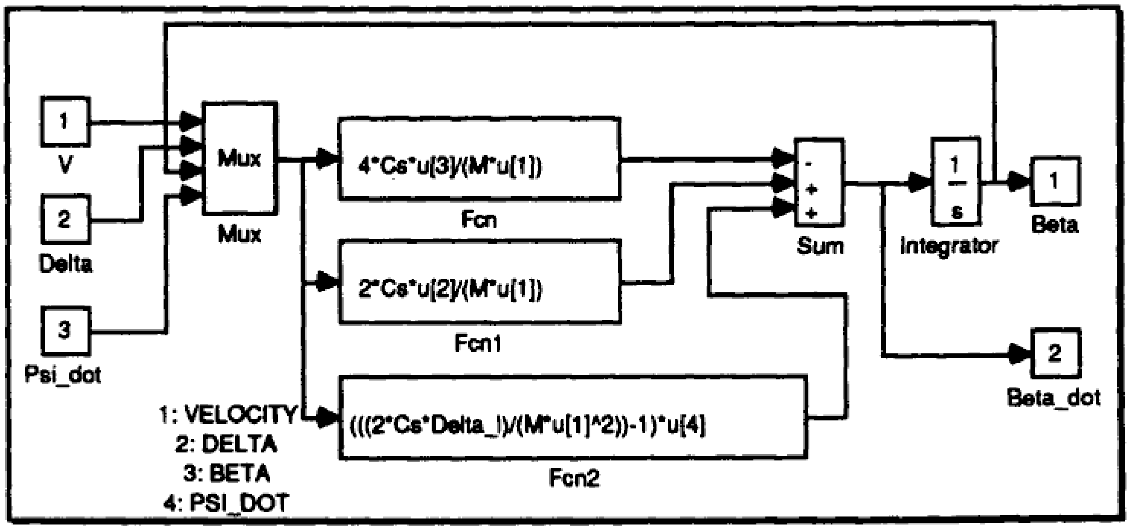


Figure 17. Beta Computations Block Diagram

4.1.2.3 Psi Computations Block

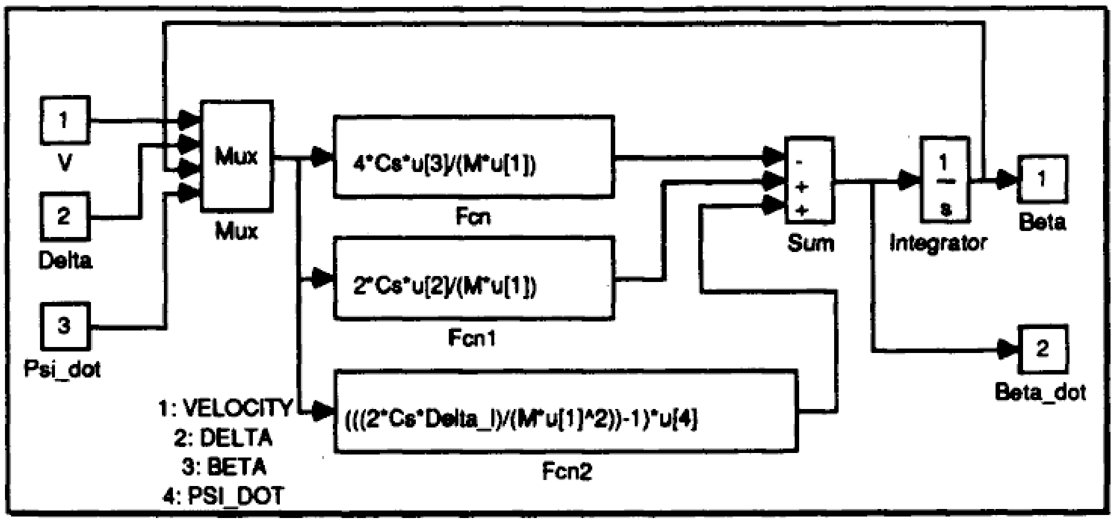


Figure 18. Psi Computations Block Diagram

4.2. Model Initialization

There are certainly a number of ways in which the vehicle model can be applied. One of those is to simulate highway speed vehicle interactions. The most efficient manner to do this in is to initialize the vehicle to some steady-state condition. This section is provided to discuss the initialization process.

There are three states which require initialization, for a highway simulation scenario; the vehicle velocity, the engine speed, and the throttle actuator position. Here we are assuming that the brake system is not playing a part in the speed maintenance process, i.e. the brake actuator has an initial force or position of 0.

4.2.1. Vehicle speed

By far the easiest to initialize is the vehicle speed. This is performed by simply loading the desired velocity into the integrator initial condition. Note that the vehicle Speed is expressed in units of miles per hour.

4.2.2. Engine RPM

The next state to initialize is the engine speed. Note that k~ is a function of vehicle speed only, and for the highway case, this becomes:

$$n_{turbine} = 27.68 * V \qquad (1)$$

The previous two equations completely specify the interaction between the transmission and the torque converter. Consider the relationship between the engine and pump speeds.

Under a load condition, e.g. driving the vehicle on the highway, one would expect that the engine speed would always exceed the pump speed. Thus if we define:

$$\theta = \arctan\left(25\left(\frac{n - n_{turbine}}{n}\right)\right) \qquad (4)$$

For a steady-state velocity of 55 mph, we have empirically determined :

$$\theta \cong 1.085$$

Using this empirical result, a reasonable approximation for the engine speed is provided by :

$$n = n_{turbine}\frac{25}{25 - \tan(1.085)}$$

or

$$n = 1.082 * n_{turbine} = 29.95 * V \qquad (5)$$

4.2.3. Throttle actuator position

The process of specifying the throttle actuator position, also know as the throttle position, amounts to specifying an ignition torque which results in a zero net engine torque. This ignition torque is used to specify the intake manifold air mass density. The mass density of the air in the intake manifold is used, intern, to define the throttle position. The first step is to define the net engine torque (reference Figure 6) as follows:

$$\frac{62558.4 * M_{air}}{n} - (\tau_{pump} + 24) = 0 = \tau_{engine}$$

Where the zero results from the zero net torque constraint. This is used to specify the air mass density as :

$$M_{air} = \frac{n}{62558.4}(\tau_{pump} + 24) \qquad (6)$$

The engine rpm, n, has been derived previously, reference equation (5). The pump torque, however, has not been defined as of yet. There are two methods which may be used to define the pump torque :

$$\tau_{pump} = 2.07x10^{-5} n^2 \theta^2$$

or

$$\tau_{pump} = \frac{\tau_{turbine}}{k_p}\text{, where :} \qquad (7)$$

$$k_p = \max\left(1, \left(2.3289 - 1.525\frac{n_{turbine}}{n}\right)\right)$$

Notice that the former uses the squares of both the approximate engine speed and the approximate torque converter slip angle, whereas the later uses only the approximate torque converter slip rate. Furthermore, note that when :

$$n < 1.15 * n_{turbine} \Rightarrow k_p = 1$$

This condition applies for at least steady-state vehicle speeds between 50 and 70 mph. This results in :

$$\tau_{pump} = \tau_{turbine} \tag{8}$$

or

$$M_{air} = \frac{n}{62558.4}\left(\tau_{turbine} + 24\right) \tag{9}$$

For a steady-state velocity to exist, the propulsion force, from the transmission, must exactly cancel the aerodynamic drag forces due to the vehicle velocity. From the source report, we can define the aerodynamic drag force as :

$$F_{resist} = 50 + 0.2175 * V + 0.02275 * V^2$$

Thus, for a steady state condition, we must have :

$$F_{drive} = F_{drive}(V) = 50 + 0.2175 * V + 0.02275 * V^2 \tag{10}$$

The driving force from the transmission is related to the torque converter turbine torque by :

$$F_{drive} = \frac{\tau_{turbine}}{k_v * 2.9503}$$

Note that k_v is a function of vehicle speed only, and for the highway case, this becomes :

$$\tau_{turbine} = 1.9767 * F_{drive} = 98.83 + 0.43 * V + 0.0475 * V^2 \tag{11}$$

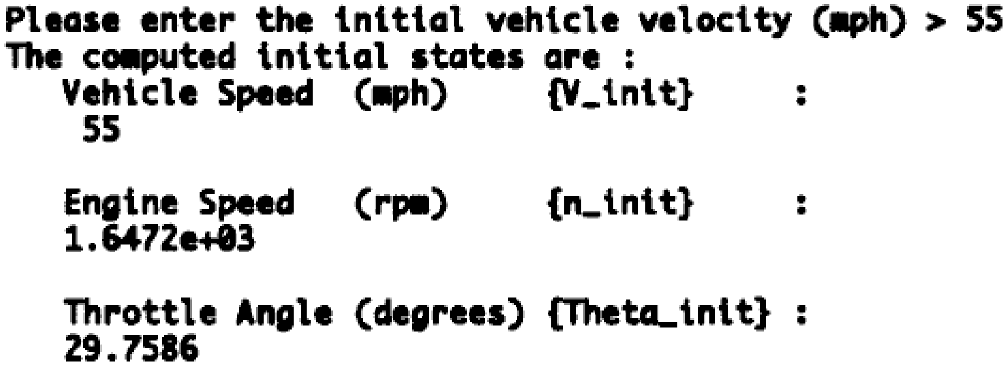
Combining equations (5), (9), and(11), we now have :

$$M_{air} = \frac{122.83 + 0.43 * V + 0.0475 * V^2}{2088.76} \tag{12}$$

From this relationship the throttle position can be derived by inverting the look-up table provided in Table 2 of the report(s) in which the model was first described. The inverted lookup table is provided in Appendix A.4. An example MatLab script which computes the steady state conditions is provided in Appendix A.3. This script provides an implementation of equations (5) and (12), and the inverse look-up of the throttle angle.

4.2.4. Longitudinal Model Initialization Evaluation

An example of initializing the longitudinal model 'night be contrived as attempting to initialize the model for a vehicle traveling 55 mph. Utilizing the script in appendix A, we are provided the following information:



```
Please enter the initial vehicle velocity (mph) > 55
The computed initial states are :
   Vehicle Speed  (mph)     {V_init}     :
    55

   Engine Speed   (rpm)     {n_init}     :
   1.6472e+03

   Throttle Angle (degrees) {Theta_init} :
   29.7586
```

Two example simulations were performed, using the nominal velocity controller while monitoring the vehicle headway error - the headway control loop was opened for these simulations. The simulations are provided to illustrate the effectiveness of the initialization algorithm, as well as to illustrate the pitfalls of failing to initialize the vehicle states. The first two figures, figures 19 and 20, illustrate the vehicle velocity response for the 55 mph and the *65* mph desired velocity cases, respectively In each case, the velocity errs for the initialized vehicles did not exceed 2.0 mph,~whereas the initialized vehicles, the dashed traces in both figures, required approximately 7 seconds to reach the same error envelope. In fact, alter about 15 seconds of simulation there is virtually no difference between the initialized and non-initialized cases.

Of more importance is the effect of the velocity error upon vehicle headway variation. During the times when the vehicle velocity falls short of the desired vehicle velocity, the vehicle headway is growing beyond the desired headway. To illustrate this, figures 21 and 22 are provided to illustrate the headway error for the 55 and 65 mph cases, respectively. In order to provide meaningful results, the figures are provided on a logarithmic scale, thus:

$$1.3326 \Rightarrow e_{headway} = 10^{(1.3326+1)} = 215.08 \text{ feet}$$

The conclusion to be drawn from this is that proper initialization of the vehicle longitudinal state minimizes perturbations to the velocity and headway controllers. If this simulation was attempting to analyze a close-order vehicle following scenario, significant simulation time would be expended simply allowing the simulation to settle into a steady-state condition.

While these initialization results were encouraging, the presence of transients for the initialized model led us to the conclusion that some additional work was needed to permit more accurate initialization. Without such improvements, the current simulation could have been used, but each run would have to be allowed to reach steady state (25 seconds of model time) before the intended disturbances could be applied. This would result in additional time and complexity in reducing the data.

Because of these and related problems, we elected instead to implement a simplified model that was better suited to the intended simulation results. This simplified model is described in the next section.

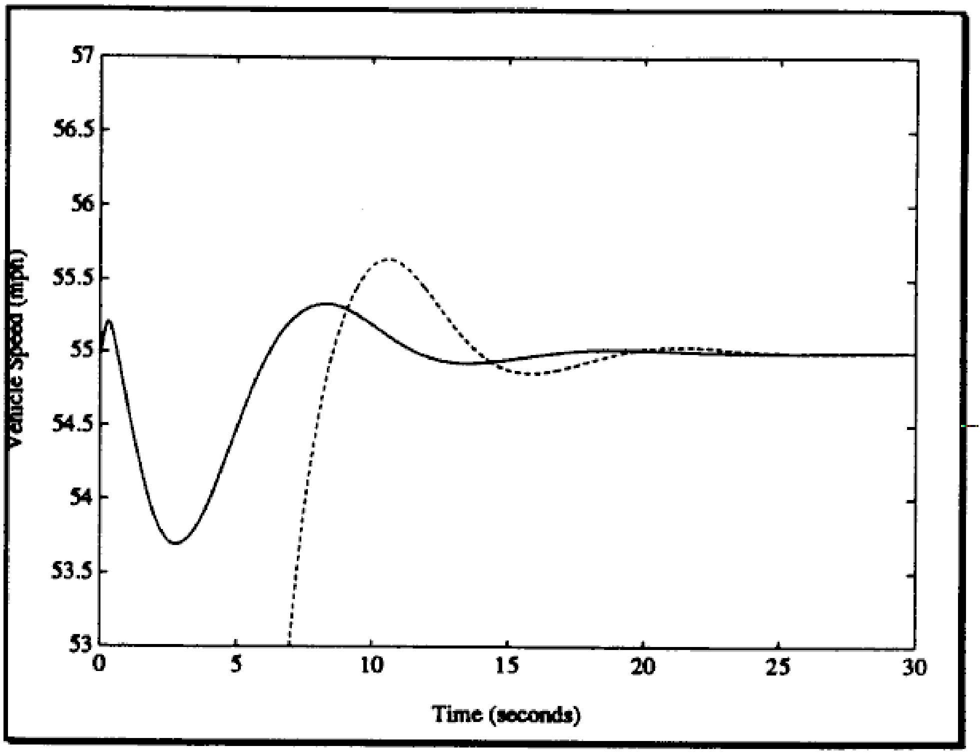


Figure 19. Velocity Response Comparison for 55 mph Case

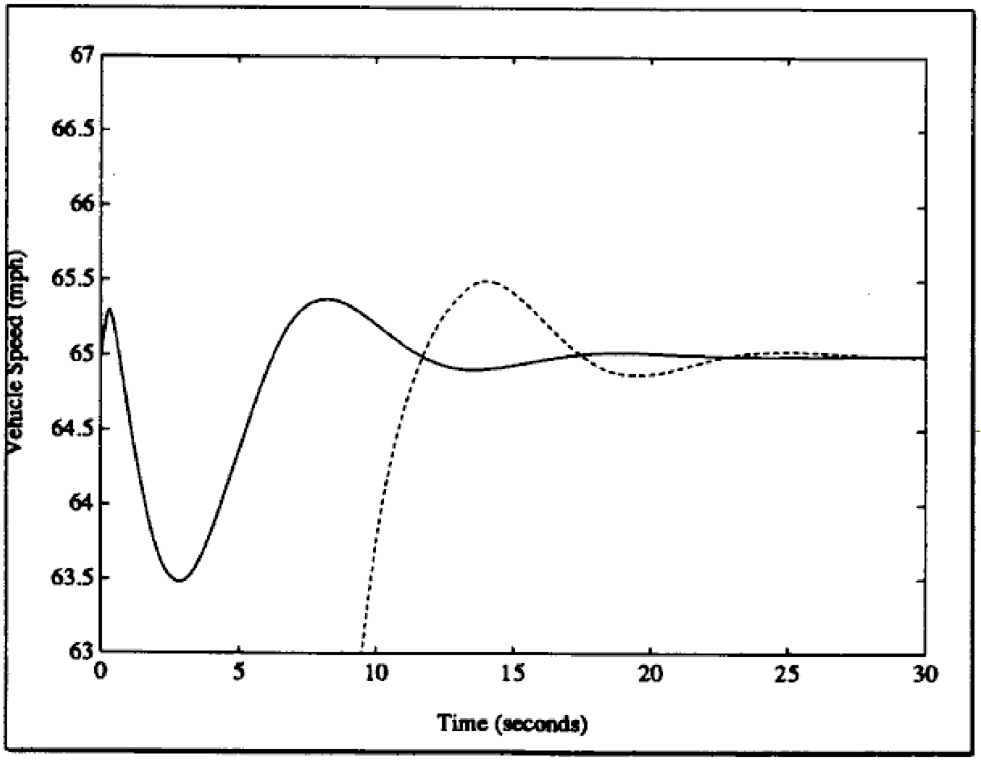


Figure 20. Velocity Response Comparison for 65 mph Case

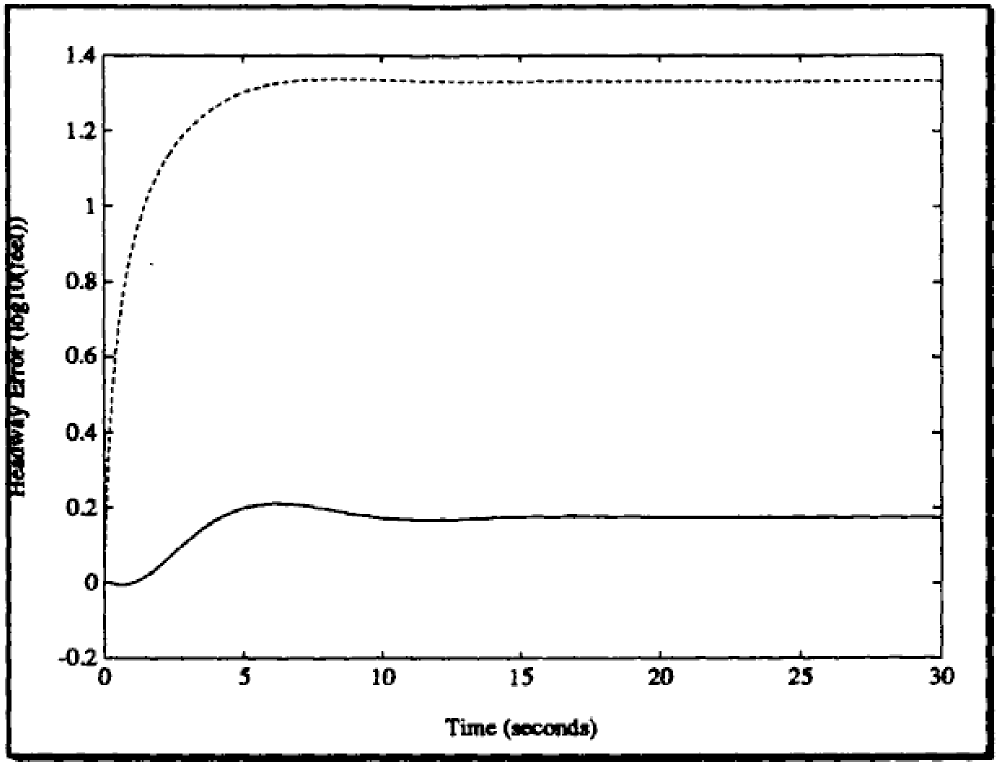


Figure 21. Headway Error Response Comparison for 55 mph Case

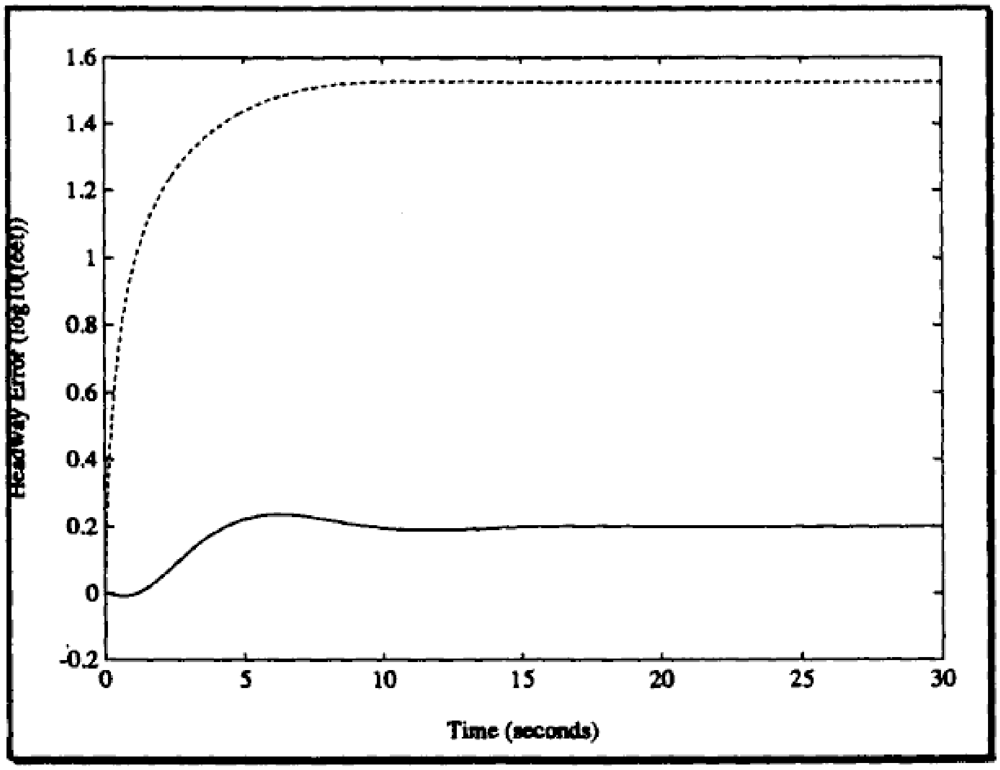


Figure 22. Headway Error Response Comparison for *65* mph Case

4.3 Model Simplification and controller Definition

In addition to the initialization difficulties noted above, we also discovered, during the course of trying to close feedback loops in a simple controller, some difficulties relating achieving stable performance in the presence of the model's non-linearities. Resolution required more effort to resolve than the study scope permitted. Since our intent was not to develop the ultimate high-fidelity model, but rather to quickly implement a model so that some issues could be highlighted through simulation, a simplified model of the longitudinal dynamics was developed based on the detailed model described above. This was implemented and tested and found to be satisfactory for the limited scope of this study. The subsections below describe that simplified longitudinal model and the controller we implemented.

4.3.1. Transfer Function Derivation

For reference, the following figure is provided to acquaint the reader with the various components of the vehicle model.

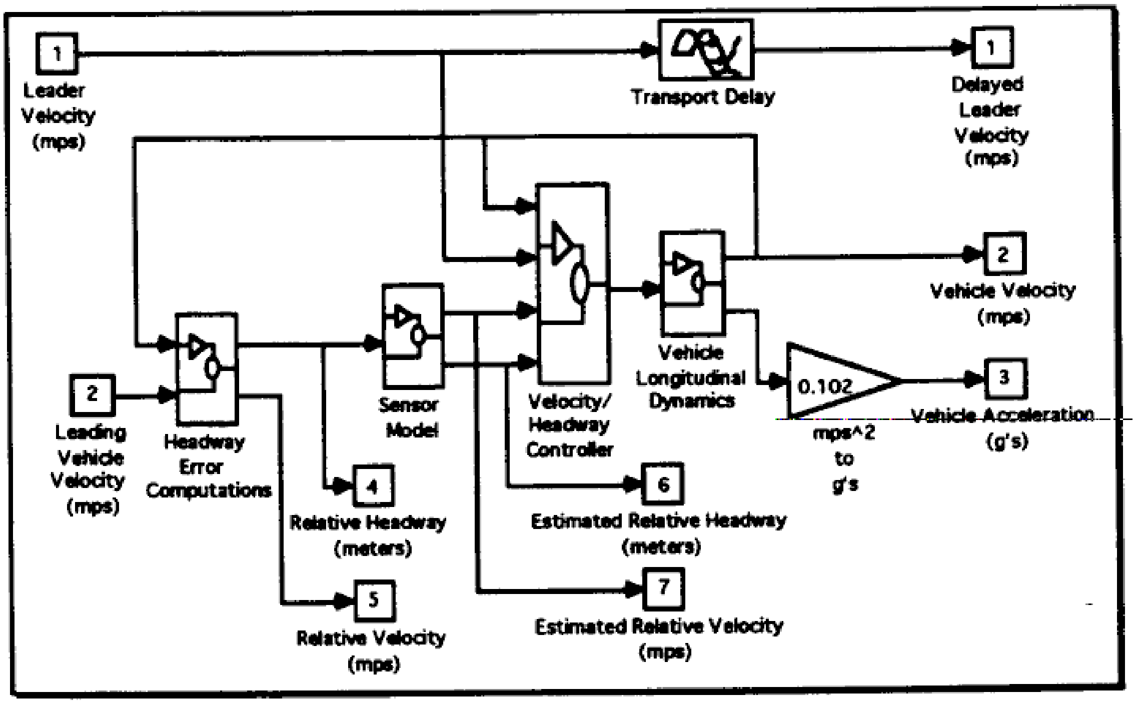


Figure 23. Simplified longitudinal Model Components

The individual components are described in the subsections below.

4.3.2. Headway Error Computations

The headway error is computed as shown in figure 24. The transfer function is provided by:

$$H(s) = \frac{1}{s}\left(V_f(s) - V(s)\right)\text{, where :}$$

H(s) is the vehicle headway error in the frequency domain,

$V_f(s)$ is the leading vehicle velocity in the frequency domain,
V(s) is the vehicle velocity in the frequency domain, and

s is the Laplace operator, i.e. $sA = \frac{d}{dt}(A)$

For simplicity sake, the **5** operator notation will be omitted for the remainder of this report. The equivalent transfer function is then written as:

$$H = \frac{1}{s}(V_f - V) \qquad (1)$$

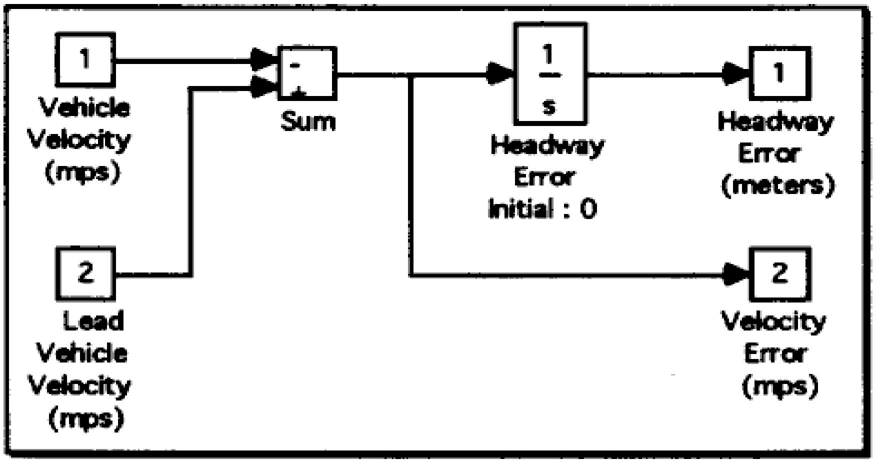


Figure 24. headway Error Computation Block Diagram

4.3.3. Sensor Model

The sensor model is defined as shown in figure 25. This element contains a particular non-linear element known as a **quantifier.** In this report, we are developing a linear system model. We will linearize and approximate this element as a unity gain **element.** The estimated headway error is then defined by:

$$\hat{H} \cong H \qquad (2)$$

The discrete filter provides the following relationship :

$$\hat{V}(t) = \frac{H(t) - H(t - T_s)}{T_s}$$

Which can be approximated as :

$$\hat{V} = \frac{s}{s + {}^{2}\!/_{T_s}}\hat{H}\text{ , where :}$$

T_S is the sensor sampling rate (samples per second)

or :

$$\hat{V} = \frac{s}{s+c}\hat{H}\text{ , where :} \tag{3}$$

$$c = \frac{2}{T_s}$$

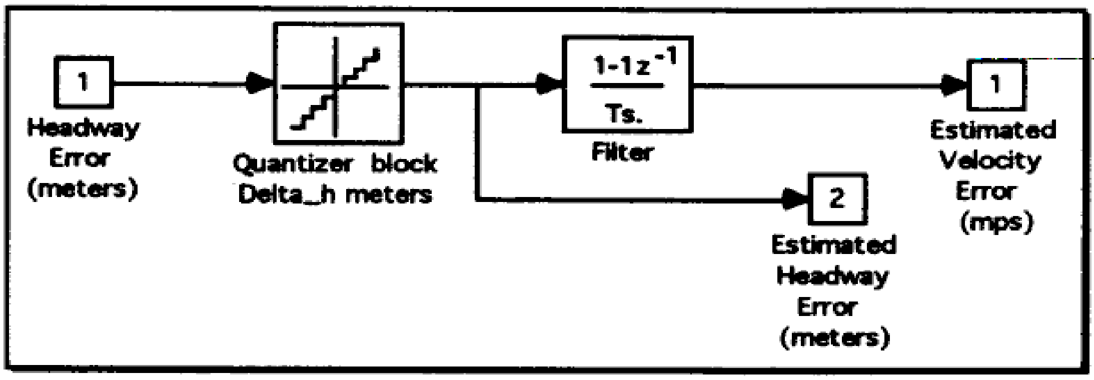


Figure 25. Headway Sensor Model Block Diagram

4.3.4. Velocity/Headway Controller

The controller block diagram is provided in figure 26. The controller includes a saturation non-linearity. This element is likewise linearized as a unity gain element. The resulting controller equation is given by:

$$V_c = K_v\hat{V} + K_h\hat{H} + K_l V_l - K_l V \tag{4}$$

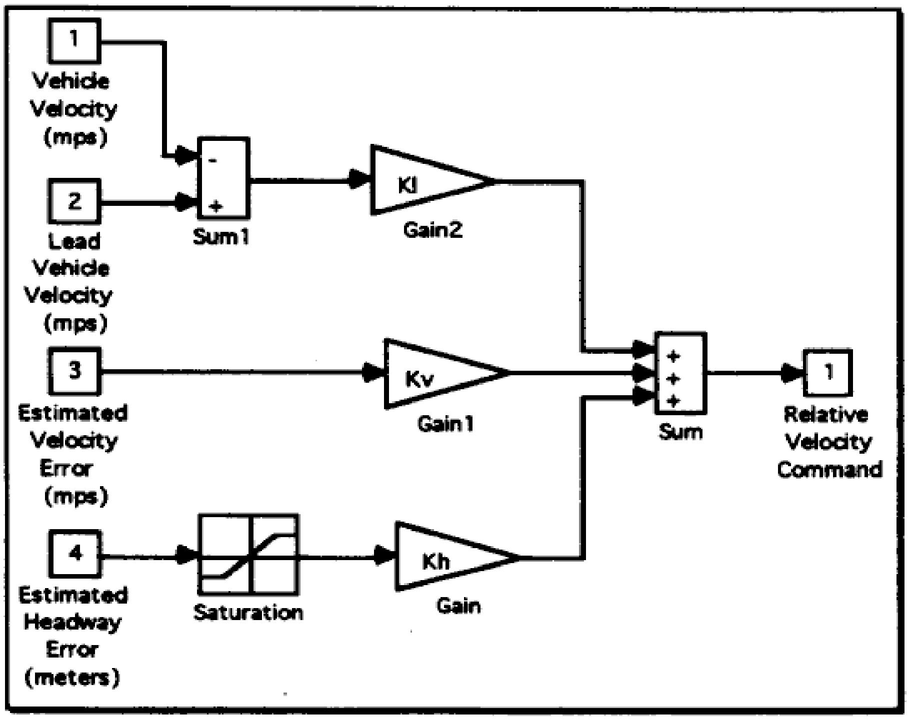


Figure 26. Velocity-Headway Controller Block Diagram

4.3.5 Simplified Longitudinal Dynamics

The vehicle longitudinal dynamics model is provided in figure 27. This model is greatly simplified from the published reports. The simplification is intended as an approximation of published work. This element is intended to encompass the net effects of the following vehicle components:

Throttle servo control,

- Throttle actuation,
- Intake manifold and engine performance,
- Torque converter, transmission, and differential transformations, and Vehicle longitudinal dynamic response

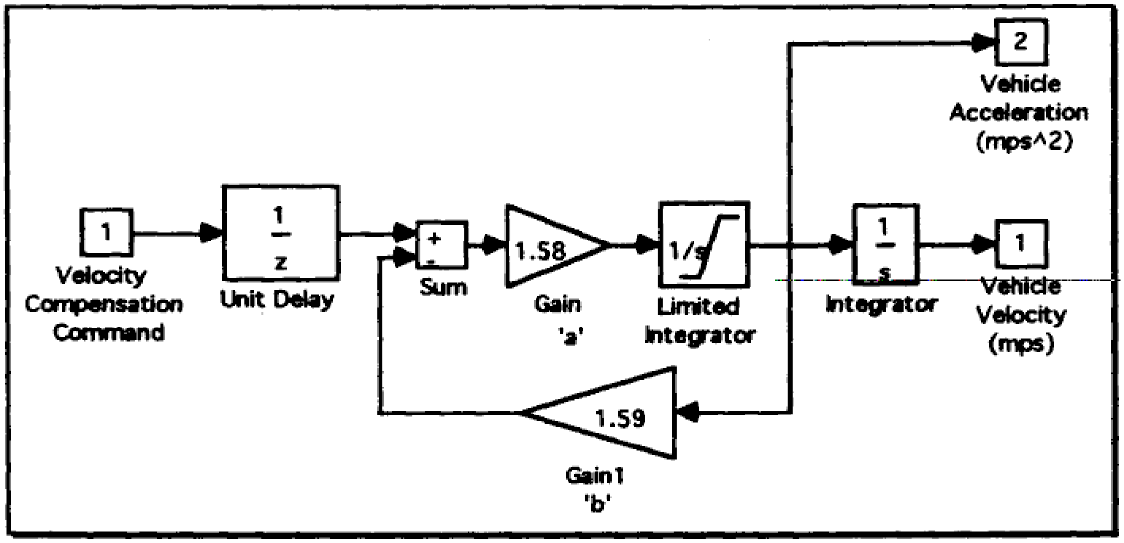


Figure 27. Vehicle longitudinal Dynamics Block Diagram

Since the simulation is based upon velocity error (relative velocity) and headway error (relative headway), the velocity result is not fed back into the acceleration integrator.

The dynamics model includes one nonlinearity; a limited integrator. The purpose for the limited integrator is to add realism to the simulation by either prohibiting deceleration in excess of -0.5 g's, i.e. service brakes applied and wheels skidding, or ~.05 g's, i.e. maximum deceleration from the engine alone, and a nominal acceleration limits, which we arbitrarily set to 0.25 g's. For the purpose of this report, we will ignore the non-linearity, and treat the limited integrator as a normal integrator.

The unit delay operator is approximated by the following relationship:

$$V_c' = \frac{s - 2/T_{s2}}{s + 2/T_{s2}} V_c$$

The resulting transfer function is given by :

$$V = \frac{a(s-d)}{s(s+ab)(s+d)} V_c \text{ , where :} \qquad (5)$$

$$d = \frac{2}{T_{s2}}$$

4.3.6. Definition of Transfer Functions

We now have a complete series of equation with which we can assemble the complete vehicle model. The equations have been provided, previously, and are repeated here, for completeness:

$$H = \frac{1}{s}(V_f - V) \tag{1}$$

$$\hat{H} \cong H \tag{2}$$

$$\hat{V} = \frac{s}{s+c}\hat{H} \text{ , where :} \tag{3}$$

$$V_c = K_v\hat{V} + K_h\hat{H} + K_l V_l - K_l V \tag{4}$$

$$V = \frac{a(s-d)}{s(s+ab)(s+d)} V_c \tag{5}$$

using (1), (2), and (3) in (4), we have :

$$V_c = \left(\frac{(K_v + K_h)s + K_h c}{s(s+c)}\right)V_f + K_l V_l - \left(\frac{K_l s^2 + (K_l c + K_v + K_h)s + K_h c}{s(s+c)}\right)V$$

using this result in (5), we have :

$$V = \frac{F}{G}V_f + \frac{H}{G}V_l \text{ , provided the following polynomials are defined :} \tag{6}$$

1) $G = G(s) = g_5 s^5 + g_4 s^4 + g_3 s^3 + g_2 s^2 + g_1 s + g_0$, where :

$g_5 = 1$

$g_4 = ab + c + d$

$g_3 = abc + abd + K_l a$

$g_2 = abcd + K_l ac + K_v ac + K_h a - K_l ad$

$g_1 = K_h ac - K_l acd - K_v acd - K_h ad$

$g_0 = -K_h acd$

2) $F = F(s) = f_2 s^2 + f_1 s + f_0$, where :

$f_2 = K_v ac + K_h a$

$f_1 = K_h ac - K_v acd - K_h ad$

$f_0 = -K_h acd$

3) $H = H(s) = h_3 s^3 + h_2 s^2 + h_1 s + h_0$, where :

$$h_3 = K_l a$$
$$h_2 = K_l ac - K_l ad$$
$$h_1 = -K_l acd$$
$$h_0 = 0$$

Equation (6) provides the transfer function where lead vehicle velocity is provided. For the case where lead vehicle velocity is not provided, we have the following :

$$V = \frac{F}{G'} V_l \text{ , provided the following polynomial is defined :} \qquad (7)$$

1) $G' = G|_{K_l=0} = g_5' s^5 + g_4' s^4 + g_3' s^3 + g_2' s^2 + g_1' s + g_0'$, where :

$$g_5' = 1$$
$$g_4' = ab + c + d$$
$$g_3' = abc + abd$$
$$g_2' = abcd + K_v ac + K_h a$$
$$g_1' = K_h ac - K_v acd - K_h ad$$
$$g_0' = -K_h acd$$

4.4. Test Run Conditions

Twenty-five test runs, summarized in table 28, were performed on the longitudinal model. The parameters for these test runs were selected to emphasize performance variations as a result of changes in sensor sample rate, control update rate, sensor quantization interval, vehicle performance bandwidth, and presence or absence of communication.

Power train response was defined in terms of slow, medium, and fast responses to throttle changes. Bandwidth values of 0.07 Hz, 0.15 Hz, and 0.20 Hz respectively were chosen as representative values for passenger automobiles and smaller heavy vehicles. For the purposes of this simulation, only homogeneous platoons were modeled; later simulation work will have to include platoons of mixed vehicle types.

Control update rates were varied between two values; fast refers to 50 Hz update and medium refers to 20 ~ Sensor update rates were varied between three values: slow = 10 Hz, medium =20 Hz, and fast =50 Hz. Sensor quantization was defined in terms of a virtual "headway sensor" that sensed headway distance between the vehicle carrying the sensor and the vehicle immediately to the front, such as radar or passive stereo. Quantization intervals were defined as coarse =0.02 meters (1%) and fine =0.002 meters (0.1%). The last column denotes whether vehicles had communicated velocity data for the lead vehicle in the platoon.

Run number 23 was a special case. This run was for a continuous model (no sampling and infinitely fast update rate) on a vehicle with the fastest power train. This case could be considered the theoretical optimum no communication case and is compared against the slowest, least-well sensed and controlled cases that had communication.

Table 28. Test Case Definition Matrix

Case #	Power Train Response	Control Update Rate	Sensor Sample Rate	Sensor Quantization	Vel. Data Comm
1	Fast	Fast	Fast	Coarse	No
2	Medium	Fast	Fast	Coarse	No
3	Slow	Fast	Fast	Coarse	No
4	Fast	Medium	Medium	Course	No
5	Medium	Medium	Medium	Coarse	No
6	Slow	Medium	Medium	Coarse	No
7	Fast	Medium	Slow	Coarse	No
8	Medium	Medium	Slow	Coarse	No
9	Slow	Medium	Slow	Coarse	No
10	Fast	Fast	Fast	Fine	No
11	Fast	Medium	Medium	Fine	No
12	Fast	Medium	Medium	Coarse	No
13	Medium	Medium	Medium	Coarse	No
14	Slow	Medium	Medium	Coarse	No
15	Fast	Medium	Slow	Coarse	No
16	Medium	Medium	Slow	Coarse	No
17	Slow	Medium	Slow	Coarse	No
18	Fast	Medium	Medium	Fine	No
19	Fast	Fast	Fast	Coarse	Yes
20	Fast	Fast	Fast	Fine	Yes
21	Fast	Medium	Slow	Fine	Yes
22	Fast	Medium	Slow	Fine	Yes
23	Fast	Continuous	Continuous	Coarse	No
24	Medium	Fast	Fast	Coarse	Yes
25	Slow	Fast	Fast	Coarse	Yes

4.5. Results and Conclusions

Our initial plan was to define the maneuvers and their requirements, define the system concepts, and seek out those issues for which a limited scope simulation effort could add some useful information. One of the difficulties in this plan was the very limited time and effort that could be budgeted for the simulation effort. In the end, we were able to do far fewer cases than we would have liked, but the cases we did run provided some valuable insight.

The simulation data were output as a series of three time history graphs for each of the test cases. Each test case is disturbed from equilibrium by a step change in acceleration by the lead vehicle until a new speed is established at 5 mph less than the initial speed.

The magnitude of the deceleration was one-half the amount of deceleration that can be achieved by completely closing the throttle but not stepping on the brake. This level of disturbance is rather mild and should not be construed to be a limiting case. Nonetheless, it is very illuminating in terms of one of the nominal operating modes of the AHS.

The first plot in each case is a velocity time history for each of the five vehicles in the platoon. The important attributes in these plots were response delay, peak response, and degree of **overshoot(undershoot.** The second plot in each case is the headway error time history between each of the four vehicle pairs in the platoon. The important attributes in these plots include total overshoot, and whether the error approached two meters (the assumed inter-platoon spacing). The third plot in each case is the acceleration experienced by each vehicle. The important attributes in these plots include degree of **overshoot/undershoot,** whether the response of subsequent vehicles crosses the 0.05 g threshold, and the smoothness of the profile. The threshold at 0.05 g corresponds approximately to the deceleration at which brakes need to be applied.

Appendix B contains the time histories, and the sections that follow summarize the conclusions drawn from comparing the time histories in various logical groupings.

4.5.1. Group #1: Cases 1 Through 9

This group of cases looked at the effects of variations in power train bandwidth, control update rate, and sensor sample rate. Sensor quantization was coarse throughout and there was no communication between vehicles. The purpose of this set of comparisons was to demonstrate the point that the slow response (long lag) of the power train coupled with added lag due to sensor sampling created difficult to solve problems in maintaining headway under speed disturbances.

Table 29. Organization of Cases in Group #1

Power Train BW	Fast Control Fast Sensors	Medium Control Medium Sensors	Medium control Slow Sensors
Fast	1	4	7
Medium	2	5	8
Slow	3	6	9

Table 29 provides a summary of this group of cases. The basic parameter was the speed of the power train bandwidth, and the subgroups (represented by the different columns) represents the influence of different control/sensing implementations on a power train of various speeds. The sensing update rate was equal to the control update rate, except for the last three **cases.** These three (7,8,9) were intended to closely model the slower sensing typical of vision-guided systems coupled with more moderate control rates required to maintain control stability. These are intended to be typical cases and do not reflect any particular system design.

In each row, there was very little difference in the peak headway error from one condition to the next. Accelerations exhibited a modest growth as the sensing(control slowed down, but in all cases the fifth vehicle had to apply the brakes to maintain the acceleration profile. Acceleration roughness reduced with slower sensing control, suggesting that the roughness (limit cycling) in acceleration was due to the simple feedback mechanisms. The lack of difference in headway error magnitude was somewhat surprising, but the loss of damping was not. The conclusion we drew was that the rate of sensor sampling and rate of control implementation was not as critical as we first expected, given the relatively low bandwidth of the typical power train.
Across each column, the single biggest difference was the reduction in limit cycling (zig-zag response) in the acceleration profiles. Since the magnitude of the peak error does not change dramatically, there is reason to believe that a more sophisticated control implementation should be easily able to eliminate the roughness in the acceleration response. As expected, as the power train lag increased, there was a growing tendency toward underdamped response, even when high rates were employed. The conclusion from this set is that without the "lead" provided by communication of velocity or acceleration state of the lead vehicle, it will not be possible to operate safely at small headways (2 meters).

4.5.2. Group #2: Cases 1,4, 10 and 11

This group of cases contrasted the effects of fast and medium **sensing(control** against quantization levels in the headway sensing mechanism for vehicles with the fast-responding power train. The premise was that sensor quantization, even for a relatively fast power train, would be an important factor in response, particularly with respect to limit cycling behaviors.

Table 30. Organization of Cases in Group #2

Quantization Granularity	Fast Control Fast Sensors	Medium Control Medium Sensors
Coarse	1	4
Fine	10	11

In comparing these four cases, we learn that there is very little difference in headway error or damping in the response. The only significant difference is the very strong impact on smoothness in the acceleration profile by going to finely discriminating range sensors. The benefits to system response derived from fine range resolution were much stronger than the benefits of a 2.5 increase in update rate. The conclusion one should draw from this is not necessarily that very finely resolved sensors are required, but rather that ride quality performance is sensitive to the range resolution and that coarser sensors will place a greater burden on the control system to compensate, which increases complexity and, hence, cost.

4.5.3. Group #3: Cases 12 Through 17

This group of runs is in direct contrast to the last six runs of the first group. The only difference between this group and that group is the presence of lead vehicle velocity information. This group did omitted the fastest sensing(control rate since the effects of communicating lead vehicle information are most obvious when contrasted against configurations having longer response latencies.

Table 31. Organization of Cases in Group #3

Power Train BW	Medium Control Medium Sensors	Medium control Slow Sensors
Fast	12(4)	15(7)
Medium	13(5)	16(8)
Slow	14(6)	17(9)

The premise of targeting this group was that regardless of the performance attributes of the first group, the addition of leading vehicle velocity information could dramatically improve performance. Table 31 shows the organization of Group 3 runs, and for each the corresponding member of Group 1 is indicated in parentheses

Compared to the Group 1 runs, as expected the performance of Group 3 was considerably superior in all cases. Except for the slowest power train model, there was little to no overshoot in the velocity and acceleration profiles. Different sensing control update rates had almost no influence on response. Peak headway error increased with the slower power train model, but not as dramatically as without lead vehicle information. This effect can be attributed to the fact that trailing vehicles reduced the peak error though anticipation, reducing the overreaction by the controller. As anticipated (and validated by similar studies undertaken at the PATH program), lead vehicle information is vital to achieving safe close following performance.

Another conclusion that we may draw from the comparison of Group 3 plots is that, even with lead vehicle communication, it is not possible to maintain two meter headways if the power train is too sluggish in its response to throttle commands. The consequence of this observation is that platoons may have to be required to be mostly homogeneous. Put simply, large trucks, aging luxury cars, and late model sports cars cannot share in the same platoon unless all vehicles are limited to the worst case performance.

4.5.4. Group #4: Cues 4,11,12, And 18

The comparison Group 4 is primarily a contrast between a absence and presence of lead vehicle information in the presence of coarse and fine range sensor quantization. These cases presumed the fastest power train model and moderate sensing and control rates. Table 32 shows the organization of Group 4 runs.

Table 32. Organization of Cases in Group #4

Quantization Granularity	Without Communication	With Communication
Coarse	4	12
Fine	**11**	18

The most noticeable effect of the addition of lead vehicle information is that it reduces dramatically the tendency toward underdamped response, all other factors being equal. In addition, the headway error and acceleration levels are greatest for the #2 vehicle in the platoon, and are successively smaller for vehicles further back. For example, case 12 showed a peak headway error values as shown in table 33 below:

Table 33. Peak Headway Error Values for Case #12

Vehicle Pair	Peak Headway Error (meters)
1-2	0.68
2-3	0.56
3-4	0.47
4-5	0.39

This decreasing trend is in contrast to the successively greater errors in all cases without communication. The qualitatively different response characteristic is the difference between purely reactive and anticipatory control, between purely self-contained sensing and coordinated operation. Without communication, sensing latency causes a delay, and the delay is further compounded by actuation and power train response. It is doubtful that With communication, vehicles further back can actually *anticipate* the impending change in state of the vehicle in front, knowing that if the lead vehicle slows, vehicles following must do likewise. This intuitively obvious result can be used to dramatically simplify control design and hence lower cost.

4.5.5. Group #5: Cue. 19 And 20

Group 5 was intended to determine whether the response was sensitive to quantization interval given all other factors being equal. These two cases included lead vehicle communication, the fastest sensing and control update rates, and the fastest power train response model. The simulation outputs indicated that there was little difference between the two cases, except for the smoothness of the acceleration response. Peak error, velocity overshoot, and damping in the acceleration were nearly identical. Given that properties of the time histories except smoothness of acceleration were equal, we conclude that in the presence of lead vehicle communication, robust digital control methods will easily compensate for the effects of coarse quantization.

4.5.6. Group .6: Cases 11, 18,21 And 22

Group 6 was intended to determine whether slowing the sensing rate down to 10 *Hz* would have a significant effect on response with and without communication. This group assumes the fastest power train response and moderate control update rates (20 Hz). The premise was that slowing the sensor rate down to that comparable to current vision-guided systems might have an adverse effect, even in the presence of lead vehicle information. Table 34 on the next page shows the organization of this group:

Table 34. Organization of Cases in Group #6

Sensor Update Rate	Without Communication	With Communication
Medium	11	18
Slow	21	22

As expected, the slower sensor model resulted in more underdamped response. However the change was not as dramatic as expected. Without communication, the difference between the moderate and slow sensor rates was a *16A%* difference in peak acceleration, and very little difference in peak headway error and acceleration roughness. With communication, there was almost no difference in performance between the two update rates.

4.5.7. Group #7: Cases 1,2,3,19,24, And 25

Group 7 was a comparison between the various power train models with and without communication. The sensing and control update rates were the fastest, and sensor quantization was coarse. The intent was to demonstrate the difference between a good, fast control system model on all vehicle types and similar conditions with communication. We know from the results of section 4.5.3 that lead vehicle information bounds the error and improves response damping. The question examined in this set, shown in table 35, was whether the damping of the response from the first three runs was dramatically improved by the lead information

Table 35. Organization of Cases in Group #7

Power Train BW	Without Communication	With Communication
Fast	1	19
Medium	2	24
Slow	3	*25*

Comparing the acceleration plots from cases 1 and 19, we discovered an unexpected, though understandable, result: the lead vehicle communication somewhat reduced the limit cycling present in case 1. The headway error between the first two vehicles is largely unaffected, but the succeeding vehicles in case 19 show the characteristically lower peak error values.

For the cases of the slowest vehicle dynamics (cases 3 and *25),* the benefits of the communicated information are even more clear. For these more sluggish vehicles, the headway error grows in the absence of communication from 2.01 meters between the first two vehicles to 4.1 meters between the fourth and fifth. With **communication,** the error between the first two is the same, but the error between the fourth and fifth is down to about 1.7 meters. The benefit of this lowered error is most dramatically demonstrated in the acceleration profiles. The peak deceleration for second vehicle is about 0.034 g, but for the fifth vehicle it was 0.062 g, representing a growth of 140% over the deceleration of the first vehicle. In addition, the acceleration profile for the fifth vehicle is a decelerate-accelerate-decelerate sequence, and during the first cycle the deceleration was large enough to require braking. This type of behavior is deleterious in the sense that it consumes more energy, increases engine wear, and inhibits longer platoons. With communication, however, the deceleration of the second vehicle is the same 0.034 g, but succeeding vehicles are successively less, and vehicles beyond the fourth actually decelerate less than the lead vehicle, and demonstrate only 1/4 the overshoot on the accelerate side of the profile compared to that of case three.

4.5.8. Group #8: Cues 23 And 25

Group 8 was a comparison between the idealized system without communication (case 23), and the two slowest power train model with communication (case *25).* Case 23 has no sensor quantization, no latency in the sensing and control elements, and a high bandwidth power train. In a sense, it is the best that can be done without communication. The latter presumes the fastest sensing and control update rates but coarse sampling. It represents what a system having marginal sensor quality and a slow power train can achieve with communication. In brief, the intent of this comparison was to demonstrate the difference between a good, fast model with no communication and a poor, sluggish model with communication.

For the continuous system (case 23), the peak headway error between the first two vehicles was approximately 0.65 meter and each successive pair experienced about 0.05 meter additional gap reduction. Assuming a 2-meter gap initially and a requirement to maintain 50% of the initial gap for safety reasons, this would suggest that the maximum platoon length of ten vehicles. However, this is an incomplete analysis, since this case initiates a minor deceleration (0.025 g, or half the amount possible by zeroing the throttle input but not applying brakes). For more significant disturbances, the peak error will be larger. The limiting case is an emergency in-lane stop, which was not modeled. In fact, fewer vehicles could be tolerated in that case.

By comparison, the sluggish vehicle with communication (case *25),* started off with a peak headway error 2 meters$_9$ and each successive pair experienced 0.2 meters less than the pair in front of it. This would suggest that, given the constraints of the input disturbance as a basis for system requirements (a dubious assumption at this stage), minimum headways for this type of configuration would have to be at least 4 meters, but the system could tolerate platoons of arbitrary length.

This analysis illustrates an interesting point for the systems definition process and particularly for the development of quantitative requirements: what is the set of conditions that define minimum (or maximum) metrics under each of the various operating conditions? Careful consideration will have to be given to each individual requirement to define the conditions of testing compliance. Merely stating the metric itself leaves compliance evaluation wide open. In the current comparison, it is possible to meet the requirement for maintaining a 50% safety margin, one only needs to specify the size of the maximum allowable disturbance and assume a suitably large headway value. However, some of the unanswered questions surrounding this testability question might include the following:

- What performance limitations (control bandwidth, deceleration performance with and without brakes, acceleration performance,) will be placed on all vehicles operating on the AHS?
- How does the selection of operating speed affect these calculations?
- Within what headway constraints will the systems be forced to perform?
- What are the reasonable best-case and worst case disturbances that will have to be handled by the system?
- How do ride quality requirements couple into these considerations?

5. Evaluation-Derived Issues

5.1. On the Use of Centrally-Provided Electric Power

There are a number of concepts under consideration at various institutions around the world that require the use of infrastructure-supplied power. However, we believe that centrally-supplied power is only superfically attractive and that deeper analysis provides compelling arguments against its use.

The basis of argument for these concepts includes some if not all the following points:

Reduction of the use official fuels will reduce pollution. In most cities, HC and CO production from private, public, and commercial traffic are generally seen as the most pressing pollution problem for which there may be economically feasible solutions.

- *Improved safety.* Eliminating the need to carry flammable fuel supplies improves safety.

- *Quieter operation.* Electric vehicles are inherently quieter, both for occupants and those nearby.

However, there are some significant drawbacks to such an approach. These include:

- *Wide dynamic range on power demand compared to existing Systems.* What is not obvious about existing electric transit systems, from the Washington Metro to the downtown Dayton electric trolleys, is that the demand for power is very nearly flat. Compared to the highways, the number of electrically-powered vehicles in such systems does not vary widely from hour to hour, though many of these systems do shut down at night. This fact makes the power generation and distribution network designs much more efficient because they can be optimized for reasonably constant operating conditions.

  On the highway, however, the number of vehicles per hour per lane can dramatically change during the diumal cycle. The new power distribution system has to be designed to carry the worst case load or else brown-outs may occur. This results in a significant over-design condition for the remainder of the time. Moreover, if the highway depends on the existing power generation and distribution system, these peaks will occur during normal business hours and therefore will compete with industrial customers.

In contrast, consider the present-day energy "system" architecture. Vehicles store the energy they need locally in their gas tanks and draw on it when needed at the rate they need. The limit of available power is limited only by the power plant (engine), which can be optimized for the intended type of use and operating environment of the vehicle.

- *Protecting people and animals from the power source.* Most existing systems operated in *protected* rights of way. Similar provision will be required for an AHS with this configuration, which will compound the cost of the infrastructure compared to concepts using on-board power generation.

- *Efficiency of power generation and use.* Components of the power system include generation, distribution network, mechanism of transfer to the vehicles, and transformation from electrical energy to locomotive force. Each of these steps has an efficiency factor associated with it. The aggregate efficiency, compared to gasoline consumption ("articulately for late model automobiles) must be fairly compared.

- *Pollution effects of central power generation.* The pollution gains inherent in eliminating fossil fuels must be offset by the pollution created by central power generation stations, many of which burn coal as their primary source. We may be trading CO for more noxious forms of pollution such as S02.

- *Cost of installing a new distribution network.* In addition to the construction of power transfer conduits along the highway, there is a cost associated with replacing existing gasoline distribution with electrical distribution. For any urban center, the number of lane-miles and the expected vehicle use suggests that a power distribution network that doubles the existing electrical power network may be needed. This means that modifying existing rights of way for power lines may be required. In some cases, the highway right of way may carry a buried cable system. The problem is that most electrical utilities use overhead wires for the ultra-high voltage distribution trunks, and only go to underground conduits for local distribution where the voltage can be dropped to levels at which leakage can be easily contained.

Hybrid vehicles provide only a partial mitigation of these concerns, but they may be the answer in the long run. Hybrid vehicles would have their own power generation/storage capacity, and when the system was unable to provide sufficient power, the on-board source could make up the difference. Under these conditions, the effective operating radius of electric vehicles could be doubled, tripled, or quadrupled, depending on what percentage of energy use came from the infrastructure. They would, however, mitigate the worst case design condition for the distribution infrastructure.

5.2. On the Need for Communication

One of the obvious deficiencies in the concept definition was the intentional lack of inter-vehicle communication in the autonomous concept Our judgment is that, unless the basic underlying concept of an AHS at large is completely change (unlikely), a concept must have some level of inter-vehicle communications to be viable. The two primary reasons for this are 1) assuring string stability in the close vehicle following mode, and 2) providing intent information so that the right actions are taken under exception conditions.

The vision-guided autonomous concept suffered by definition from an inability in this area. That in itself should not invalidate the concept. Rather, it would be a simple matter to revise the concept to include the ability to communicate and alter the ratings accordingly. This would have the net effect of closing the gap in the overall ratings as they relate to requirements satisfaction, but does not affect the weighted criteria evaluations.

However, communication of state information and intended activity is not a panacea. As the simulation results in section 4 point out, lead vehicle information does not compensate for a power train that responds too slowly. Headway will have to be sufficiently long to accommodate longitudinal response characteristics. Conversely, if close vehicle following is a required maneuver to assure the desired levels of throughput on the highway, serious consideration must be given to the limitations that places on minimum longitudinal response. Depending on the requirements on ability to maintain small headways, large trucks might be precluded from the AHS. Permitting this condition to be built into the AHS specifications could result in loss of support of a key stakeholder category: the commercial trucking industry.

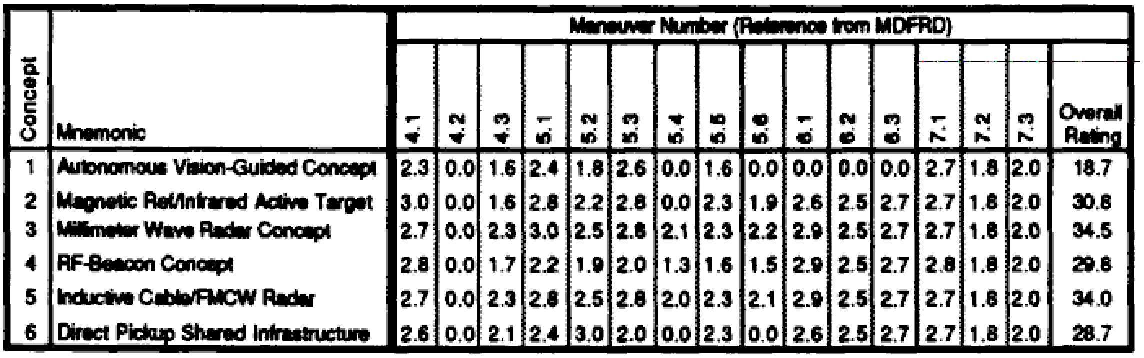
6. Program Conclusions and Recommendations

6.1. Assessment of the Study Results

6.1.1. The Bottom Line

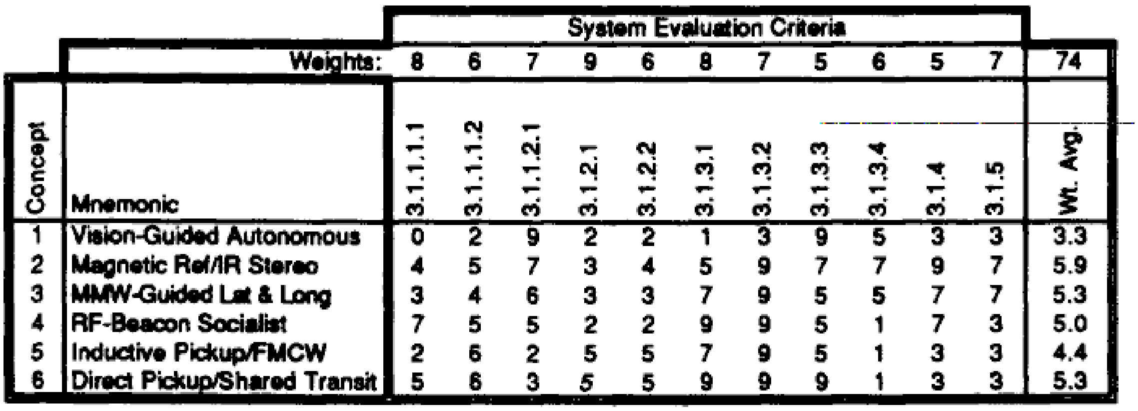
If one were to attempt to summarize the results of the entire study, they may be captured from several places. First, the evaluation is summarized in tables 16 and 26, repeated here for convenience as tables 36 and 37:

Table 36. Concept Requirements Evaluation Summary



Concept	Mnemonic	Maneuver Number (Reference from MDFRD)															
		4.1	4.2	4.3	5.1	5.2	5.3	5.4	5.5	5.6	6.1	6.2	6.3	7.1	7.2	7.3	Overall Rating
1	Autonomous Vision-Guided Concept	2.3	0.0	1.6	2.4	1.8	2.6	0.0	1.6	0.0	0.0	0.0	0.0	2.7	1.8	2.0	18.7
2	Magnetic Ref/Infrared Active Target	3.0	0.0	1.6	2.8	2.2	2.8	0.0	2.3	1.9	2.6	2.5	2.7	2.7	1.8	2.0	30.8
3	Millimeter Wave Radar Concept	2.7	0.0	2.3	3.0	2.5	2.8	2.1	2.3	2.2	2.9	2.5	2.7	2.7	1.8	2.0	34.5
4	RF-Beacon Concept	2.8	0.0	1.7	2.2	1.9	2.0	1.3	1.6	1.5	2.9	2.5	2.7	2.8	1.8	2.0	29.8
5	Inductive Cable/FMCW Radar	2.7	0.0	2.3	2.8	2.5	2.8	2.0	2.3	2.1	2.9	2.5	2.7	2.7	1.8	2.0	34.0
6	Direct Pickup Shared Infrastructure	2.6	0.0	2.1	2.4	3.0	2.0	0.0	2.3	0.0	2.6	2.5	2.7	2.7	1.8	2.0	28.7

Table 37. System Evaluation Summary



		System Evaluation Criteria											
	Weights:	8	6	7	9	6	8	7	5	6	5	7	74
Concept	Mnemonic	3.1.1.1.1	3.1.1.1.2	3.1.1.2.1	3.1.2.1	3.1.2.2	3.1.3.1	3.1.3.2	3.1.3.3	3.1.3.4	3.1.4	3.1.5	Wt. Avg.
1	Vision-Guided Autonomous	0	2	9	2	2	1	3	9	5	3	3	3.3
2	Magnetic Ref/IR Stereo	4	5	7	3	4	5	9	7	7	9	7	5.9
3	MMW-Guided Lat & Long	3	4	6	3	3	7	9	5	5	7	7	5.3
4	RF-Beacon Socialist	7	5	5	2	2	9	9	5	1	7	3	5.0
5	Inductive Pickup/FMCW	2	6	2	5	5	7	9	5	1	3	3	4.4
6	Direct Pickup/Shared Transit	5	6	3	5	5	9	9	9	1	3	3	5.3

Second, strengths and weaknesses of each of the representative system configurations are summarized in section 3.4. These are too lengthy to repeat here, and the reader is referred to that section directly.

Third, each of the documents in the series (MDFRD, SCDD, and SCED) contains various sections in which significant issues have been identified. During the course of the study, a total of 87 issues were captured in the section of documentation with which they were most closely associated. For easy reference, the summary statements for each has been tabulated in appendix C.

To determine the most likely winning concept from this evaluation, we refer again to tables 36 and 37. The second table is actually the primary means for determining a winner. The former table, since it is based on requirements, merely serves to "qualify" a concept for consideration. The latter table provides the relative figure of merit for surviving concepts. In table 36, the first. concept receives a very low rating, and we previously noted that this rating was strongly influenced by the lack of communication and was easily corrected. However, that lack has relatively little influence in the results tabulated on table 37, and still the concept rates low compared to the others. The combination of low rating on both tables makes it a likely loser.

On the other hand, the second concept rates very highly on table 37, and is in the top three in table 36. That combination, and the assessment of its strengths and weaknesses, make it a likely winner in our assessment Using the same logic, the second most highly ranked concept overall is concept #3.

The common elements among the leading candidates includes the following:

- They require relatively simple equipment, both on the vehicle and in the infrastructure for both primary and backup (redundant) functions.

- They distribute control functionality as much as possible to limit the impact of systemic failures.

- They have an easily-defined path for evolutionary deployment.

- They limit the public liability for failure-related incidents.

6.1.2. Key Points for the Final Results Workshop

One of the directed tasks under the study is to present the key points or issues for the final results workshop. That workshop will have a broad audience of participants, many of whom may have little background in the AHS. These points are an attempt to encapsulate the most important messages we would pass on to the consortium and to the broad community of stakeholders as a result of this study. The points we identified and submitted in preparation for the workshop include the following:

- The breadth and complexity of system trades will require a *well-defined* evaluation methodology agreed to before concept evaluations start. The diverse, distributed nature of the consortium staff coupled with the need to generate public support and support of stakeholders not directly participating in the consortium efforts makes it mandatory that the process be well established and faithfully adhered to before the results can be meaningful and generally accepted. The community must achieve a priori consensus on:
    - system requirements, including satisfaction threshold values
    - evaluation metrics
    - relative importance (weighting) factors for those metrics
    - specific configurations to be evaluated

- The importance of phased, evolutionary implementation cannot be underestimated for the winning concept
    - Compared to mass options, the benefits of AHS options are difficult for public to conceptualize; justifying expenditures is made more difficult by this problem.
    - Public experience base with performance and benefits (public "trust" in system) achievable for a given cost needs to be developed; this requires time and familiarity with the enabling technologies. That familiarity is best achieved through gradual development and fielding of new capabilities.
    - Infrastructure improvements will not be justified unless there are enough vehicles to make use of them, and vehicles will not appear on the market in any significant numbers until enough miles of roadway have the required improvements. We refer to this as the "market penetration chicken-and the egg syndrome." Concepts that avoid this syndrome by allowing market forces to determine what capabilities are fielded at a given point in time are more likely to succeed.
- Vision-guided approaches appear to be weak candidates at this time
    - There are significant problems of robustness with respect to night and weather given the current state of the art
    - The expense of in-vehicle equipment may be prohibitive, particularly for redundant "fail-safe" designs.
    - Some of the difficulties of reducing various latencies in the system for improved performance greatly exacerbate the expense problem.

- Centrally-powered vehicles appear to be weak candidates at this time
    - They suffer from the chicken-and the egg syndrome referred to above.
    - Safety and public liability for the aftermath of a power failure will be serious concerns.
    - The wide dynamic range on power demand could lead to over designed, expensive power distribution systems.

- Of the six approaches we evaluated, magnetic nails for lateral control with either stereo IR correlation or radar for longitudinal sensing appears to be the leading concept because of the following factors:
    - a very robust implementation
    - a combination of relatively simple vehicle equipment complement and simple infrastructure complement - results in the lowest overall cost profile
    - it is very well-suited for phased implementation - market-driven forces will dominate how the system evolves
    - it provides the best combination of near-term implementation and and far-term growth potential for gradual building of public confidence in system's capability

- Low-latency, low-bandwidth communication of state information among vehicles will be essential if close vehicle following is a requirement

- simulation results show unbounded errors if platoon length is not limited
- even for sluggishly-responding vehicle types, communication bounds the worst case error and allows bounded performance specifications
- barring a breakthrough in communications technology, interference among communicating entities will likely result in a limiting constraint of low-bandwidth communication; systems designs will have to work within that constraint.

6.1.3. On the Method for Combining Requirements Rating

The method we chose for combining ratings did exactly what it was designed to do: it carried through the rating system a strong negative impact for any zero rating merited by total inability to meet a specific requlrement. However, this had a stronger effect on the overall ratings than we anticipated because of the prevalence for communications requirements to achieve coordination. The autonomous vision-guided concept in particular suffered from this effect because of its specific exclusion of any communication. That exclusion was intentional to make the effect on the system evaluation more obvious, and the conceptual design was defined before all the requirements were enumerated. Another area where this effect was felt was in the concepts that specifically excluded rearward-facing sensors.

This should not to be construed as a failing of the study. Rather, it is a strength of the structure of the study because we have documented the process of trial and error that is inevitable when postulating high-level conceptual designs for an ill-defined set of requirements. It is all too easy to modify concepts as soon as deficiencies are uncovered. However, doing so is a little like modifying an experiment before it has been completed and documented because one tends to loose the reasons why those modifications had to be inserted in the first place. Instead, it is better to set the evaluation rules in place and complete the process before embarking on refinements. By using this approach, the effect of particular requirements on the various system concepts is more obvious and will hopefully provide system engineers to more rationally develop a set of requirements in which there is stronger justification.

The right approach for the next iteration of concept trades is to define or refine the true system requirements based on the preliminary set contained in the MDFRD and then modify surviving candidate concepts to cover all known requirements. For the vision-guided concept, this would mean including the ability to perform low-bandwidth coordination communication with surrounding vehicles. A higher-fidelity, more directed trade off would then result, and comparing this study with that second-generation result would provide the evolution from rough first concept to final candidate design. If done right, this approach should result in no candidate receiving a zero rating in any area, and the evaluations may be less skewed.

6.2. Other Possible Assessment Approaches

During the course of defining our approach to this study, we explored other evaluation approaches. While we elected not to employ them, some of these approaches had some merits on their own and we felt that future evaluations, such as will be performed by the AHS Consortium, might wish to utilize them. Hence, the comparison schemes having the most potential utility are described in the sections below, though they played no part in the overall conclusions drawn under this study.

6.2.1. Assessing Automatability

An approach to assessing the viability or desirability of automating various functions is proposed in this section. Each task (maneuver) can be assessed in terms of the required levels of vigilance and judgment to be performed. Depending on these assessments, one may predict the suitability of that flinction for automation.

To properly apply these assessments, we need to define judgment and vigilance on a course (low, medium, high) scale. The two tables below present one description of these factors. Table 38 describes how to rate functions in terms of the required level of judgment.

Table 39 addresses the definition of vigilance, again on a scale of (low, medium, high). This table is suggestive of how much of the user's attentiveness is required and therefore unavailable for other tasks. Vigilance is the degree to which attention must be paid to meet demands of rate, regularity, or volume of information over a long duration of time.

Underlying the concept is the postulate that humans are better than computers at tasks requiring high levels of judgment and low levels of vigilance, whereas automatons are superior at tasks requiring high levels of vigilance and low levels of judgment. This premise is based on the observation that highly repetitive tasks are boring to people, whereas complex tasks involving deep judgment are difficult to model and write programs to solve.

Table 38. Explanation of Degree of Judgement Rating Scale

Judgment Factor	Explanation
Low	Action requires only reflexive actions that can be defined by predictable algorithmic processes. Examples include tracking a lane center, decelerating to a stop, or braking for a known obstacle.
Medium	Actions involve reaction to external stimuli in a complex or highly non-linear fashion, or involve a significant multivariate model and/or database to describe them. Examples include assessing trajectories for potential collision, planning an optimal route, or plotting best strategy for maneuvering through traffic toward an exit.
High	Action requires highly complex decision-making involving the use of experience and/or training and does not lend itself to modeling or programming practices. Examples include reacting to an in-progress multiple vehicle collision immediately ahead, or assessing the impact of weather patterns on near-term travel plans.

Table 39. Explanation of Degree of Vigilance Rating Scale

Vigilance Factor	Explanation
Low	Activity requires only occasional sampling of the state of the external world and/or infrequent application of process controls to maintain proper functioning. Precise timing of the activity is unimportant Frequency of the activity is no more often than once every few seconds. Examples include determining the state of an approaching traffic signal or monitoring the movement of cars behind. The activity can be treated as a background process most of the time, until a significant event occurs.
Medium	Activity requires moderately frequent sampling of a few states or infrequent monitoring of a large number of states. Actions must be routinely performed, but not necessarily on a rigidly periodic schedule. The task can be relegated to the background from time to time for short durations. Examples include maintaining following spacing in dense traffic, looking for a hole in traffic to merge into, monitoring oncoming traffic at an intersection, or scanning for obstacles in the lane of travel.
High	Activity requires close monitoring of all relevant states with a moderately high frequency or on a continuous basis, or execution of a control task on a highly periodic or continuous basis. The task must remain in the fore-ground at all times. Examples include tracking a hole into which to merge and controlling acceleration, maintaining very short headways in high-speed traffic, and performing skid recovery.

Table 40. Criteria for Automatability.

Vigilance	Judgment	Automation Potential
Low	Low	Don't care -- automate for user convenience if cost is very low.
Medium	Low	Moderate automation potential exists if user convenience, safety, or performance enhancement warrants.
High	Low	if safety and performance improvements are demonstrable, and costs are in line with the level of improvement indicated, definitely automate. Tasks of this type are frequently relegated to classical control systems approaches. Many safety critical tasks lie in this domain (see §1A.2 below).
Low	Medium	Automate with provision for operator takeover provided there is a substantial capability to reduce the impacts of human error or boost system performance.
Medium	Medium	Tasks of this type may provide the opportunity for *M* decision aids. The complexity of the problem domain must be manageable and expressible in some form of knowledge base. The vigilance demands are high enough that users would prefer to be unloaded of the requirement if possible, but not so high that the processing requirements are beyond what is within reasonable cost constraints.
High	Medium	Cost of automating may be high because of the high rate implied by the vigilance rating and the complexity associated with the moderate judgment rating.
Low	High	Leave in human control Tasks of this type are ideally left in the hands of the user, because the cost of automation will likely be high to be able to deal with the full complexity of the problem, and human control is not challenging.
Medium	High	Cost of automation is likely to be high, automation may be a future option.
High	High	Cost of automation is likely to be quite high due to demanding performance level. Automation is likely to be a distant future option. However, humans are likely to have trouble with these functions, since they will generally be called upon to make complex decisions under time constraints. It is desirable to seek a way to avoid requirements of this class.

Given these definitions, it is possible to develop a set of criteria for assessing the potential for automating a given function. The approach is to assess each function in terms of both figures of merit, and then apply the criteria of table 40 (or something similar).

6.2.2. Assessing Levels of Criticality

Level of criticality is another dimension that could be added to the evaluation of concepts. This approach has been traditionally used in the functional evaluation and performance specifications for flight controls with some success (1) Typically, there are four classes of functional criticality in assessing tasks, adapted as follows:

- Safety Critical--- There is significant risk of damage to persons or property is high if the task is not properly executed.
- Performance Critical--- The level of performance can be significantly affected by the task, but the system safety is not impaired by its omission or reduced effectiveness.
- Mission Critical-- The task is essential for performing the desired mission (e.g. transporting people from Point A to Point B.), but has no impact on how well the mission is executed.
- Non-Critical -- Impact of the task is minimal.

Levels of criticality are dependent to a limited extent on architecture and design choices. However, at the functional requirements level, they can be used to help determine where designers must employ redundancy for assuring safety and adequate performance. For example, table 6-3 in report (1), adapted below as table 41 below, provides recommendations for levels of required redundancy based on the assessed levels of criticality. These criteria also tend to help determine how much cost can or should be borne in the automation of a given task, not whether the task can be automated.

Table 41. Levels of Criticality and Redundancy Requirements

	Safety Critical	Performance Critical	Mission Critical
Representative Functions	Force / moment generation, stability and control augmentation, path tracking, manual command insertion and overrides	Path selection, position tracking, obstacle avoidance	Route planning, sensing of the operating environment
Typical Reaction Time Domain	≤0.5 sec	0.5< t< 5.0 sec	≤ 5 sec
Recommended Redundancy l-evel	Fail Op/Fail Op/Fail Safe	Fail Safe or Fail Op/Fail Safe	Fail "Soft"

When we first considered using these criteria, we found that assessing level of criticality in the limited domain of the maneuvers defined in the MDFRD was not particularly enlightening. Since we were contemplating only issues of Longitudinal control, there was not much discriminating power in comparing system concepts using these criteria. Rather, we judged that such evaluations only become meaningful in the full system context including such functions as route management and optimization.

It should be noted that the elements of table 41 are not to be taken as absolute discriminators, but merely as "guidelines" in specifying requirements and developing implementation architectures.

6.3. Recommendations to the AHS Consortium

6.3.1. Recommendation for expanding and deepening this study's results

The overarching intent of this study was to provide a structure for evaluation of concepts and to uncover, in a first pass evaluation, those issues that should be investigated in further detail during the system definition phase of the AHS program. We believe that the structure of this study, as reflected in the chain of three documents produced under this effort, is the right methodology for the consortium to follow.

We have also attempted to perform our specific analyses within that structure as a means of demonstrating how the structure can be used. However, we also recognize that there are some shortcomings in the specific outputs coming from this effort that could be addressed by the Consortium should they choose to follow this approach. These include:

- *Incomplete maneuver definition* - The maneuvers set the stage for the definition of functional requirements that in turn drive the system design at both the conceptual and detailed levels. Having defined the taxonomy of maneuvers and proceeded with the evaluation, we soon realized that there were probably some sub-categories of maneuvers that may have been omitted. However, we believe that the structure of the taxonomy provides the basis for filling in the "holes". Some effort should be expended in filling out the list of required maneuvers so that all required activities are defined.

- *Incomplete requirements definition* - Developing a consistent and all-inclusive set of requirements generally requires multiple iterations for which there was insufficient time under this limited scope study. We attempted to define a set of requirements on a first-pass basis, and performed one iteration of review and refinement. However, we recognize that this set has many points of incompleteness that will require broader expertise than our limited team could provide. Nonetheless, we believe that the requirements provided should be a good start set to generate discussions from which the full set of requirements will emerge. That discussion should be on a national basis and should involve participation by all categories of stakeholders. Failure to do so will induce the risk of rejection of whatever solution the Consortium settles on. If you don't support the requirements set, you can't possibly endorse the solution that arose from that requirements set.

- *Incomplete system concept definition* - Not only because of the limited time and resources but also because of incomplete requirements at the time of concept selection, there was demonstrably less detail in the concept definitions than needed to fully evaluate the them in a completely meaningful way. As we stated several times in the preceding sections, we determined from the outset to define some

> concepts and then hold those definitions constant. This approach was necessary to avoid an open ended process of modify-reevaluate-modify-reevaluate ad *nauseam.* Our recommendation, however, is to avoid detailed concept definition before there is general agreement on a complete set of requirements. The system definition phase of the program should allocate sufficient time allocated for iterating on both requirements and concept definition *and* to *maintain broad involvement on all intermediate steps.* Failure to do so will be costly in terms of dead-end pursuits and unfocused, unproductive debate in the community at large.

Of course, the core activity of the Consortium is to develop the system definition. Our evaluations and recommendations are not so much intended to skew the Consortium toward or away from particular concepts, but to highlight the major issues we could see and to demonstrate what we believe is a rational, traceable approach to defining the final concept. Without a reasonably rigorous methodology that is agreed to from the outset of the system definition phase, the effort to define a workable AHS concept will be mired by the diverse and distributed nature of the consortium. It is our hope that the product of this effort will provide the basis to avoid that pitfall.

Undoubtedly, some will criticize some specific aspects of this study's results because of those deficiencies. However, we believe that those criticisms, however valid in content, will most likely not invalidate the correctness of the method. Though we would welcome any constructive criticism, we would also point out that once the precursor studies have been concluded, they should be directed toward the AHS Consortium, whose job it will be to carry this process through to the selection of the final AHS conceptual design.

6.3.2. Classifying Issues

One suggestion to classify issues according to the type and utility of issues. Some of the issues we have identified are dependent upon the specific implementation, but have no impact on the viability of the concept. Some of the issues identified herein should drive the conceptual design. Still other issues are major barriers to concept feasibility, regardless of design and implementation approach.

In gathering and assessing all the issues in a full trade study, it might be useful to categorize issues as conceptual, design, or implementation level issues. A conceptual level issue is one that determines whether or not the concept could be put into practice; these tend to be the high-level approach and philosophy issues, such as where the threshold of pain is on per-vehicle-cost. Design level issues are those that impact the top-level specification of the system structure, such as applicable standards for communication and how the architecture is to be structured. Implementation level issues are those that designers developing detailed implementation of the system will have to worry about. Parties responsible for performing the in-depth "de studies should concentrate on the first category and perform only cursory review of the latter two categories. Clearly, there is little value in resolving implementation issues before the viability and feasibility of the concepts at large are determined.

Appendix A. MatLab Simulation Code

A.1. Kv Lookup function

```
function kv=kv_lookup(Vel);

% kv_lookup
%
%   This function implents the look up table for the kv
%  coefficient.  This function is defined by Table 1 in
%  'Vehicle Model' by Petros Ioannou
%
%  P.H.Argo 1/31/94
%  Martin Marietta - AHS LLCS PSA Contract
%

if (Vel>=35)
   kv=0.67;
else
   if (Vel>=25)
      kv=1.0;
   else
      if (Vel>=15)
         kv=1.47;
      else
         kv=2.4;
      end
   end
end
```

A.2. MDAIR Lookup function

```
function MDAIR=MDAIR_lookup(Theta);

% MDAIR_lookup
%
%   This function implents the look up table for the MDAIR
%  coefficient.  This function is defined by Table 2 in
%  'Vehicle Model' by Petros Ioannou
%
%  P.H.Argo 1/31/94
%  Martin Marietta - AHS LLCS PSA Contract
%
% incremental linear interpolation added 12/28/94 - PHA
%

if (Theta<5)
   MDAIR=0.168+0.006*(Theta);

elseif (Theta<7)
   MDAIR=0.198+0.086*(Theta-5);

elseif (Theta<9)
   MDAIR=0.37+0.11*(Theta-7);
```

```
elseif (Theta<11)
   MDAIR=0.59+0.155*(Theta-9);

elseif (Theta<13)
   MDAIR=0.9+0.23*(Theta-11);

elseif (Theta<15)
   MDAIR=1.36+0.235*(Theta-13);

elseif (Theta<17)
   MDAIR=1.83+0.37*(Theta-15);

elseif (Theta<19)
   MDAIR=2.57+0.29*(Theta-17);

elseif (Theta<21)
   MDAIR=3.15+0.375*(Theta-19);

elseif (Theta<23)
   MDAIR=3.9+0.45*(Theta-21);

elseif (Theta<25)
   MDAIR=4.8+0.35*(Theta-23);

elseif (Theta<27)
   MDAIR=5.6+0.325*(Theta-25);

elseif (Theta<29)
   MDAIR=6.25+0.425*(Theta-27);

elseif (Theta<31)
   MDAIR=7.1+0.45*(Theta-29);

elseif (Theta<33)
   MDAIR=8.0+0.4*(Theta-31);

elseif (Theta<35)
   MDAIR=8.8+0.5*(Theta-33);

elseif (Theta<37)
   MDAIR=9.8+0.35*(Theta-35);

elseif (Theta<39)
   MDAIR=10.5+0.15*(Theta-37);

elseif (Theta<41)
   MDAIR=10.8+0.25*(Theta-39);

elseif (Theta<85)
   MDAIR=11.3+0.1*(Theta-41);

else
   MDAIR=15.7;
end
```

A.3. Longitudinal Initiaization Computation Script

```
% Longitudinal Initialization Script
%
%  This script performs all computations required to initialize the
%  vehicle states defined in the 'Vehicle Model' by Petros Ioannou.
%  The computations are derived in the report
%      'Vehicle Simulation : Structure, Initialization, and Results'
%
%  P.H.Argo 3/9/94
%  Martin Marietta - AHS LLCS PSA Contract
%

V_init=input('Please enter the initial vehicle velocity (mph) > ');

% Compute initial engine speed (rpm) i.a.w. eqn. (5)
n_init=29.95*V_init;

% Compute initial MDAIR i.a.w. eqn. (12)
MDAIR_init=(V_init*(122.83+V_init*(0.43+V_init*0.045)))/2088.76;

% Use the inverted lookup table to define the
%   initial throttle angle (degrees)
Theta_init=Theta_lookup(MDAIR_init);

disp('The computed initial states are :')
disp('    Vehicle Speed  (mph)     {V_init}      :'):disp(V_init)
disp('    Engine Speed   (rpm)     {n_init}      :'):disp(n_init)
disp('    Throttle Angle (degrees) {Theta_init} :'):disp(Theta_init)
```

A.4. Theta Lookup function

```
function Theta=Theta_lookup(MDAIR);

% Theta_lookup
%
%   This function implents the inverse of the look up table
%  for the MDAIR coefficient.  This function is based upon
%  Table 2 in  'Vehicle Model' by Petros Ioannou
%
%  P.H.Argo 3/9/94
%  Martin Marietta - AHS LLCS PSA Contract
%

if (MDAIR<0.198)
   Theta=(MDAIR-0.168)/0.006;
   if (Theta<3)
      Theta=3;
   end

elseif (MDAIR<0.37)
   Theta=5+(MDAIR-0.198)/0.086;

elseif (MDAIR<0.59)
   Theta=7+(MDAIR-0.37)/0.11;
```

```
elseif (MDAIR<0.9)
   Theta=9+(MDAIR-0.59)/0.155;

elseif (MDAIR<1.36)
   Theta=11+(MDAIR-0.9)/0.23;

elseif (MDAIR<1.83)
   Theta=13+(MDAIR-1.36)/0.235;

elseif (MDAIR<2.57)
   Theta=15+(MDAIR-1.83)/0.37;

elseif (MDAIR<3.15)
   Theta=17+(MDAIR-2.57)/0.29;

elseif (MDAIR<3.9)
   Theta=19+(MDAIR-3.15)/0.375;

elseif (MDAIR<4.8)
   Theta=21+(MDAIR-3.9)/0.45;

elseif (MDAIR<5.6)
   Theta=23+(MDAIR-4.8)/0.35;

elseif (MDAIR<6.25)
   Theta=25+(MDAIR-5.6)/0.325;

elseif (MDAIR<7.1)
   Theta=27+(MDAIR-6.25)/0.425;

elseif (MDAIR<8.0)
   Theta=29+(MDAIR-7.1)/0.45;

elseif (MDAIR<8.8)
   Theta=31+(MDAIR-8.0)/0.4;

elseif (MDAIR<9.8)
   Theta=33+(MDAIR-8.8)/0.5;

elseif (MDAIR<10.5)
   Theta=35+(MDAIR-9.8)/0.35;

elseif (MDAIR<10.8)
   Theta=37+(MDAIR-10.5)/0.15;

elseif (MDAIR<11.3)
   Theta=39+(MDAIR-10.8)/0.25;

elseif (MDAIR<15.7)
   Theta=41+(MDAIR-11.3)/0.1;

else
   Theta=85;
end
```

Appendix B. Simulation Data Plots

B.1. Case 1.

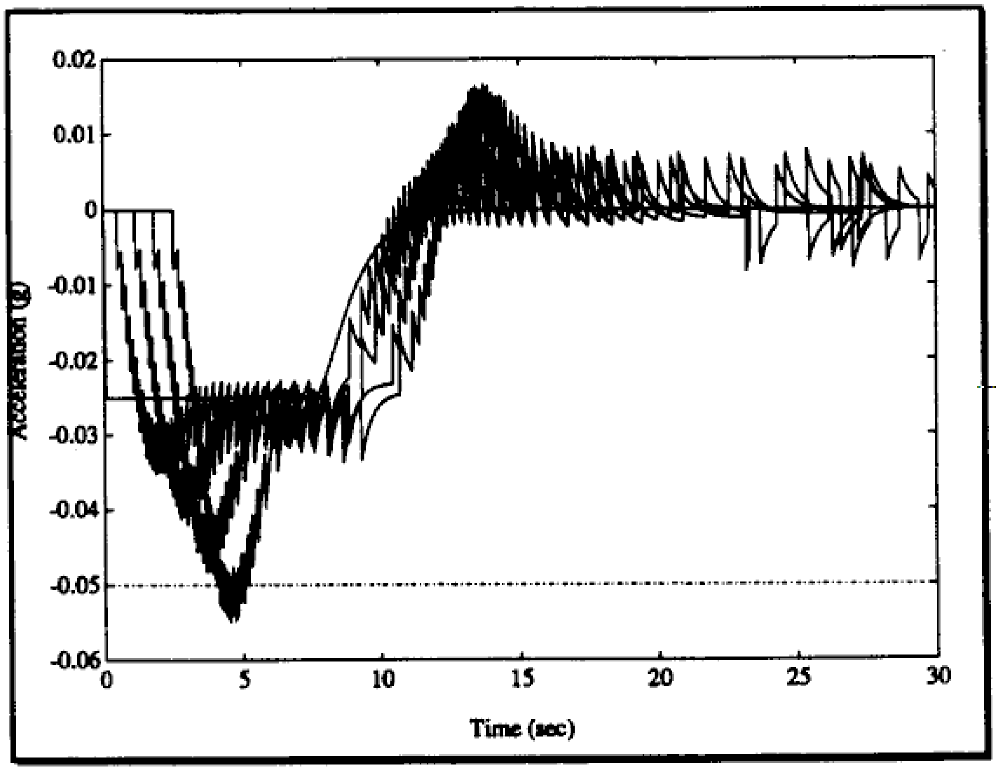


Figure 28. Case #1 Acceleration Plot

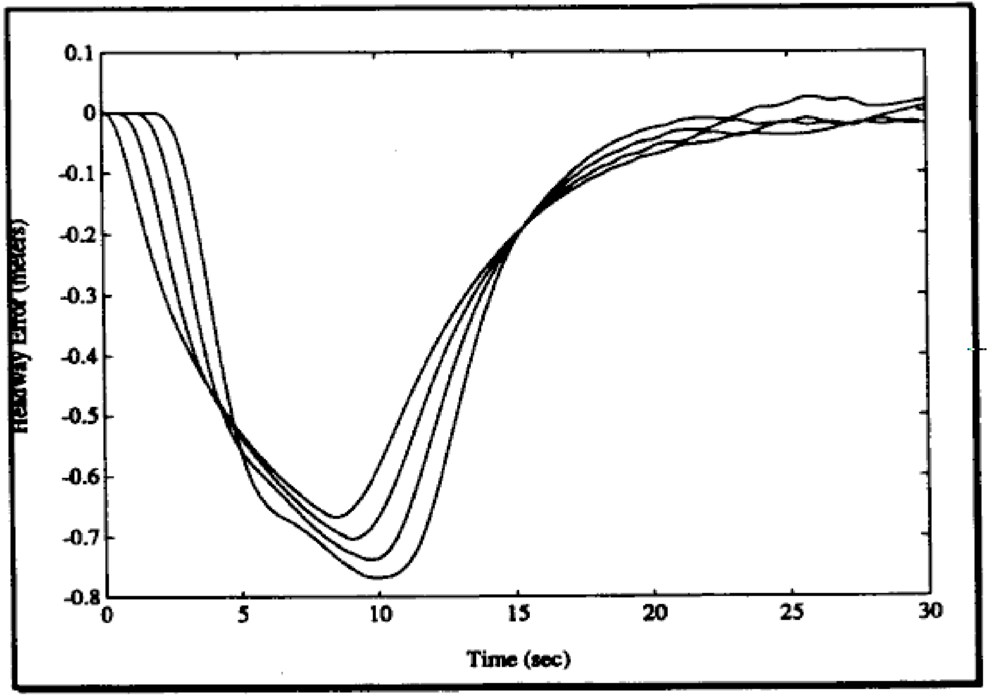


Figure 29. Case #1 Headway Error Plot

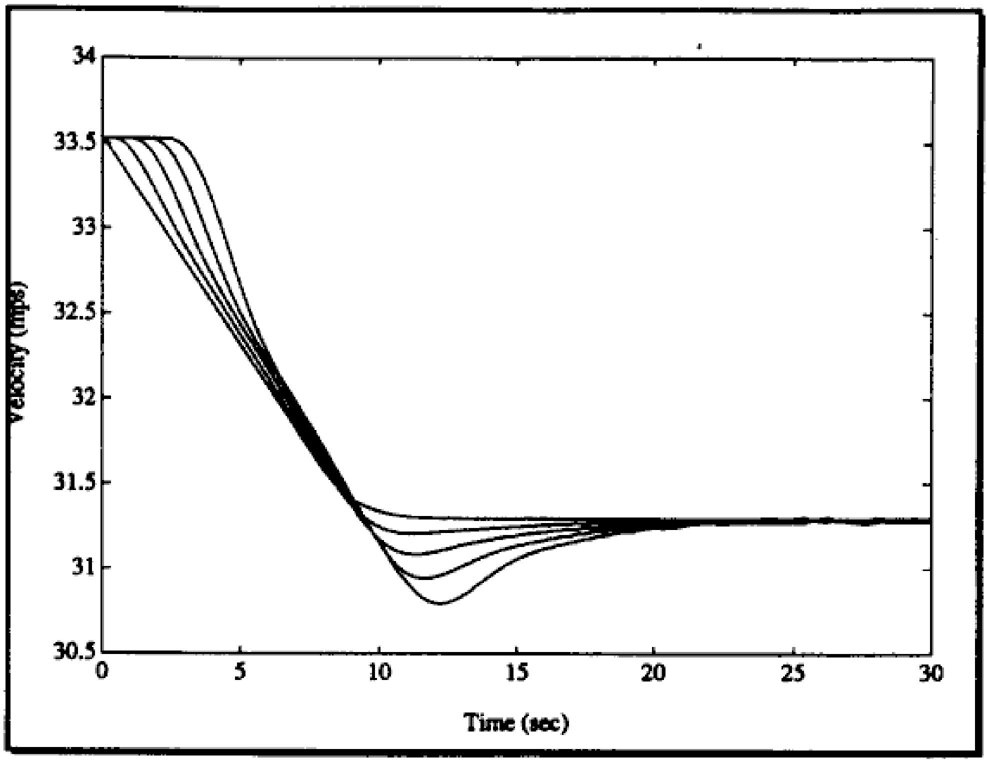


Figure 30. Case #1 Velocity Plot

B.2. Case 2.

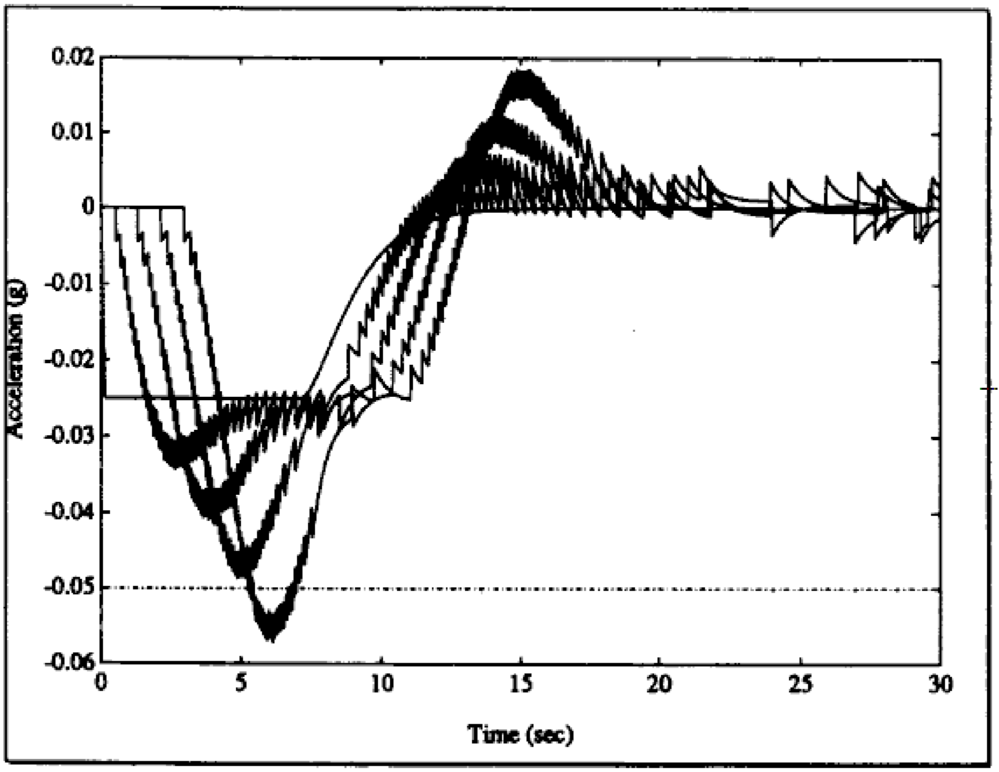


Figure 31. Case #2 Acceleration Plot

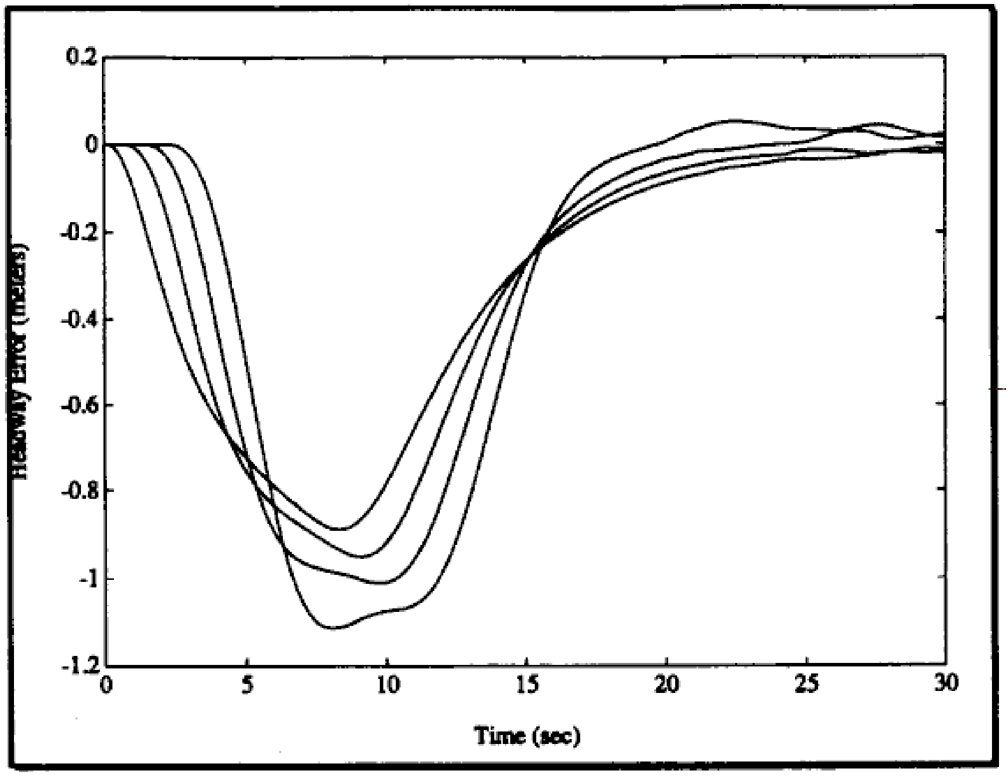


Figure 32. Case #2 Headway Error Plot

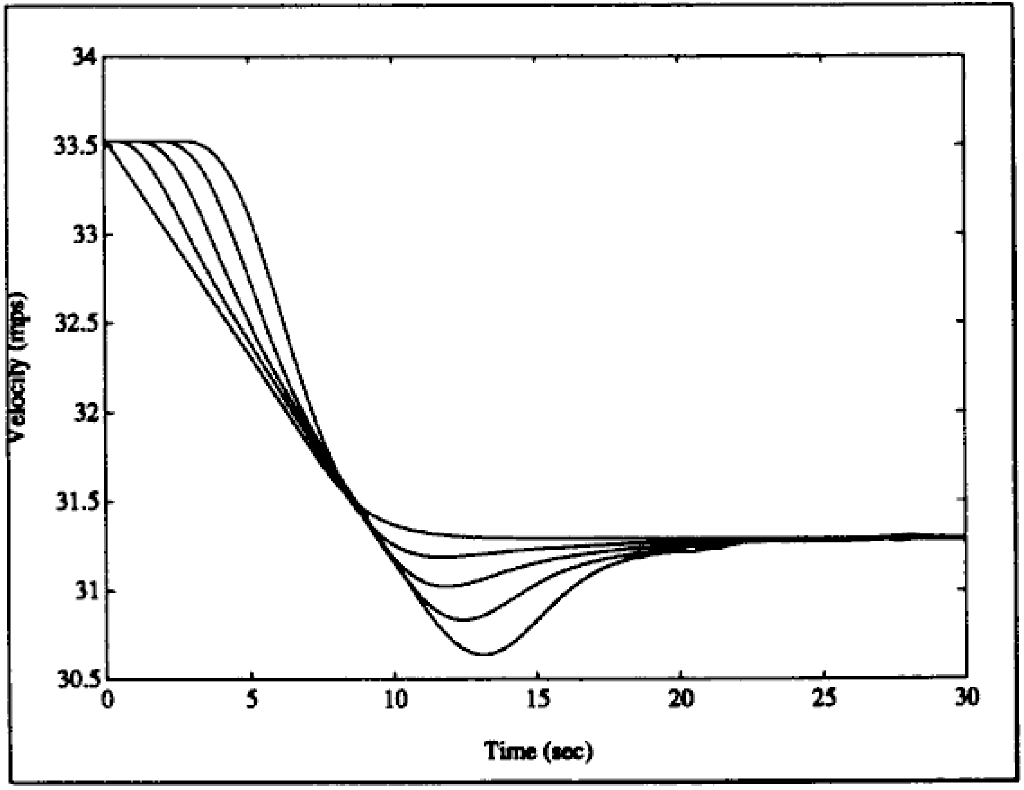


Figure 33. Case #2 Velocity Plot

B.3. Case 3.

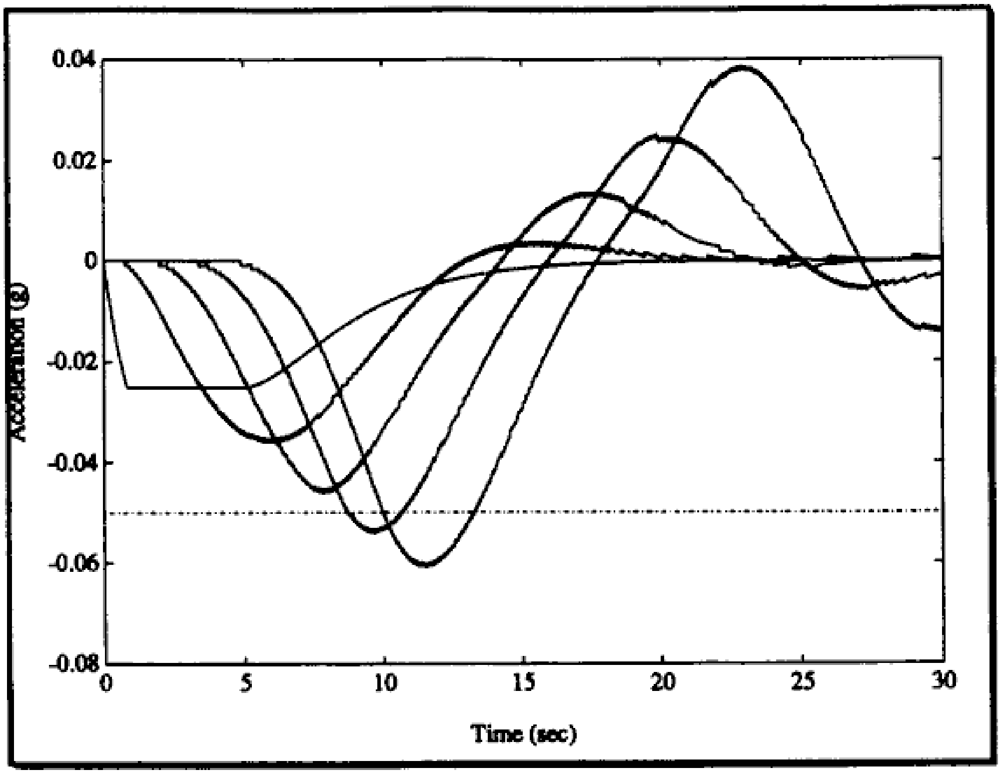


Figure 34. Case #3 Acceleration Plot

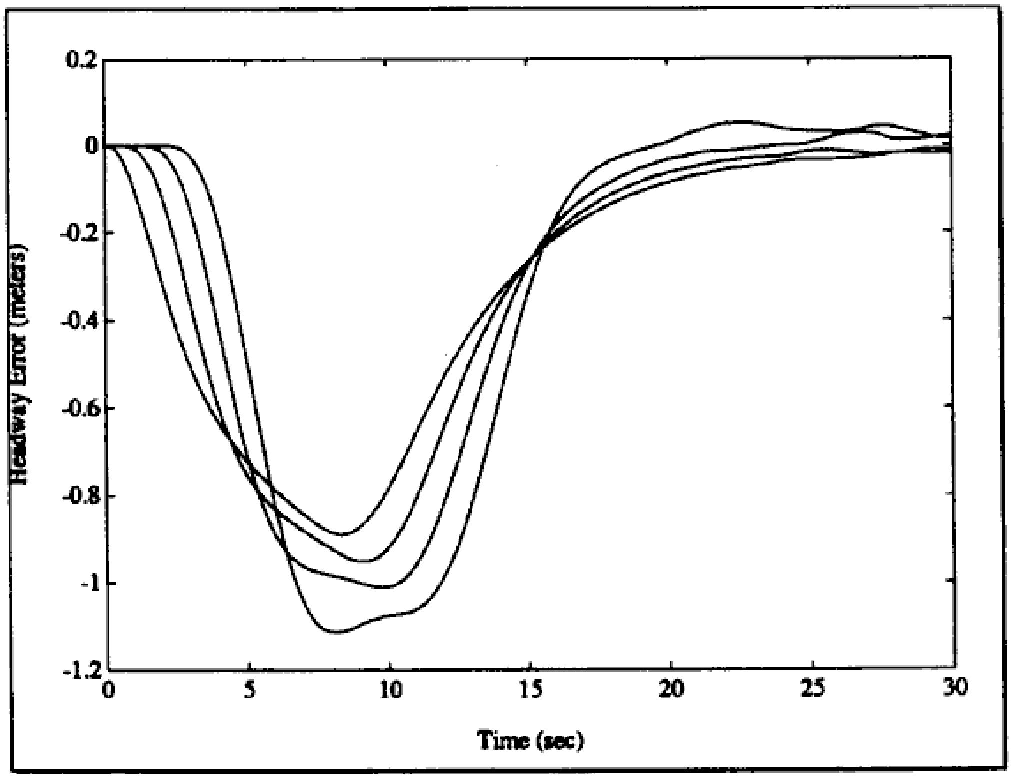


Figure 35. Case #3 Headway Error Plot

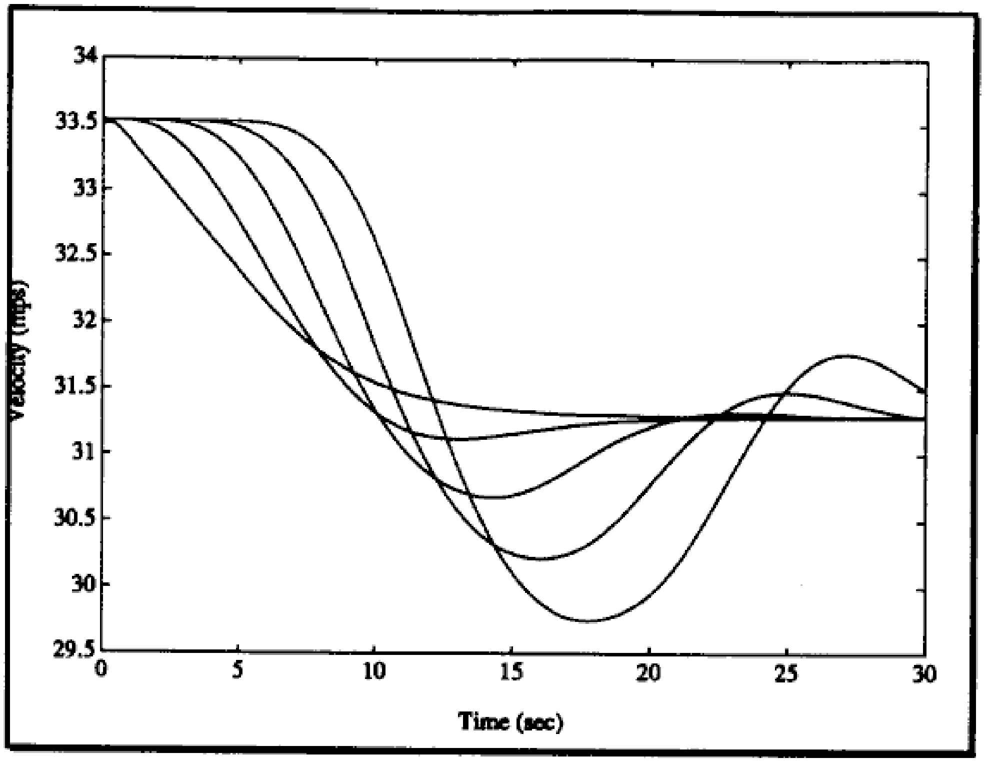


Figure 36. Case #3 Velocity Plot

B.4. Case 4.

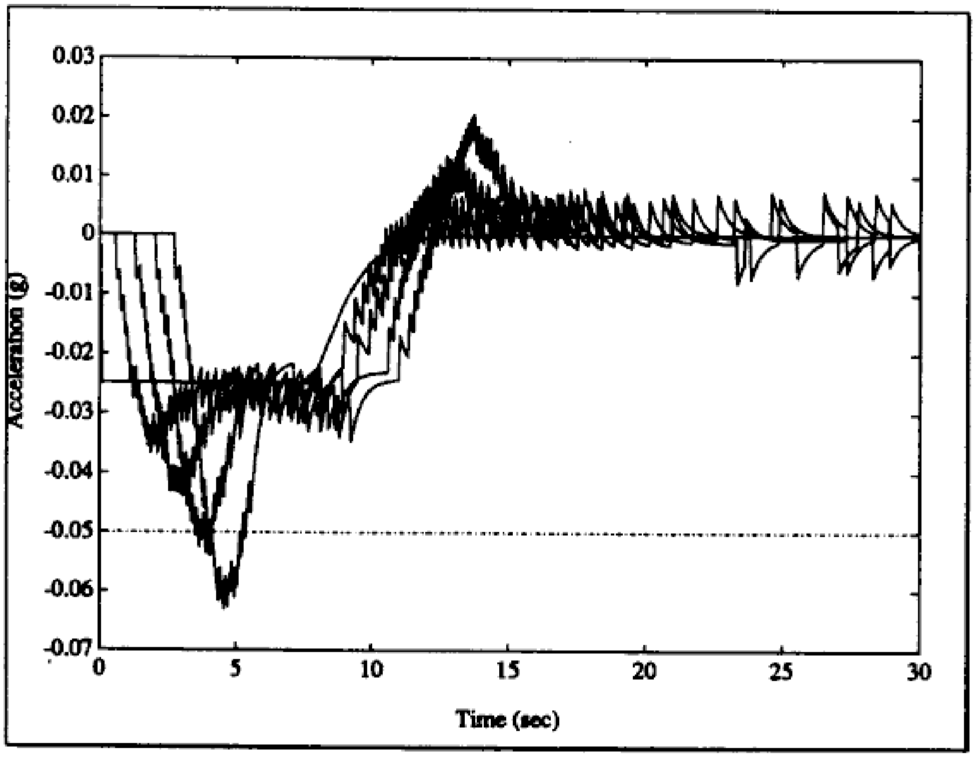


Figure 37. Case #4 Acceleration Plot

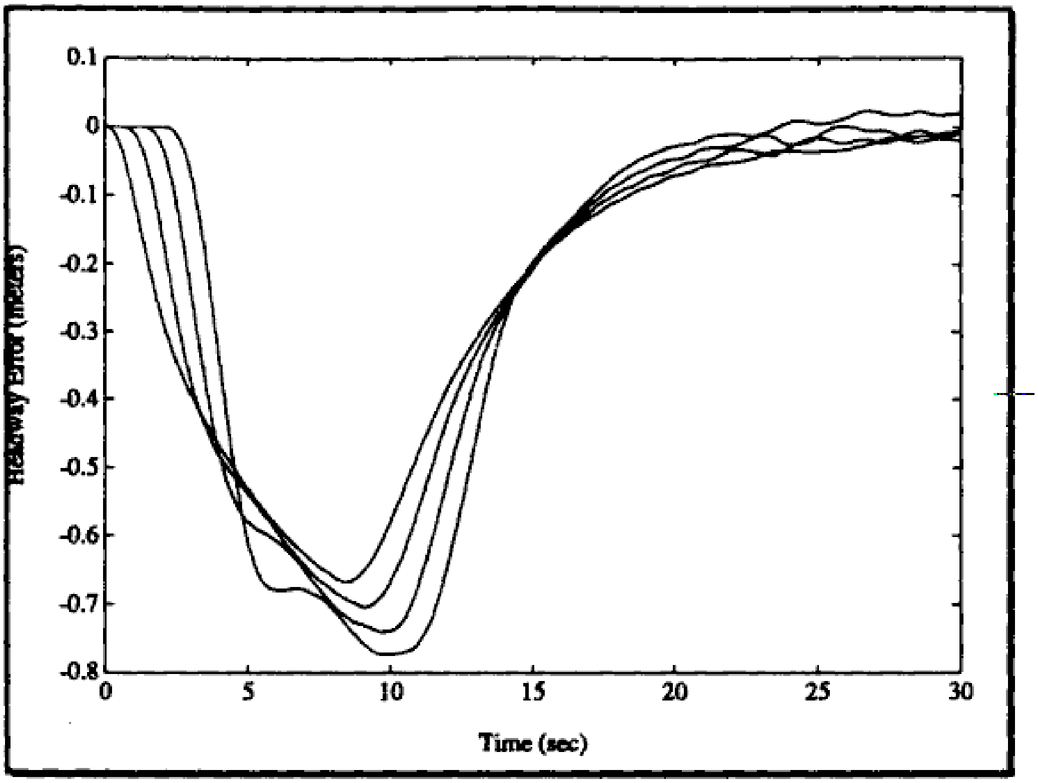


Figure 38. Case #4 Headway Error Plot

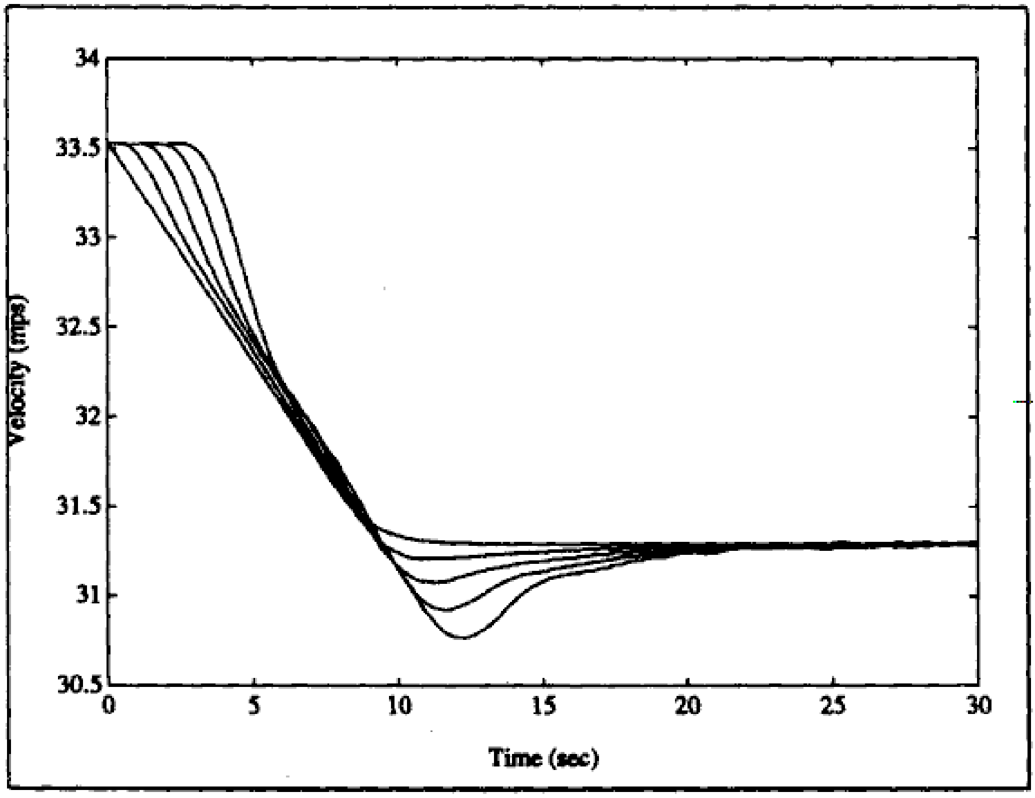


Figure 39. Case #4 Velocity Plot

B.5. Case 5.

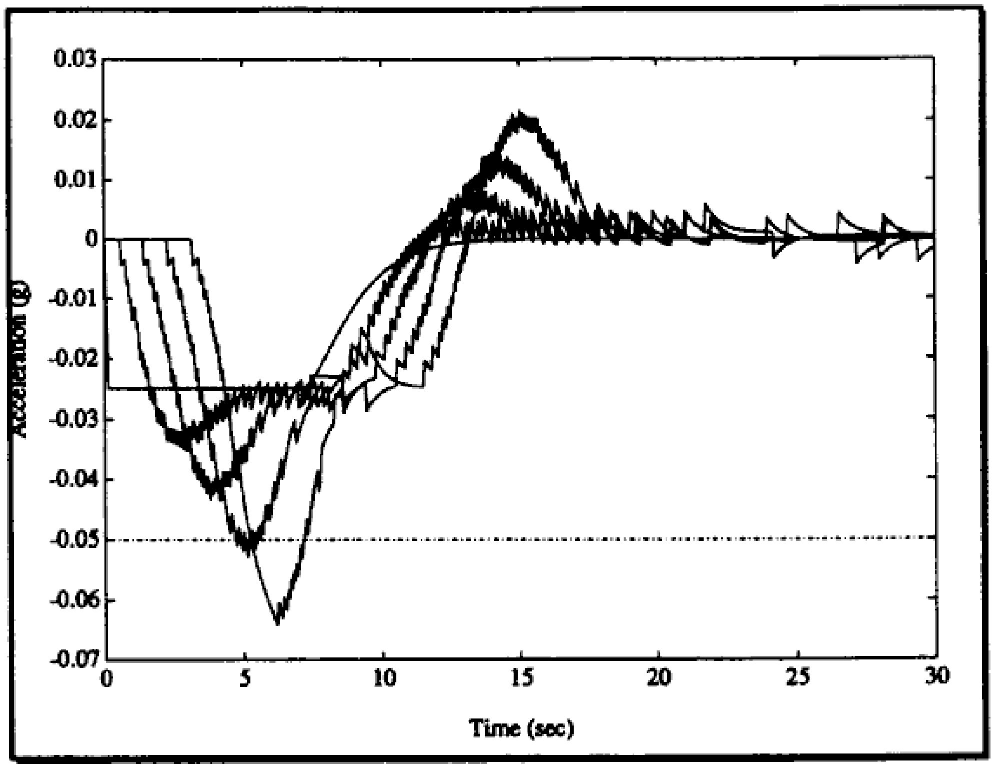


Figure 40. Case #5 Acceleration Plot

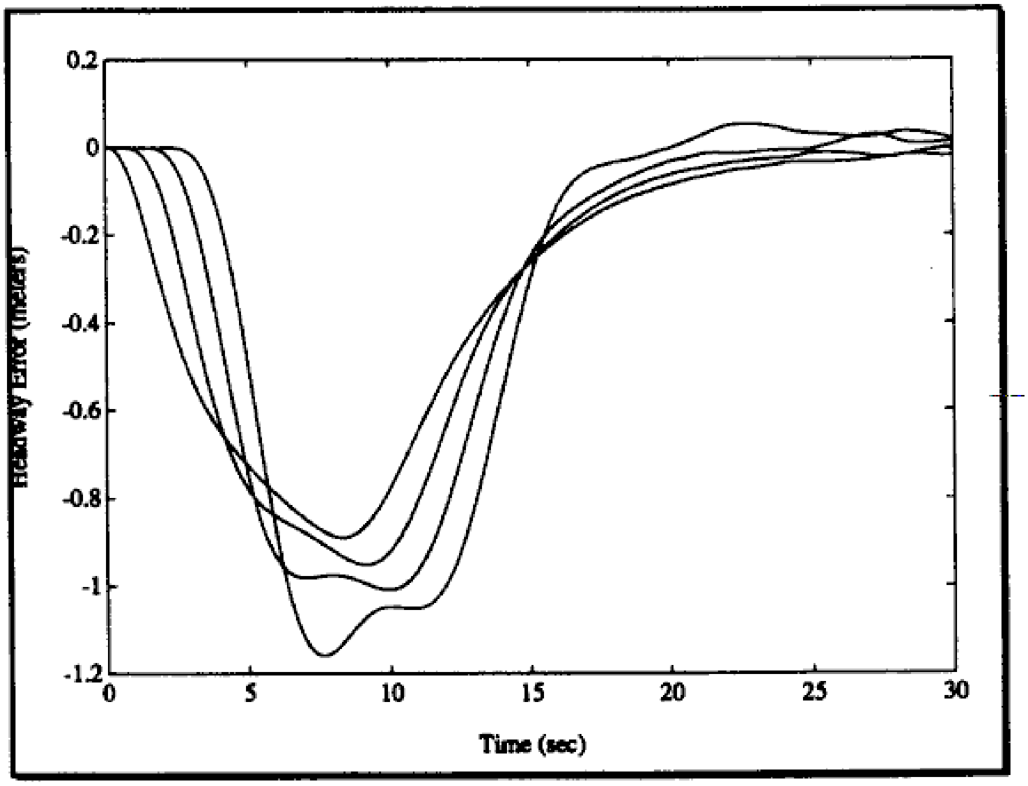


Figure 41. Case #5 Headway Error Plot

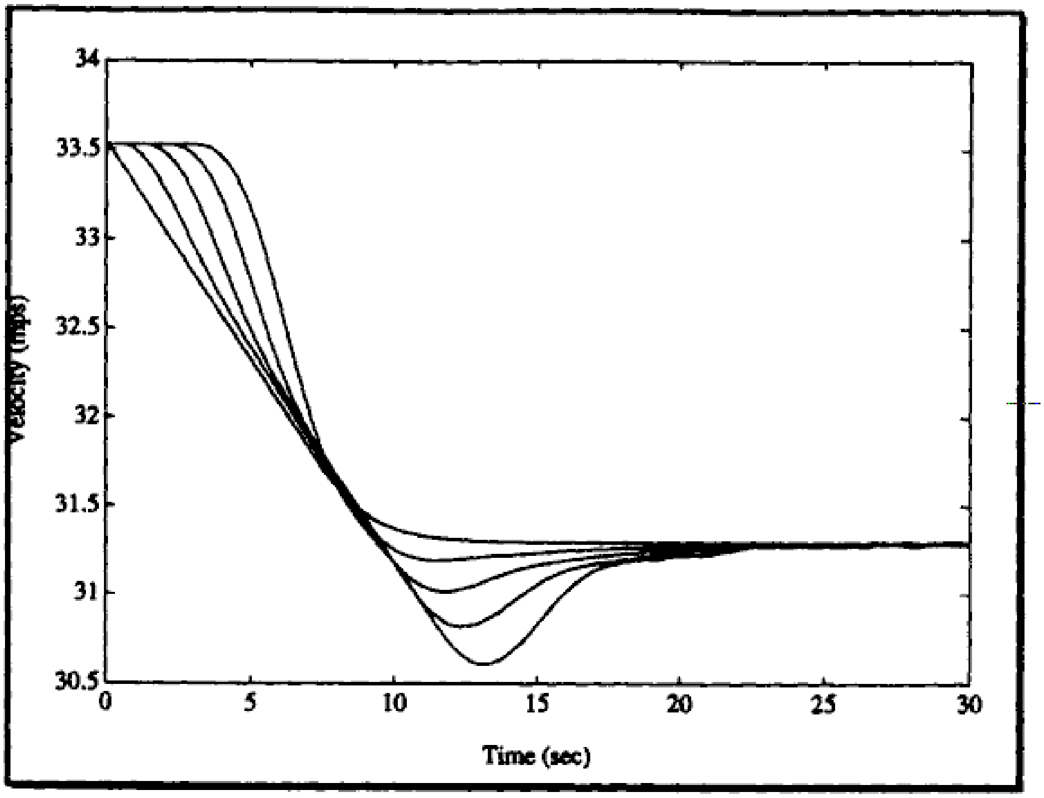


Figure 42. Case #5 Velocity Plot

B.6. Case 6.

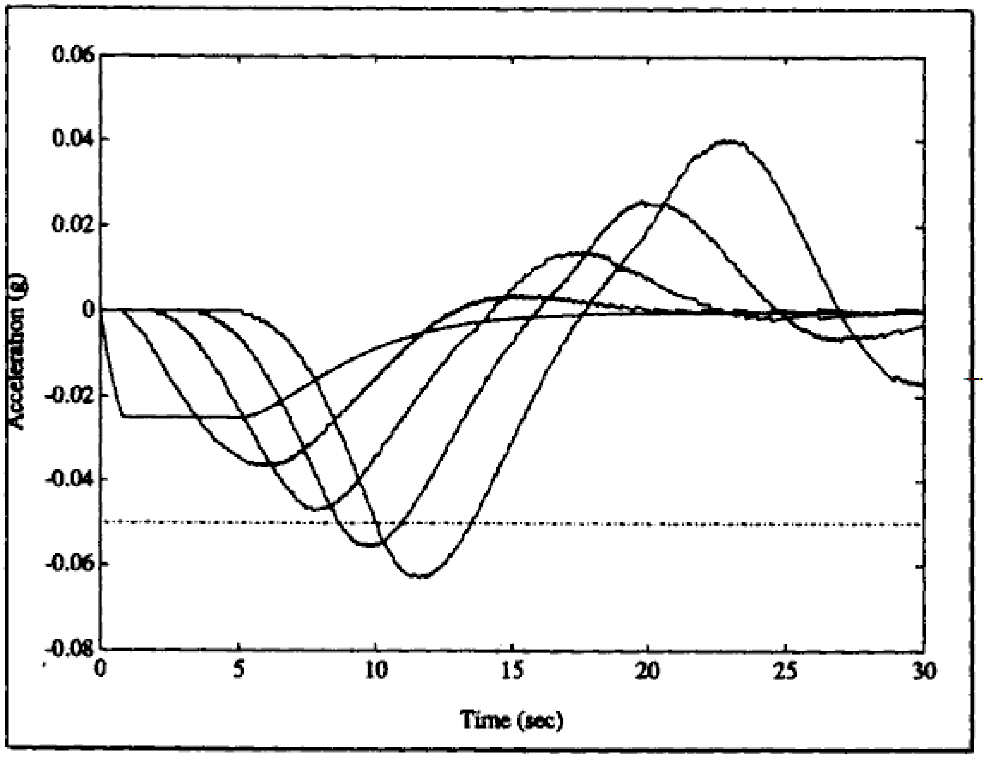


Figure 43. Case #6 Acceleration Plot

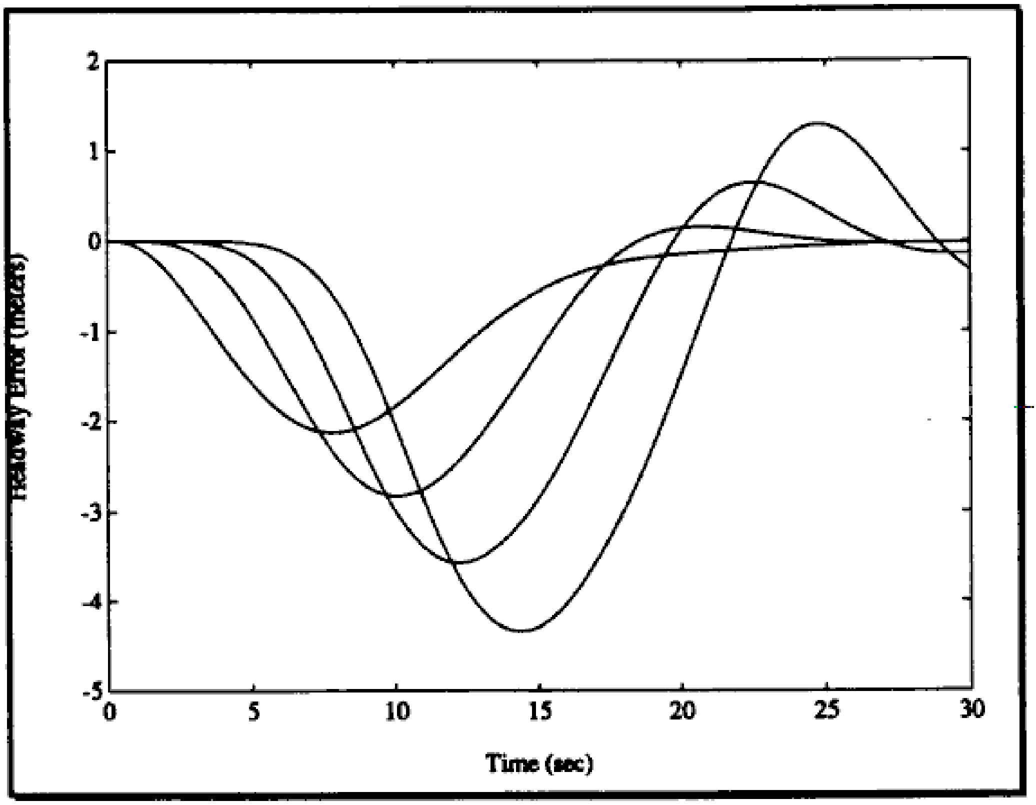


Figure 44. Case #6 Headway Error Plot

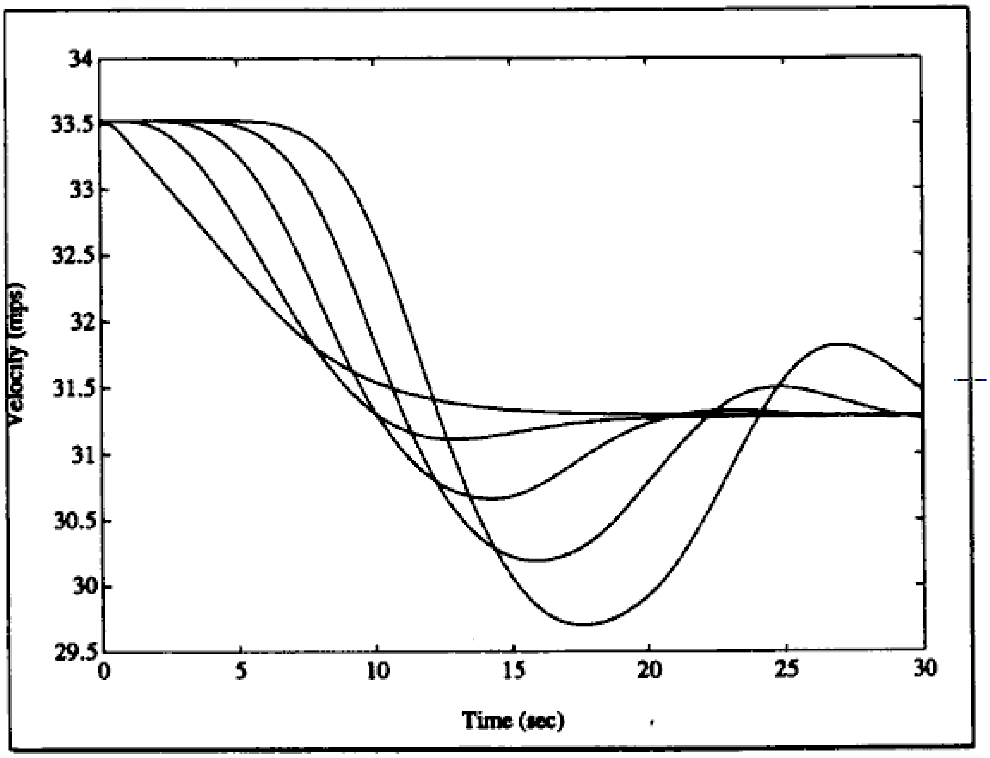


Figure 45. Case #6 Velocity Plot

B.7. Case 7.

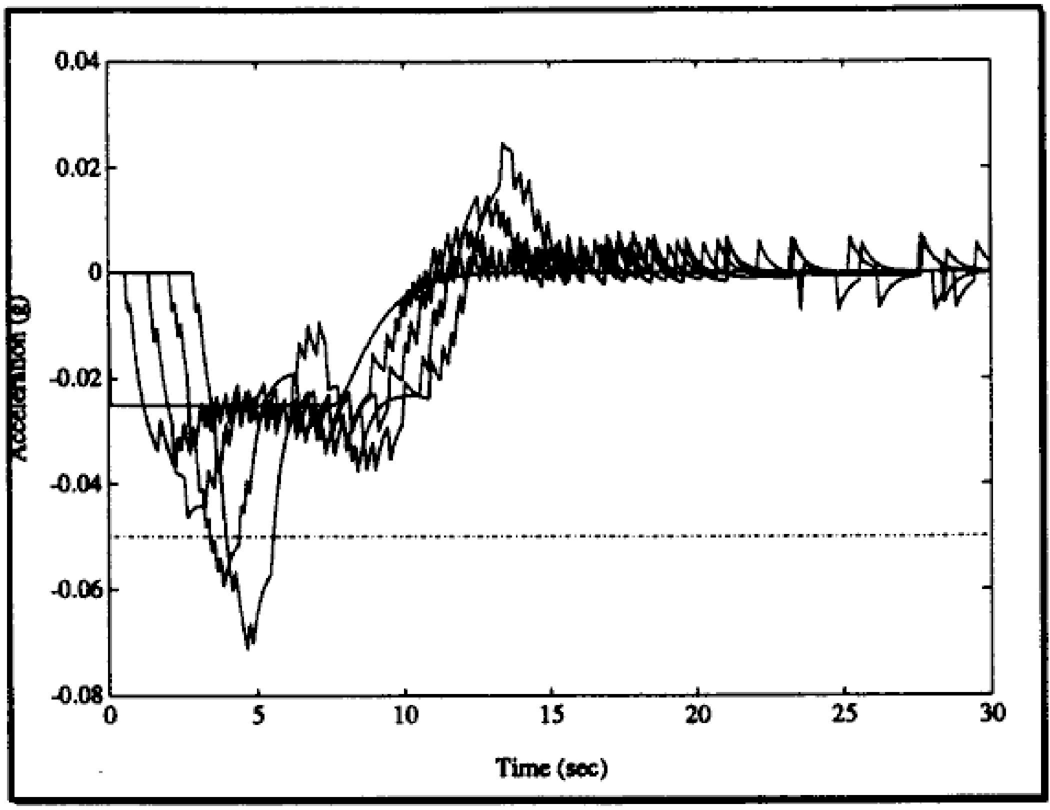


Figure 46. Case #7 Acceleration Plot

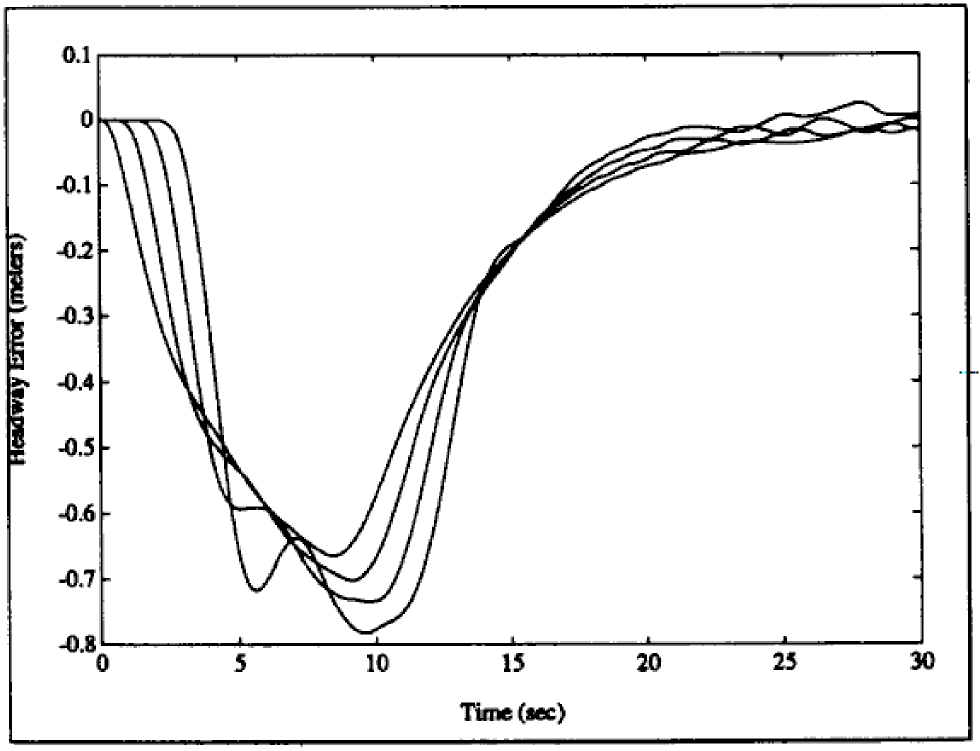


Figure 47. Case #7 Headway Error Plot

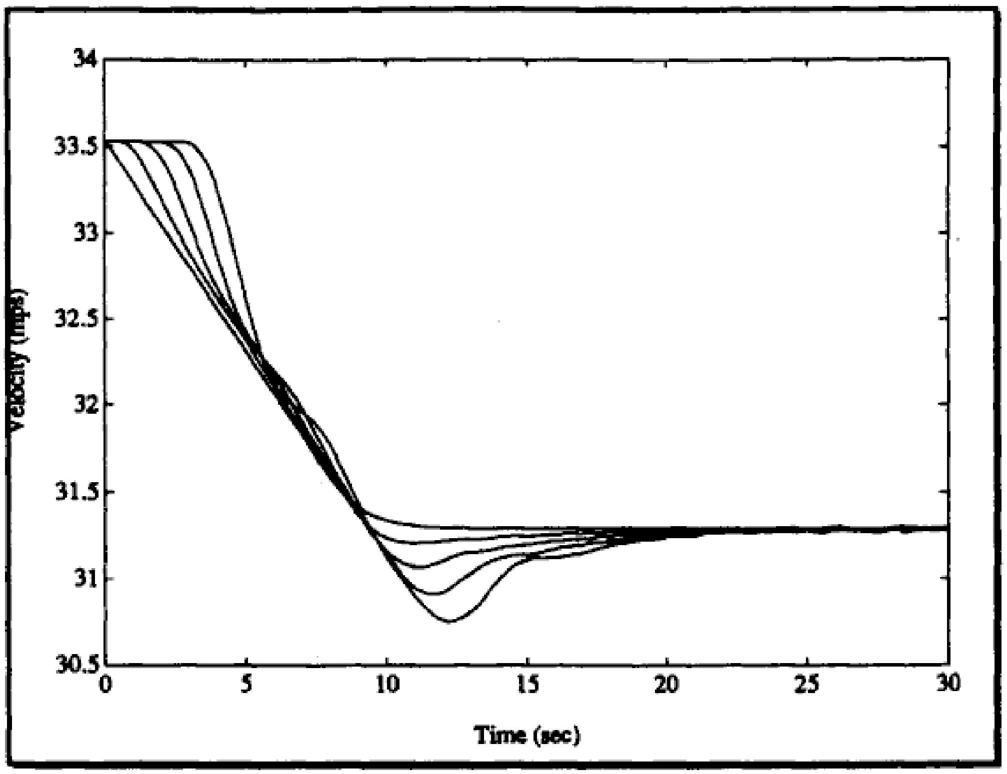


Figure 48. Case #7 Velocity Plot

B.8. Case 8.

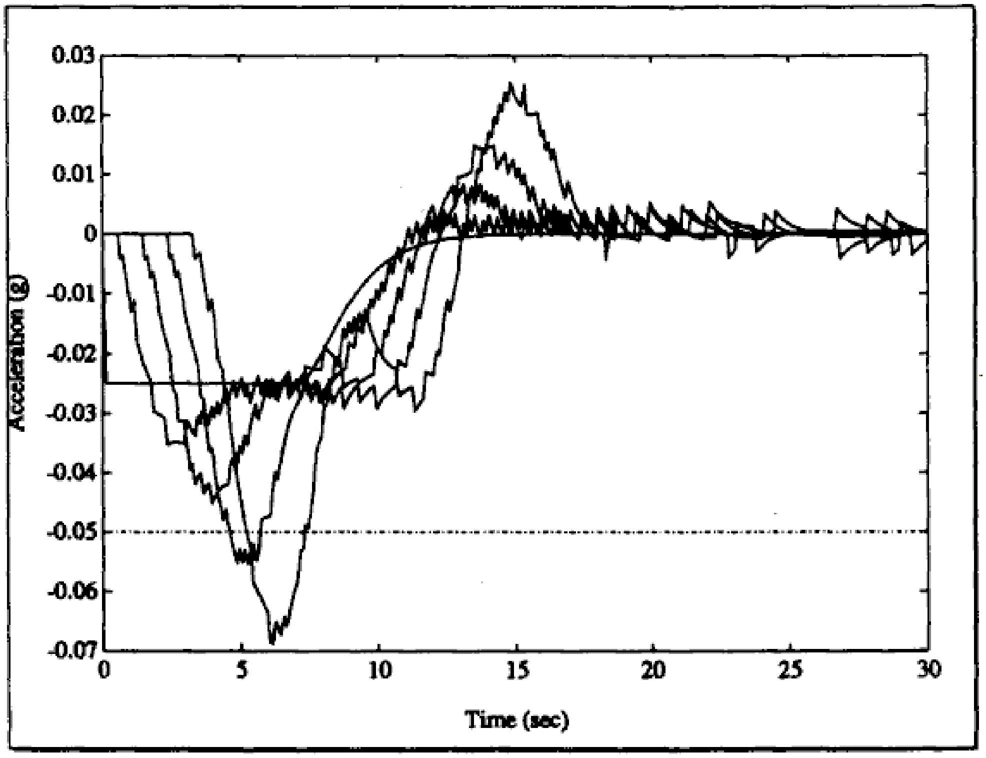


Figure 49. Case #8 Acceleration Plot

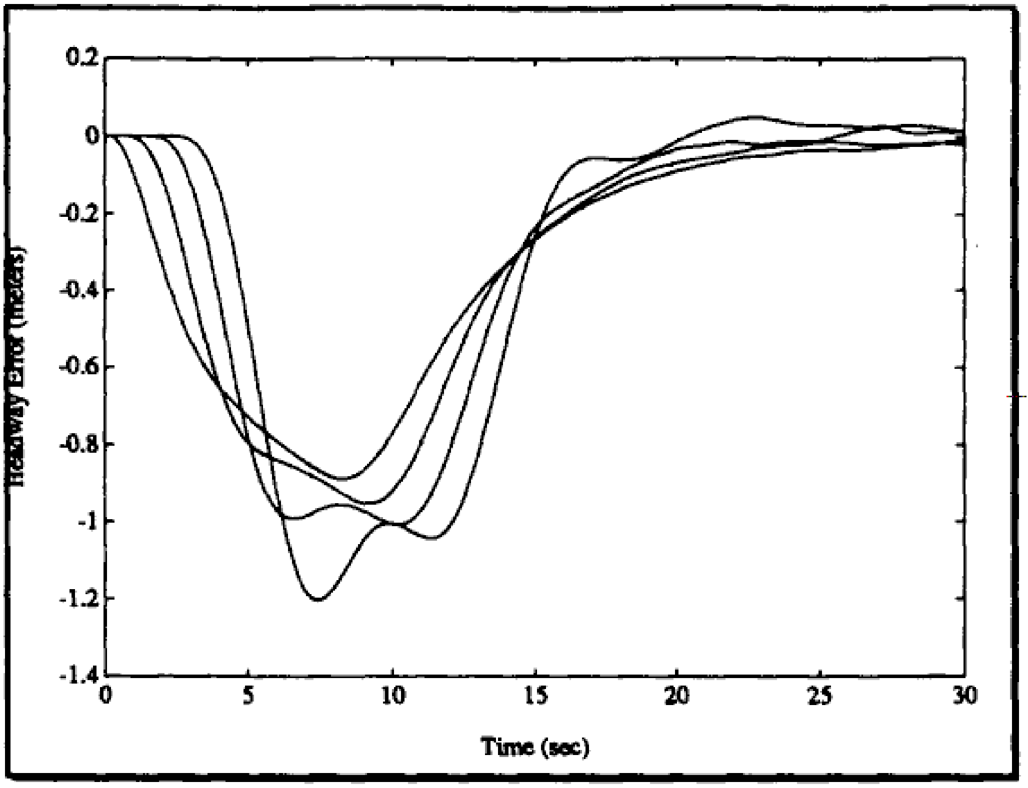


Figure 50. Case #8 Headway Error Plot

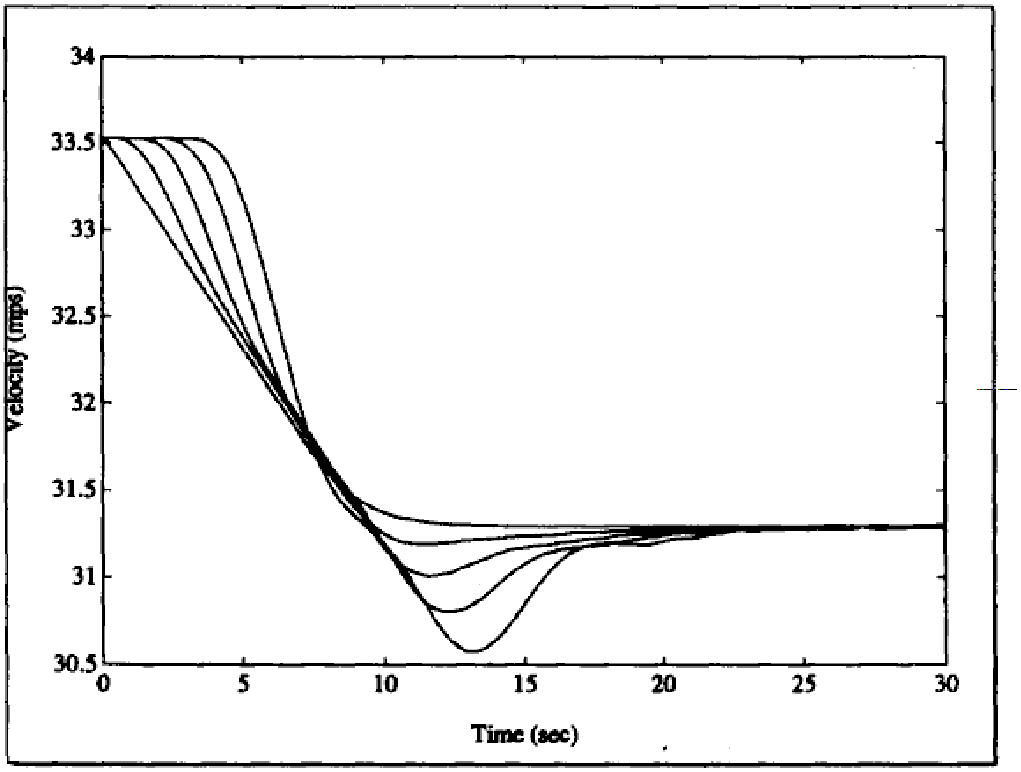


Figure 51. Case #8 Velocity Plot

B.9. Case 9.

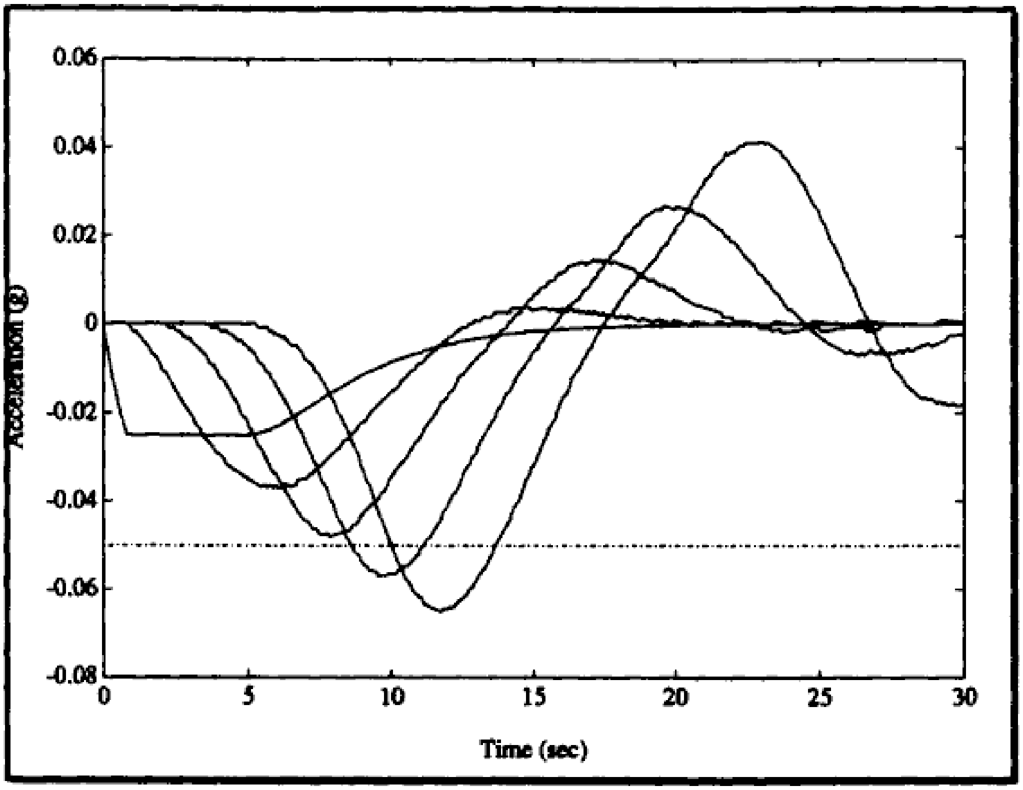


Figure 52. Case #9 Acceleration Plot

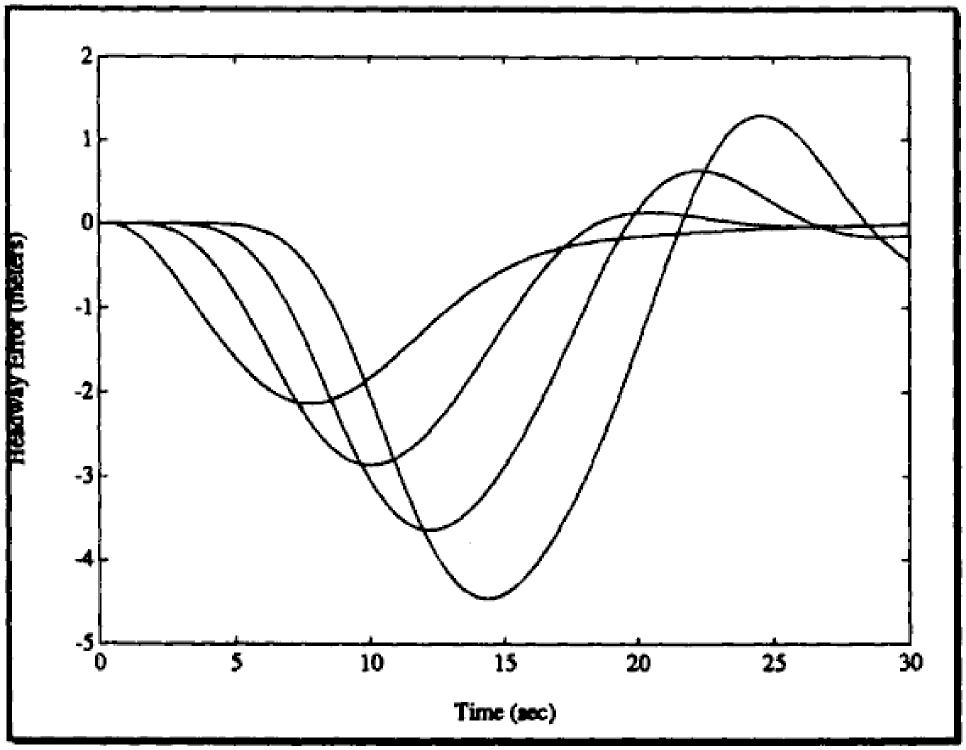


Figure 53. Case #9 Headway Error Plot

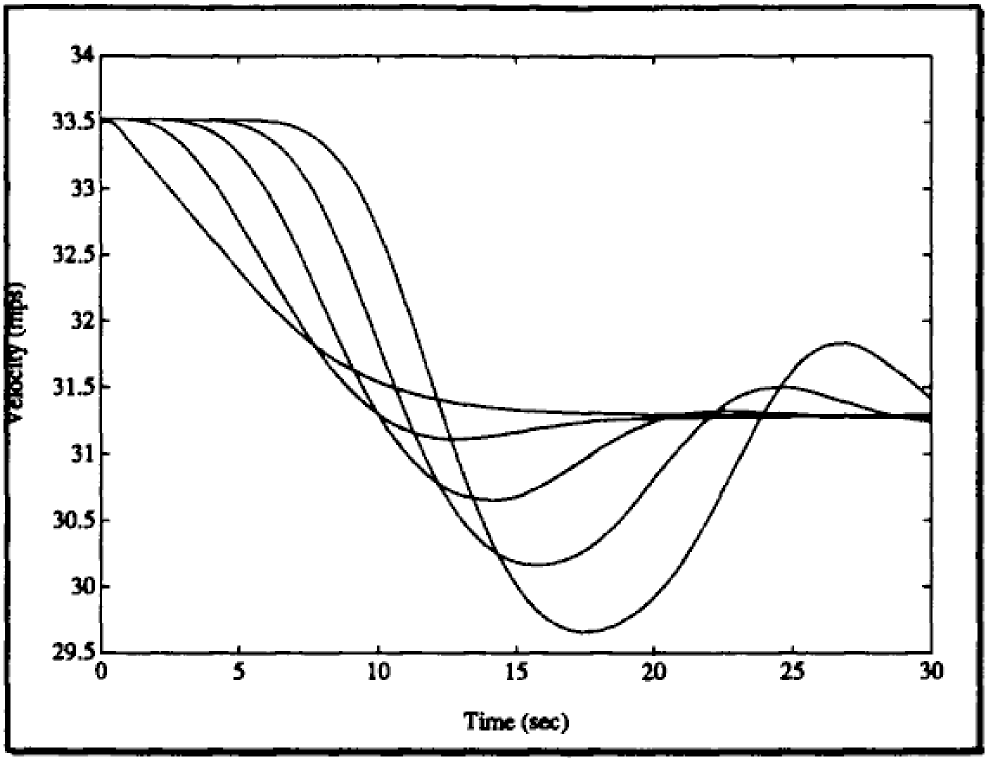


Figure 54. Case #9 Velocity Plot

B.10. Case 10.

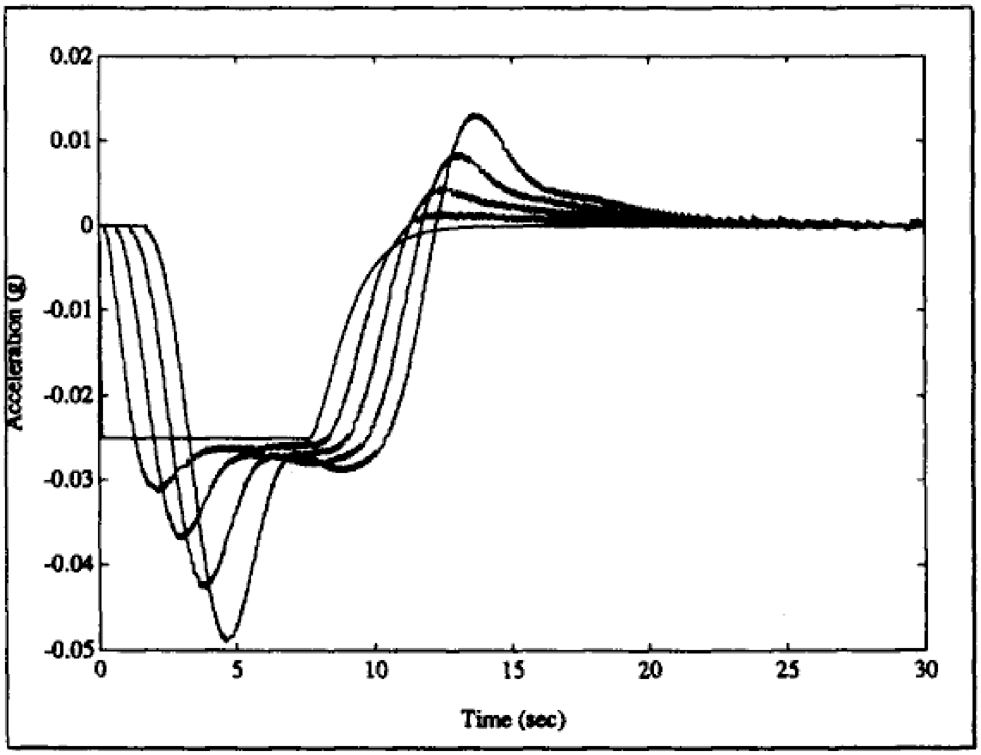


Figure 55. Case #10 Acceleration Plot

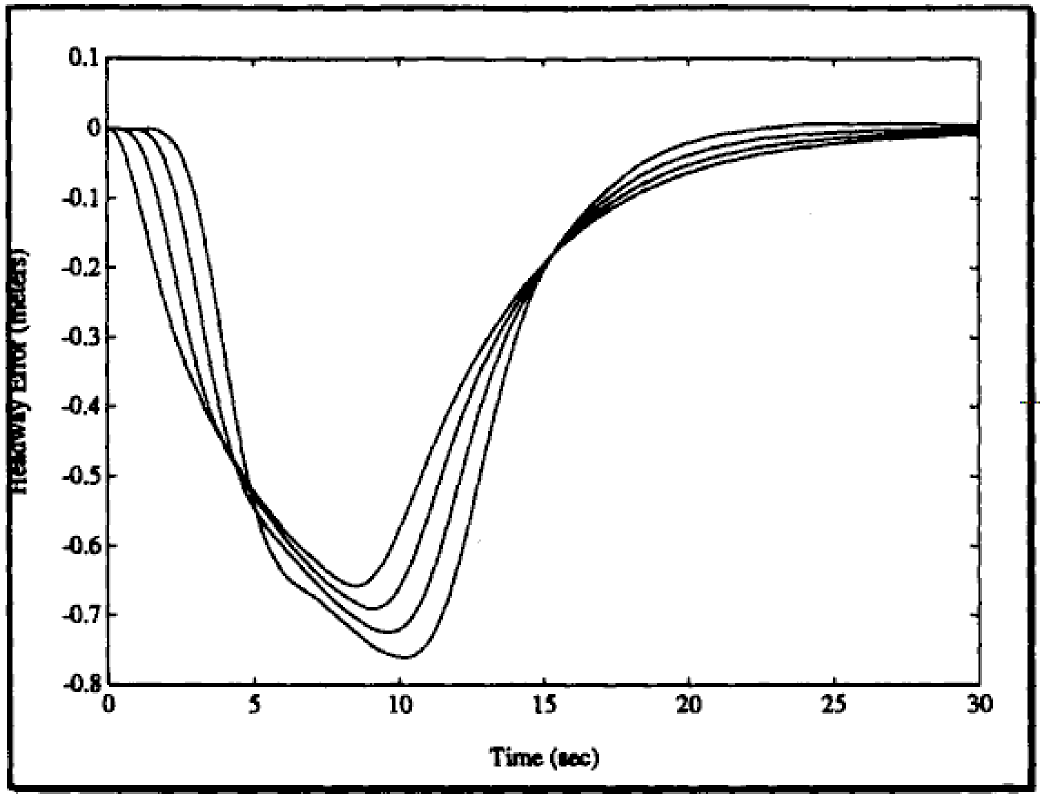


Figure 56. Case #10 Headway Error Plot

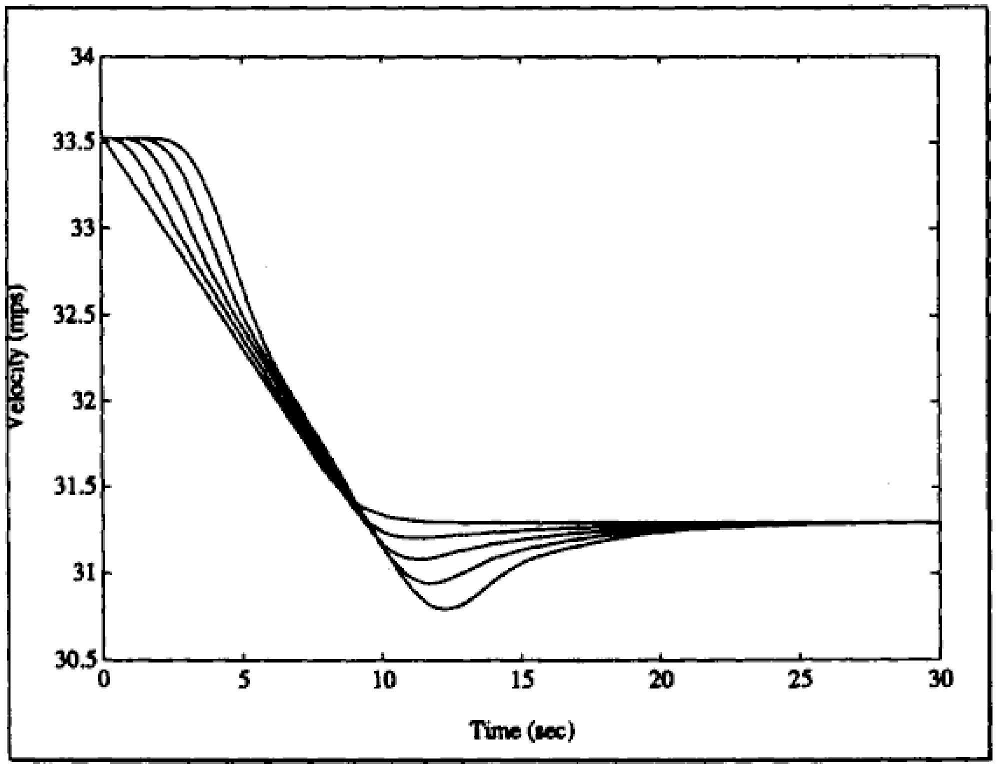


Figure 57. Case #10 Velocity Plot

B.11. Case 11.

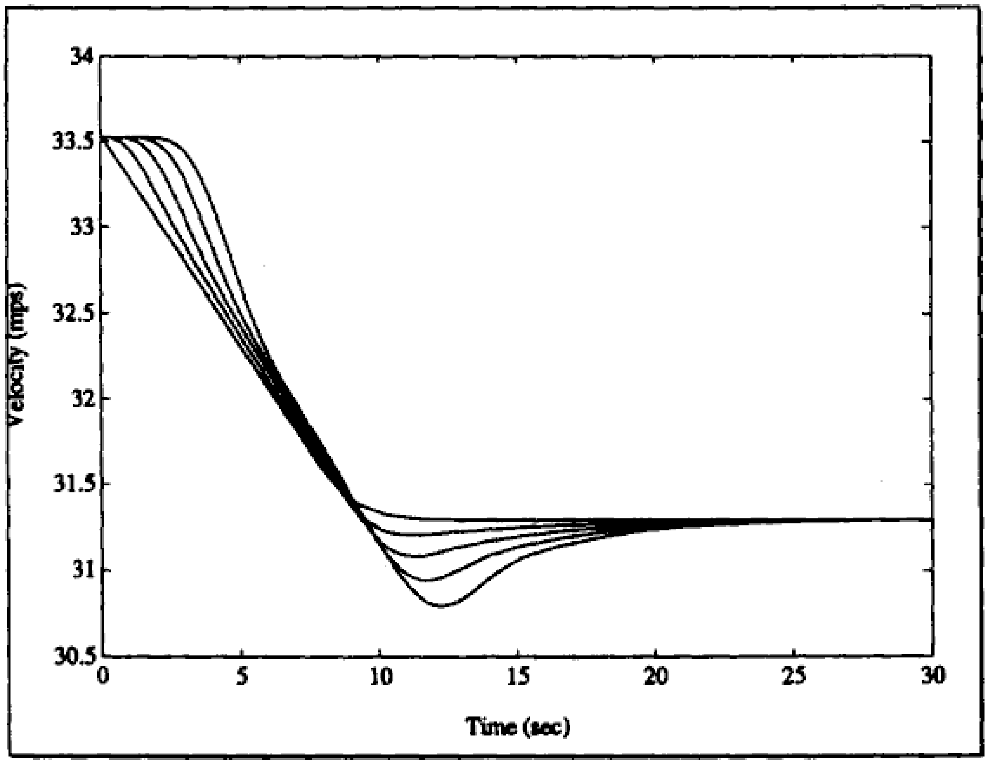


Figure 58. Case #11 Acceleration Plot

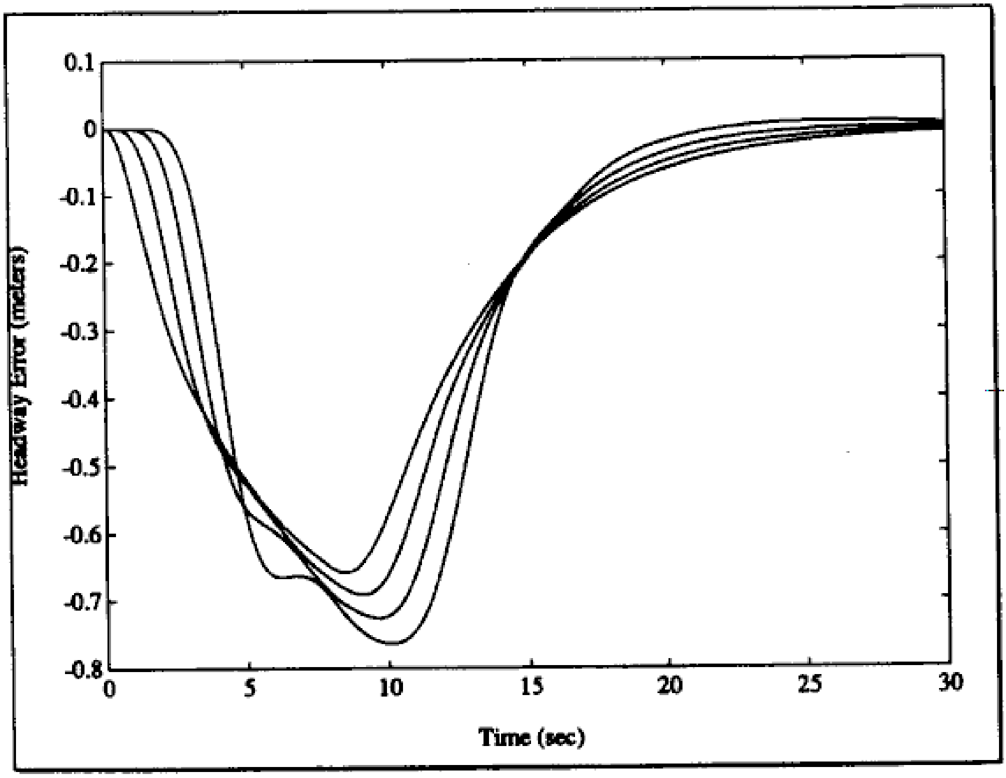


Figure 59. Case #11 Headway Error Plot

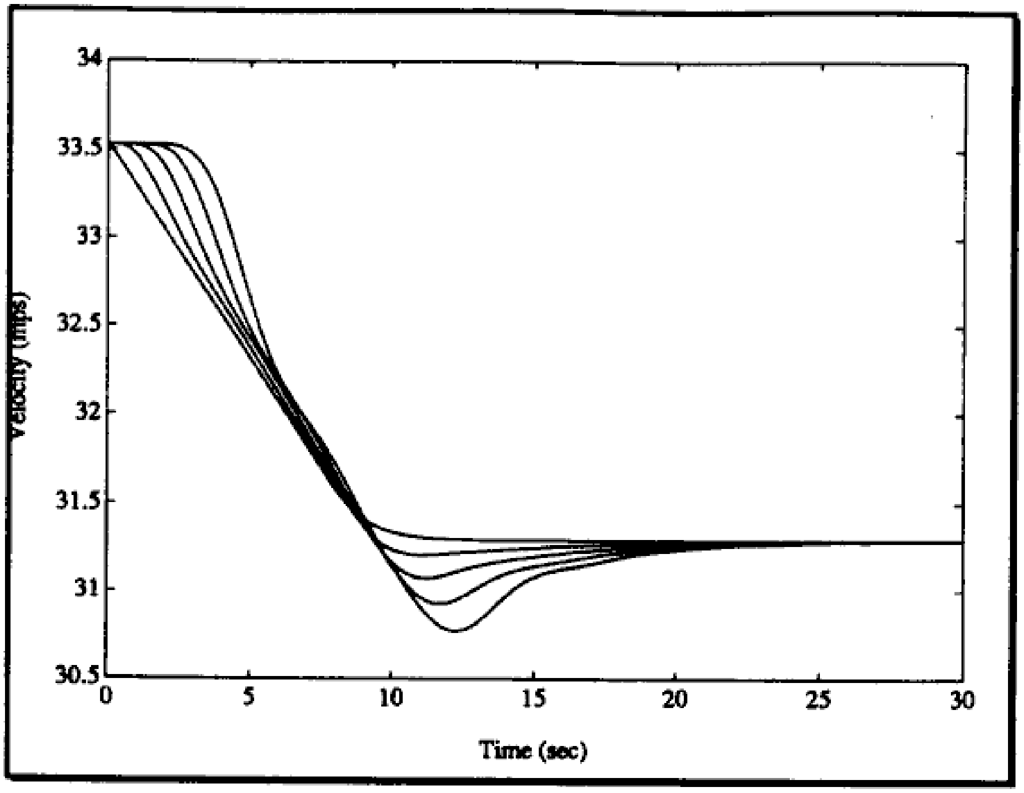


Figure 60. Case #11 Velocity Plot

B.12. Case 12.

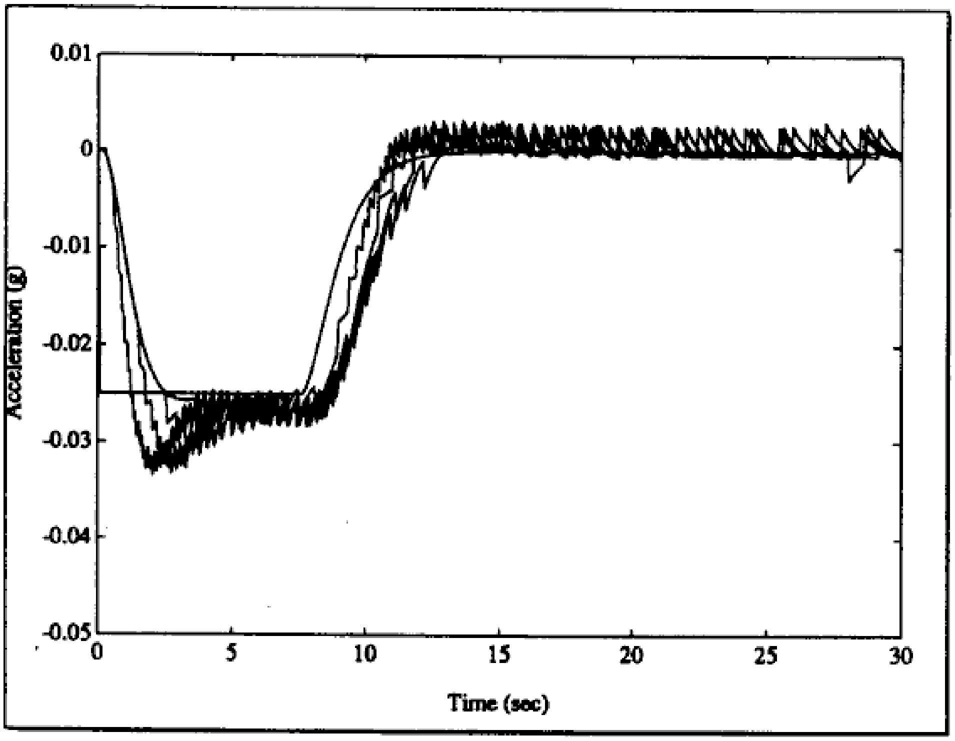


Figure 61. Case #12 Acceleration Plot

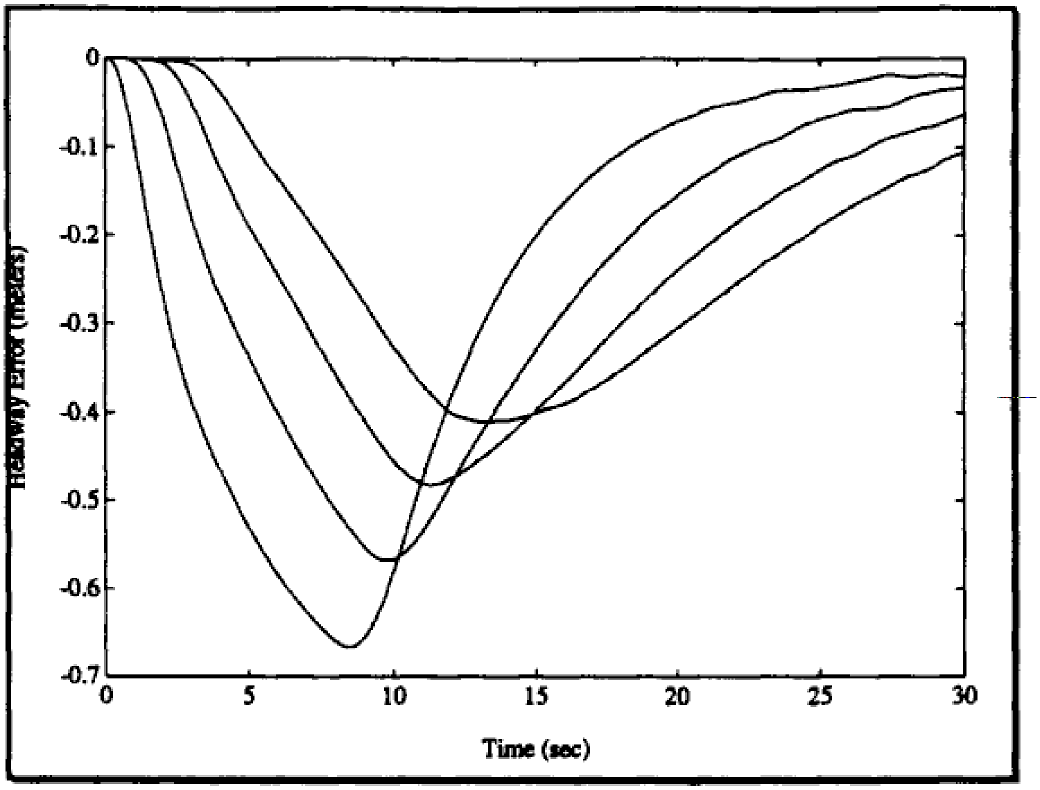


Figure 62. Case #12 Headway Error Plot

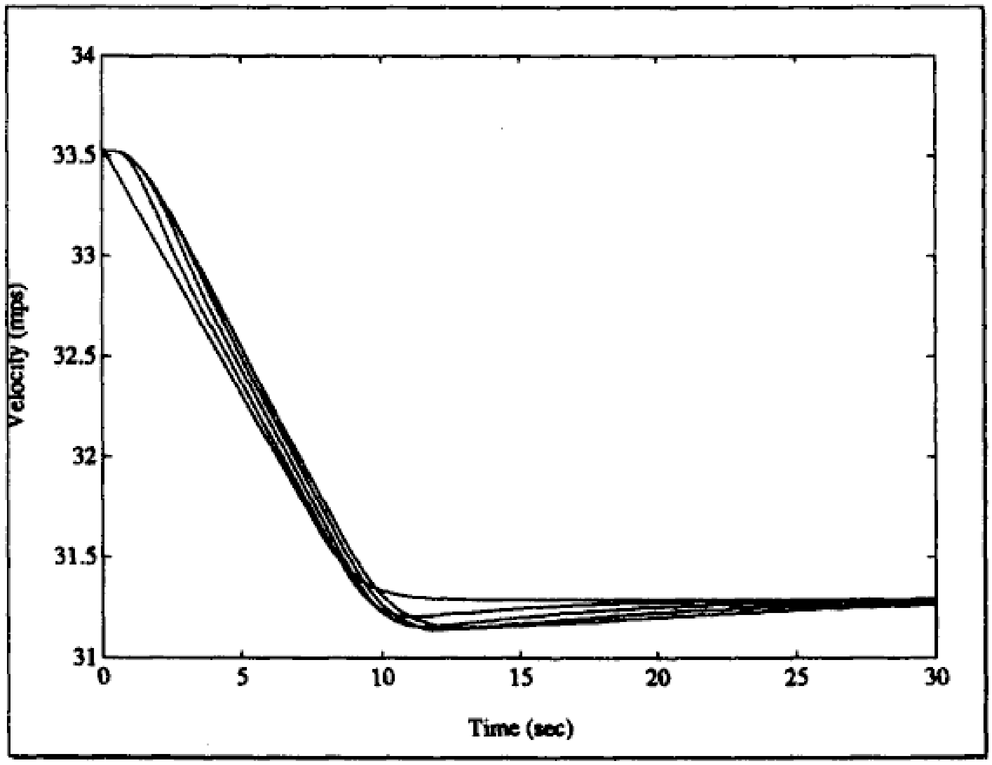


Figure 63. Case #12 Velocity Plot

B.13 Case 13.

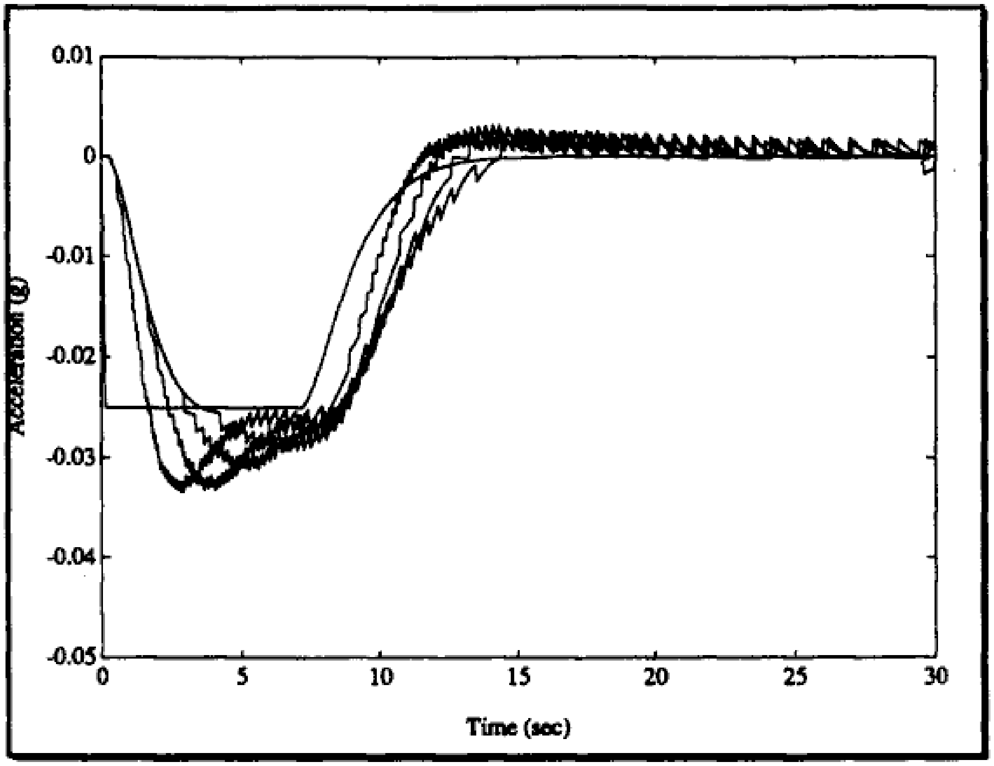


Figure 64. Case #13 Acceleration Plot

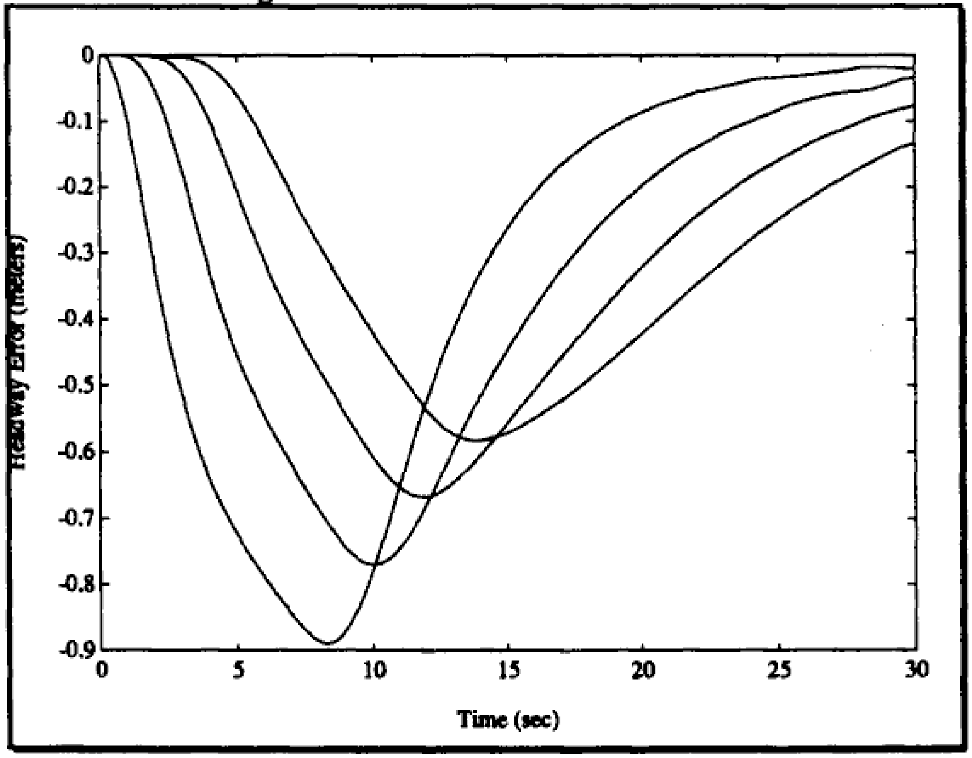


Figure 65. Case #13 Headway ~ Plot

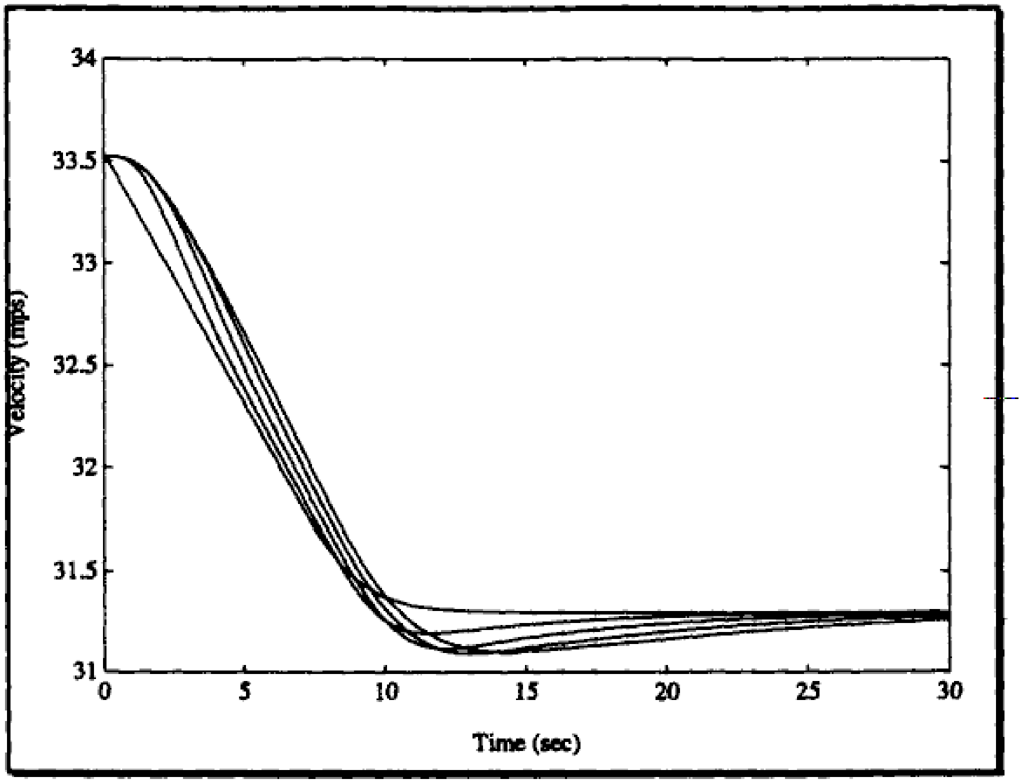


Figure 66. Case #13 Velocity Plot

B.14 Case 14.

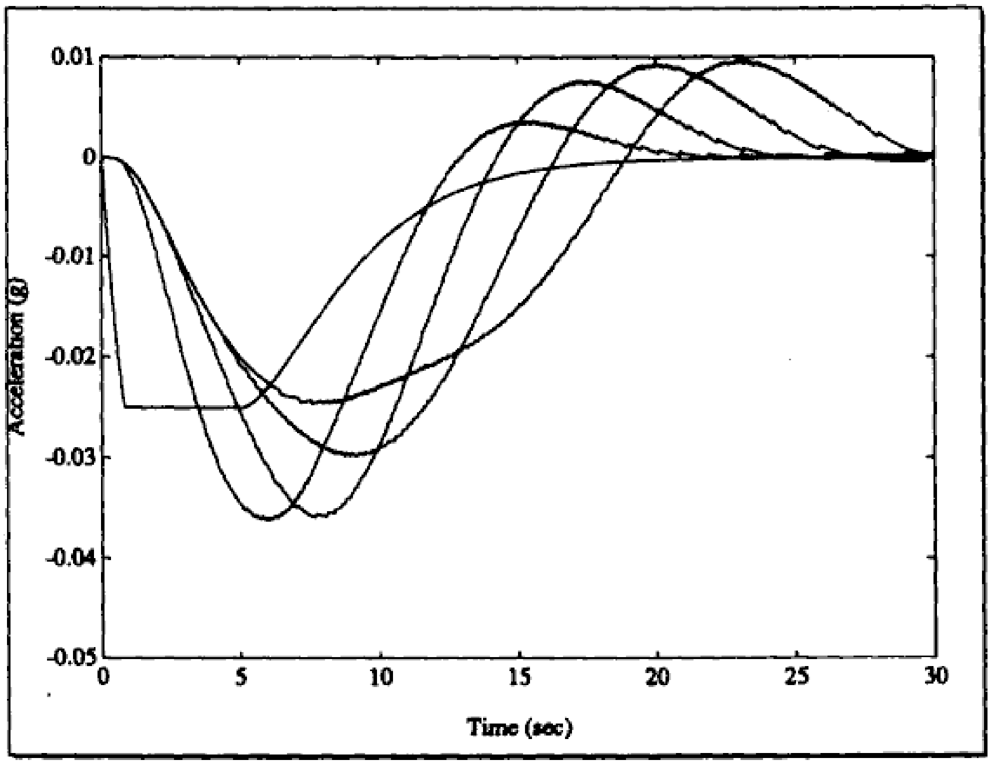


Figure 67. Case #14 Acceleration Plot

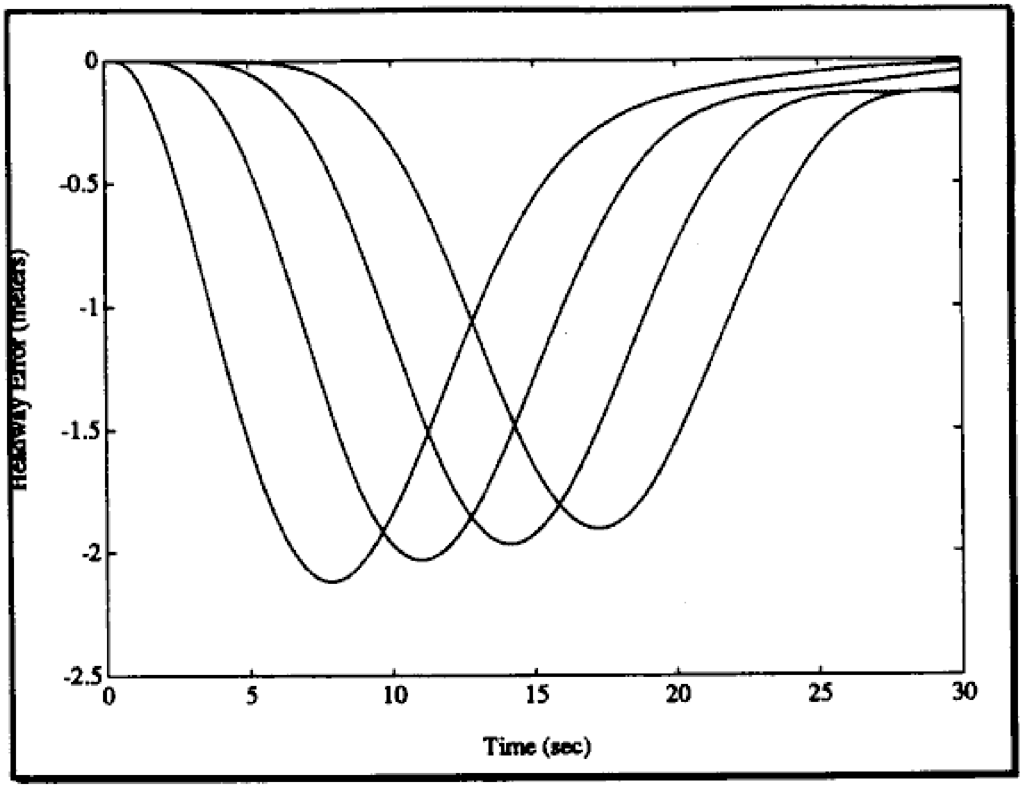


Figure 68. Case #14 Headway Error Plot

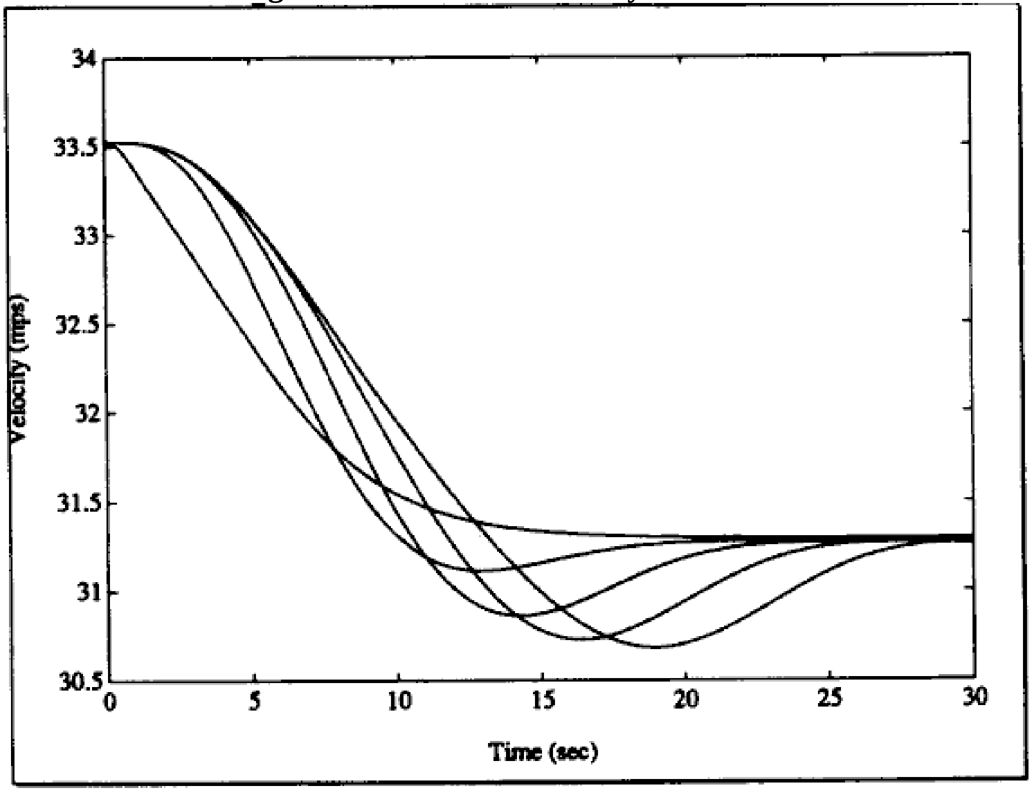


Figure 69. Case #14 Velocity Plot

B.15 Case 15.

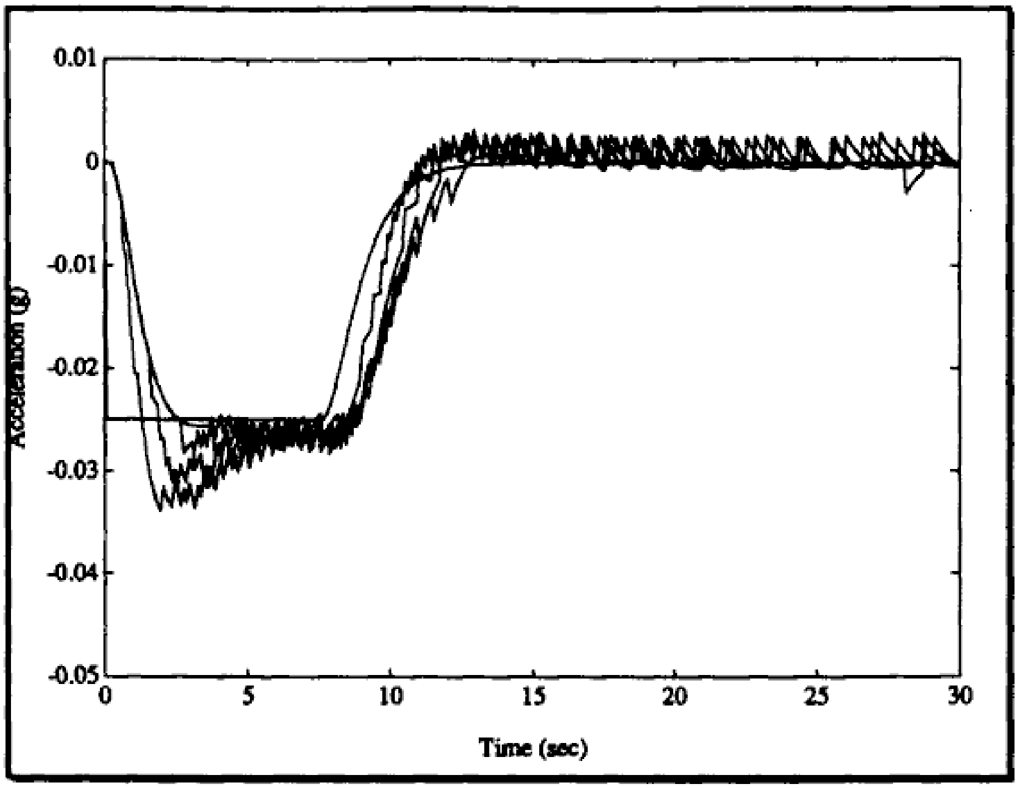


Figure 70. Case #15 Acceleration Plot

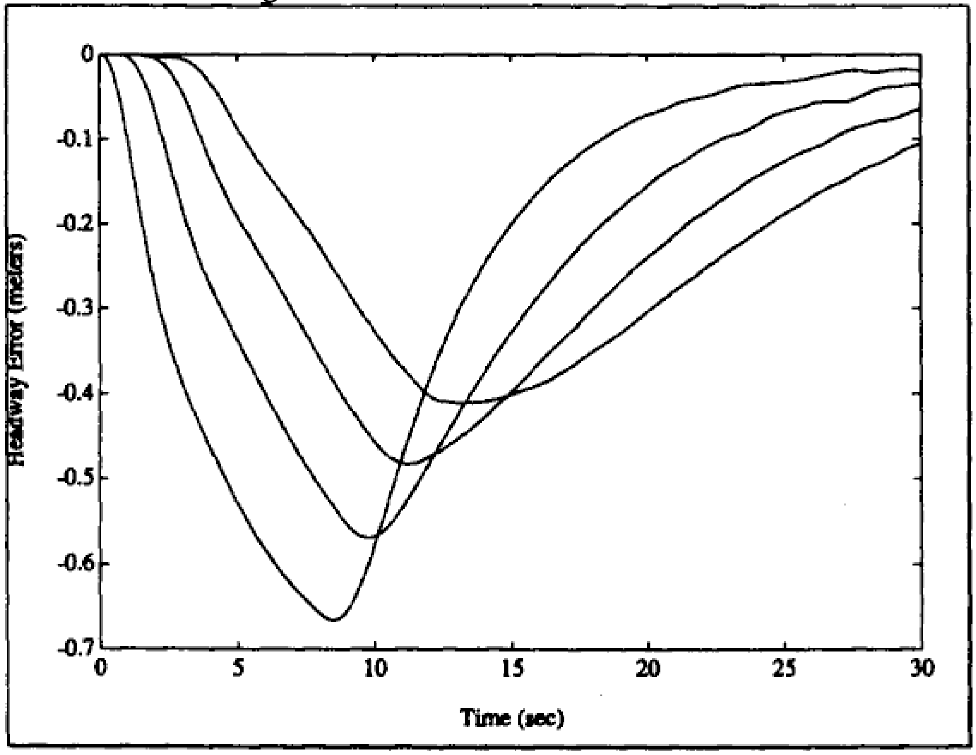


Figure 71. Case #15 Headway Error Plot

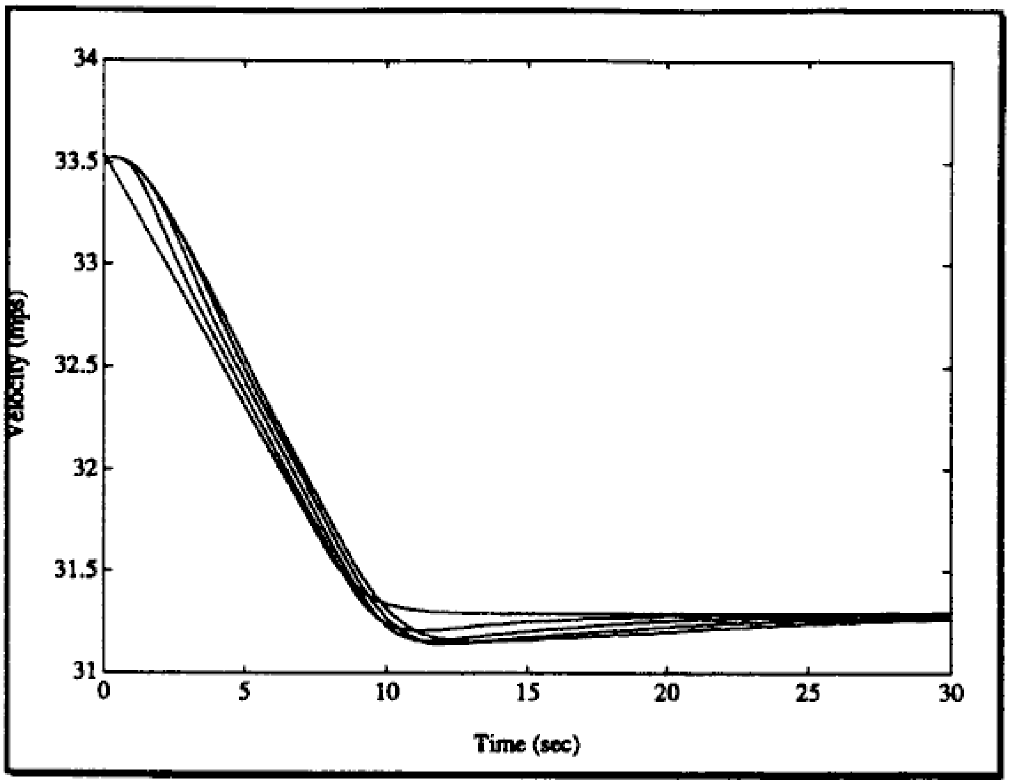
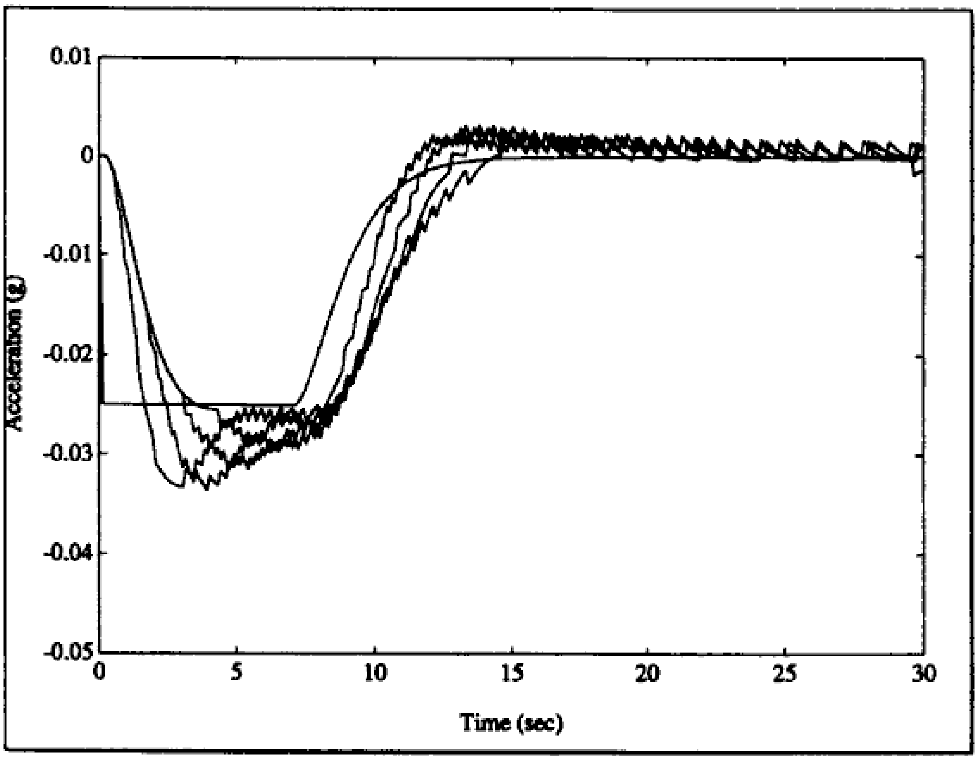


Figure 72. Case #15 Velocity Plot

B.16 Case 16.



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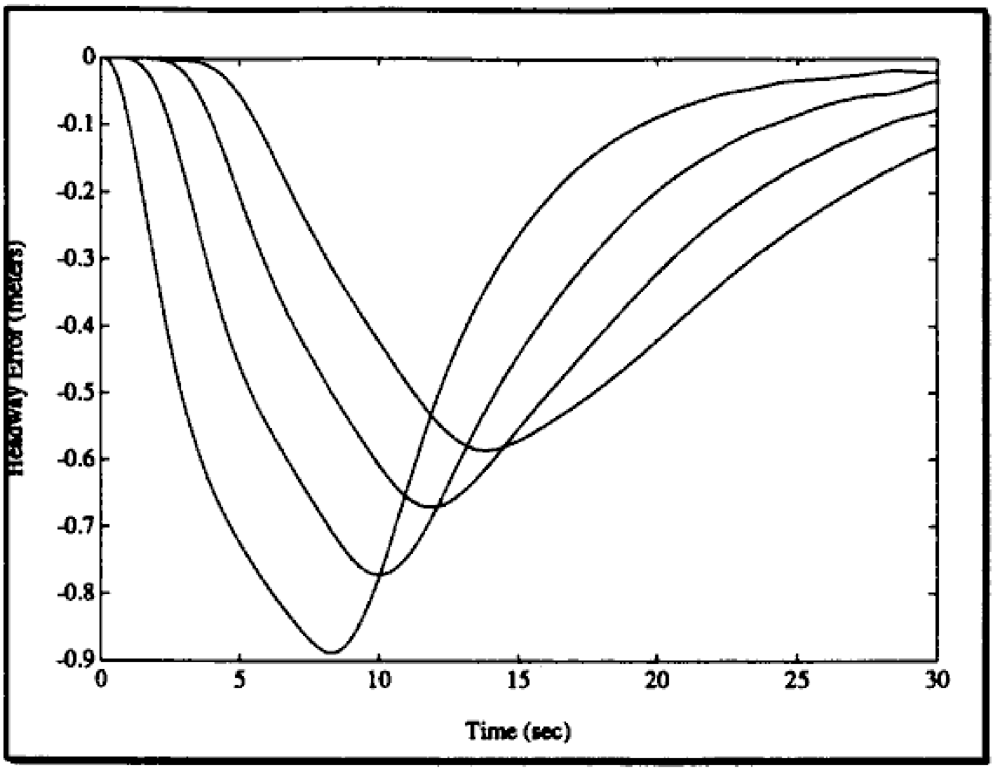

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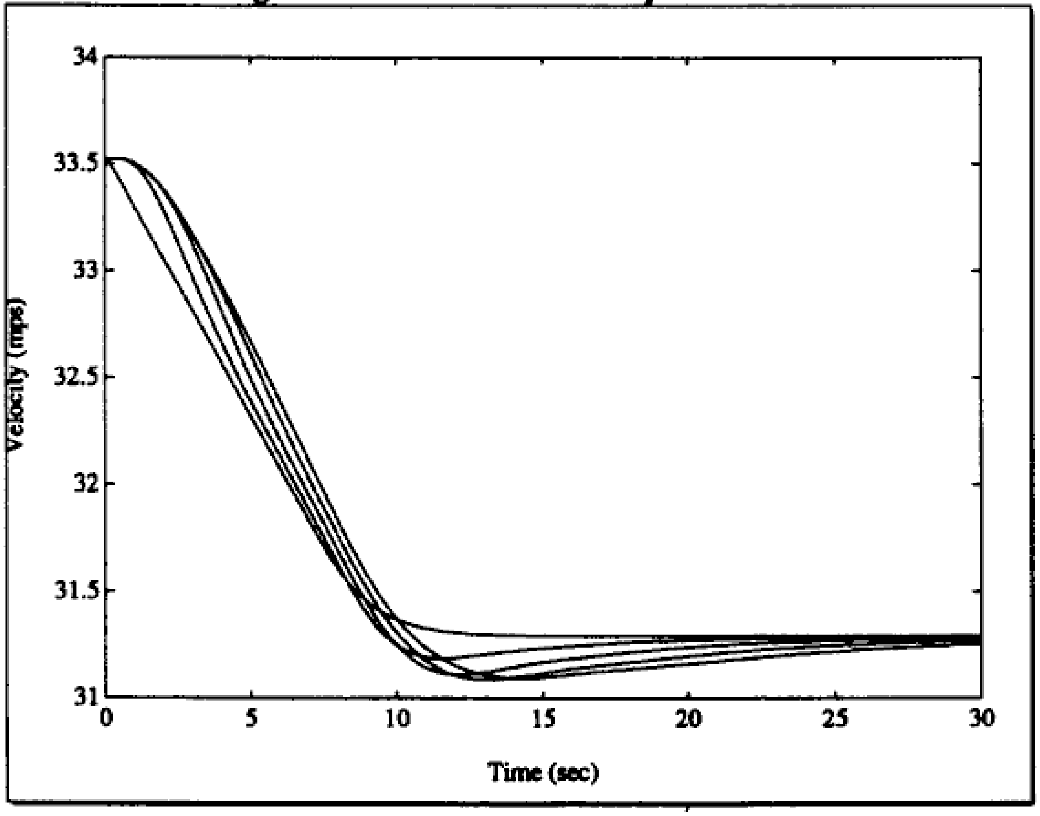
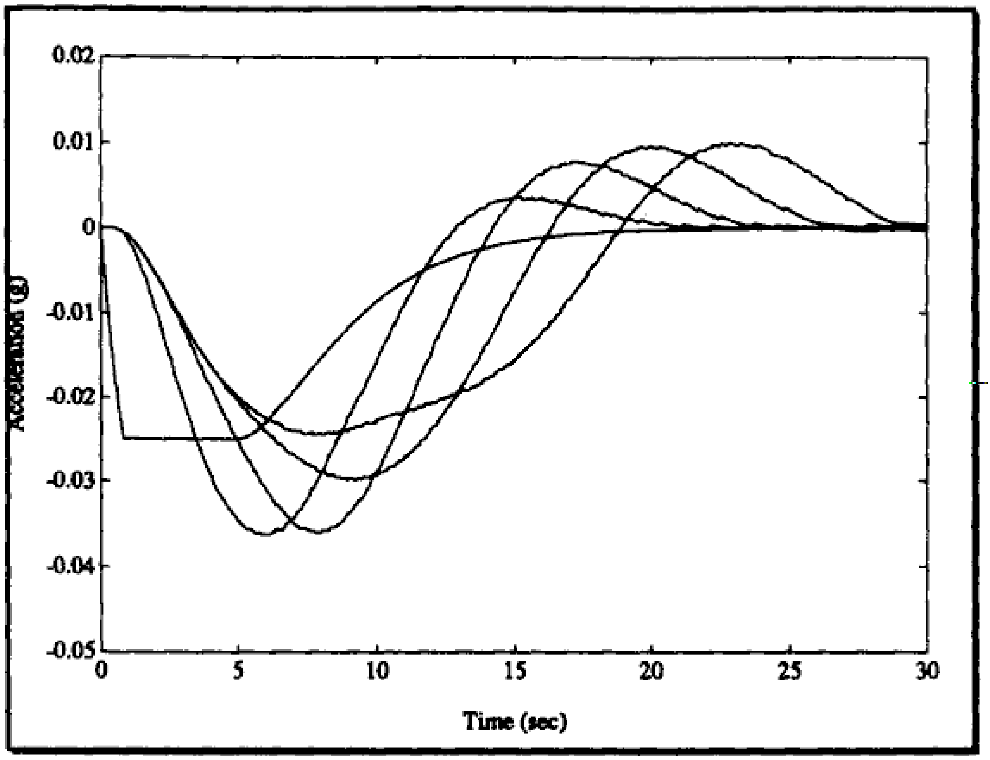


Figure 75. Case #16 Velocity Plot

B.17 Case 17.



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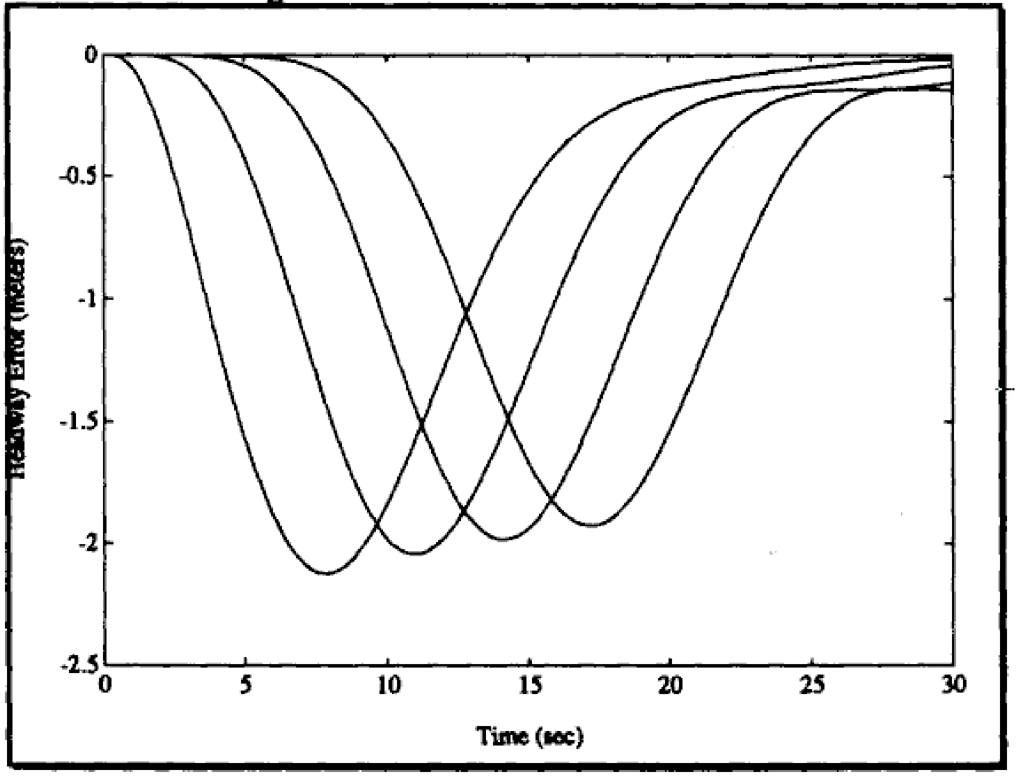


Figure 77. Case #17 Headway Error Plot

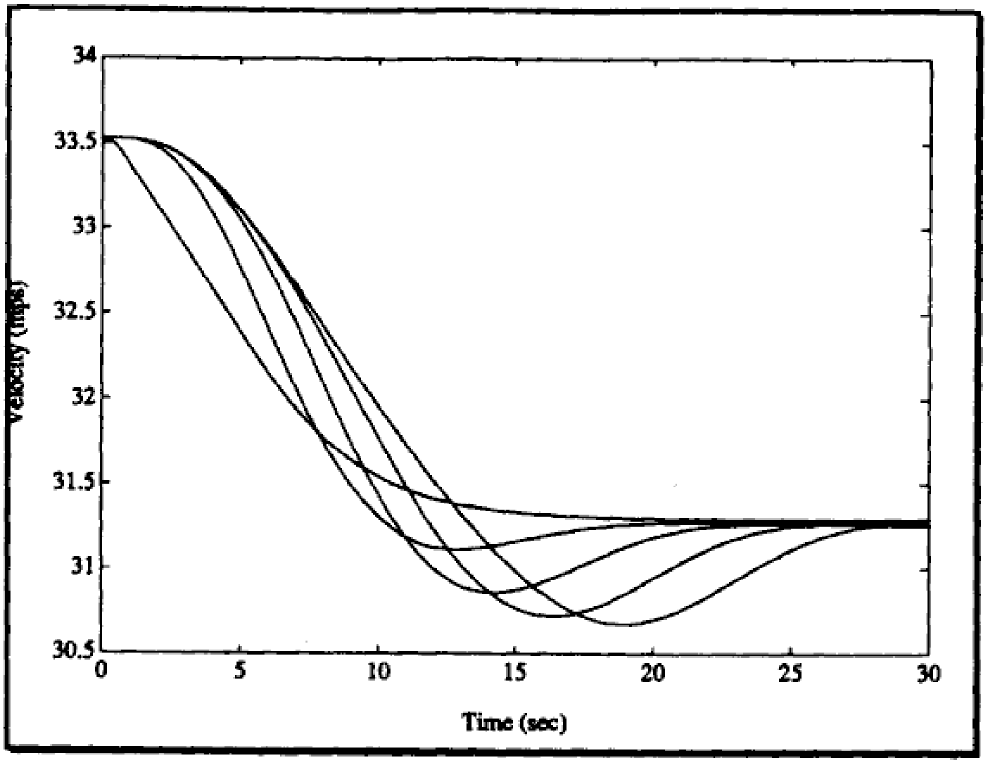


Figure 78. Case #17 Velocity Plot

B.18 Case 18.

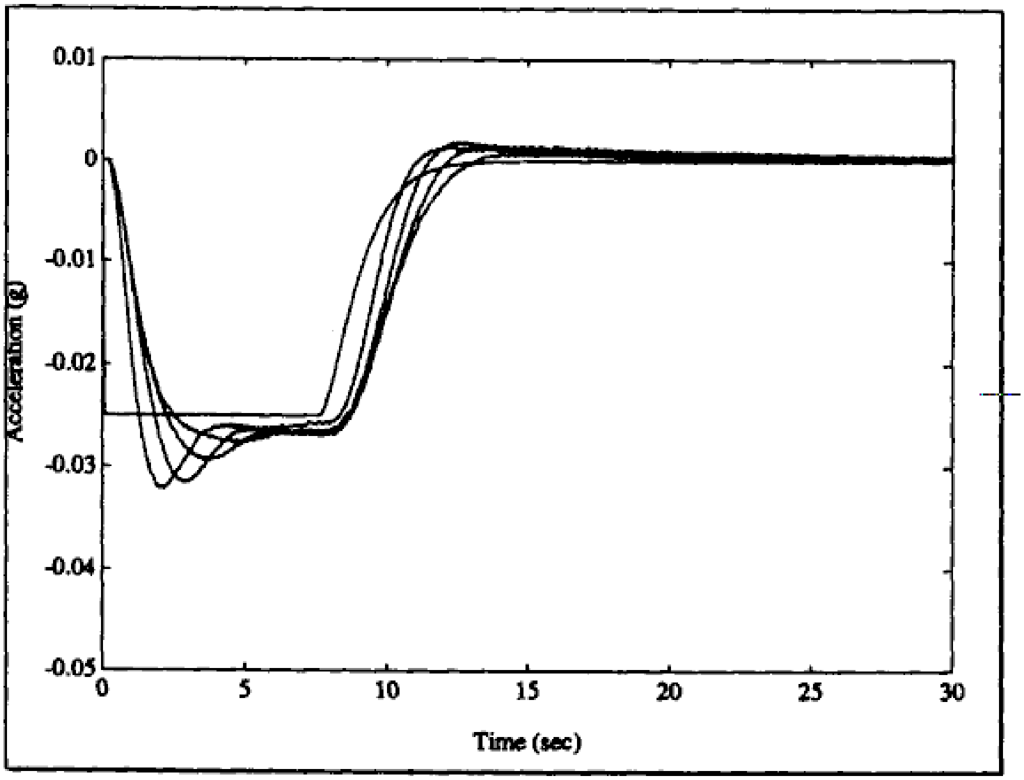


Figure 79. Case #18 Acceleration Plot

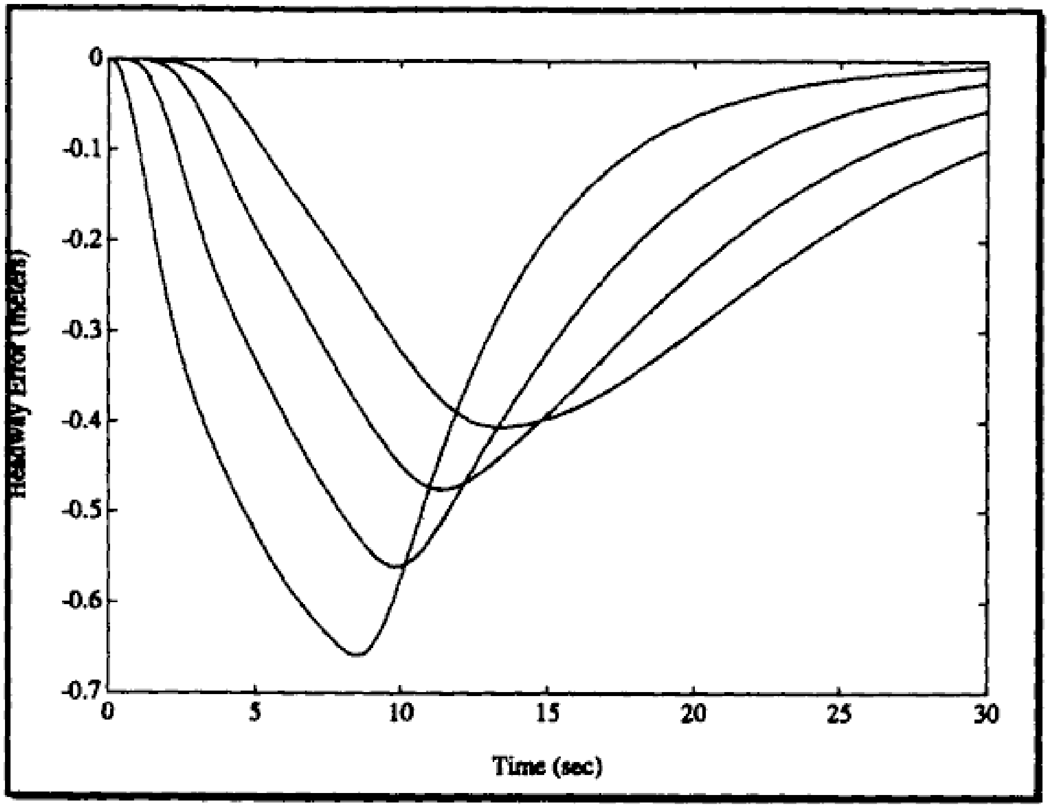


Figure 80. Case #18 Headway Error Plot

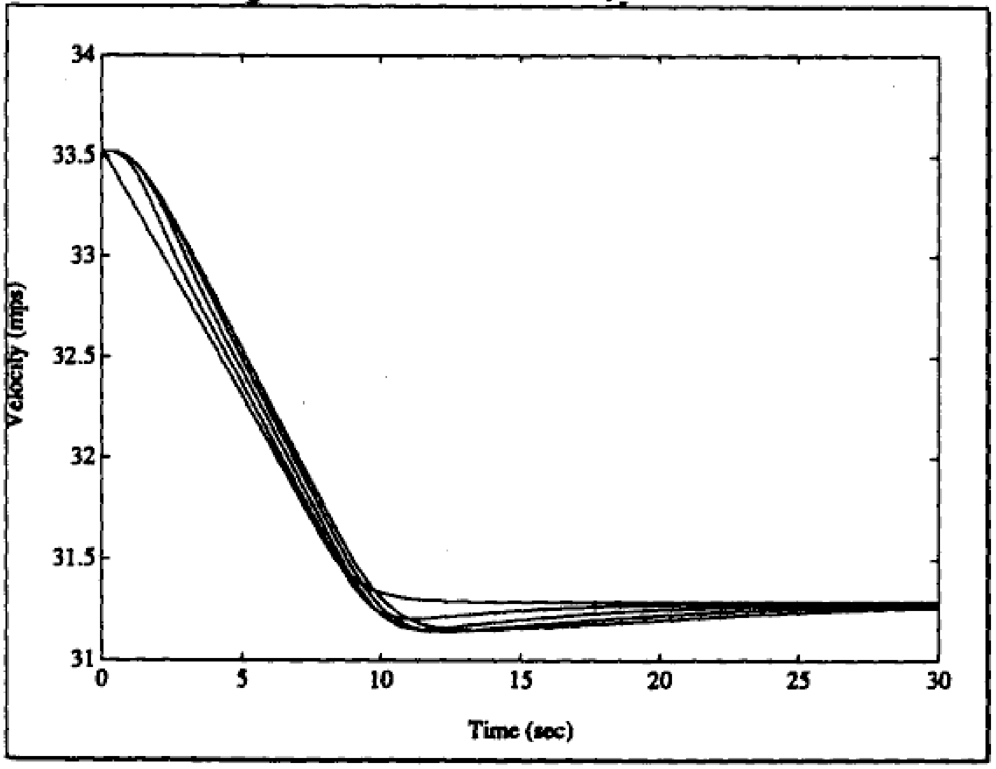
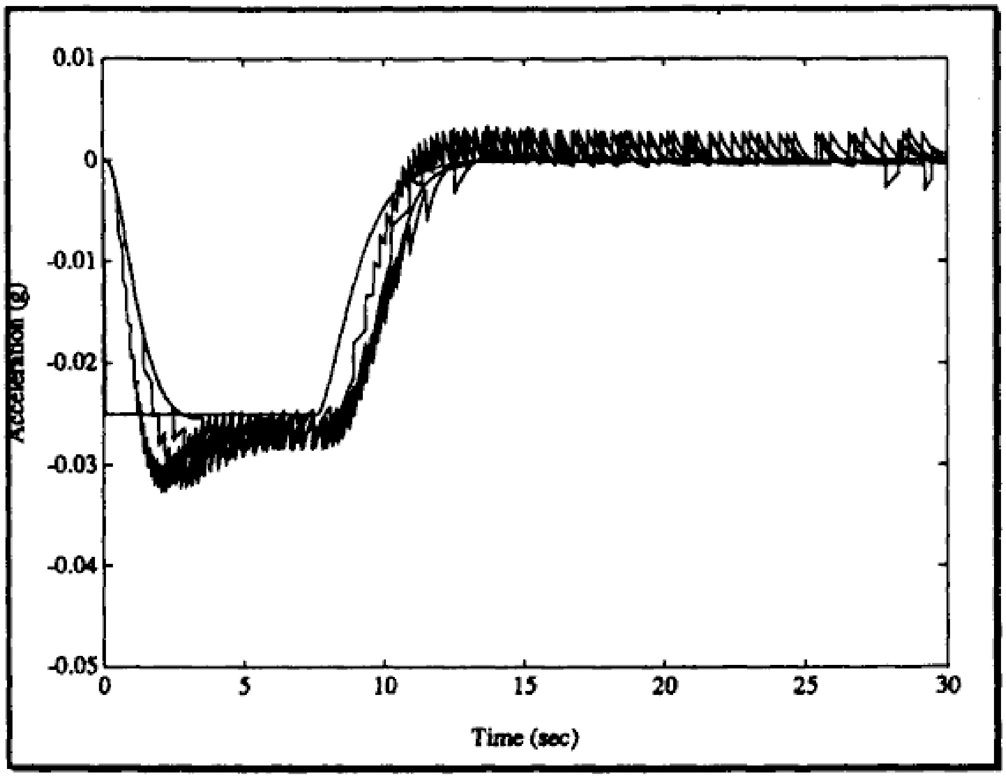


Figure 81. Case #18 Velocity Plot

B.19 Case 19.



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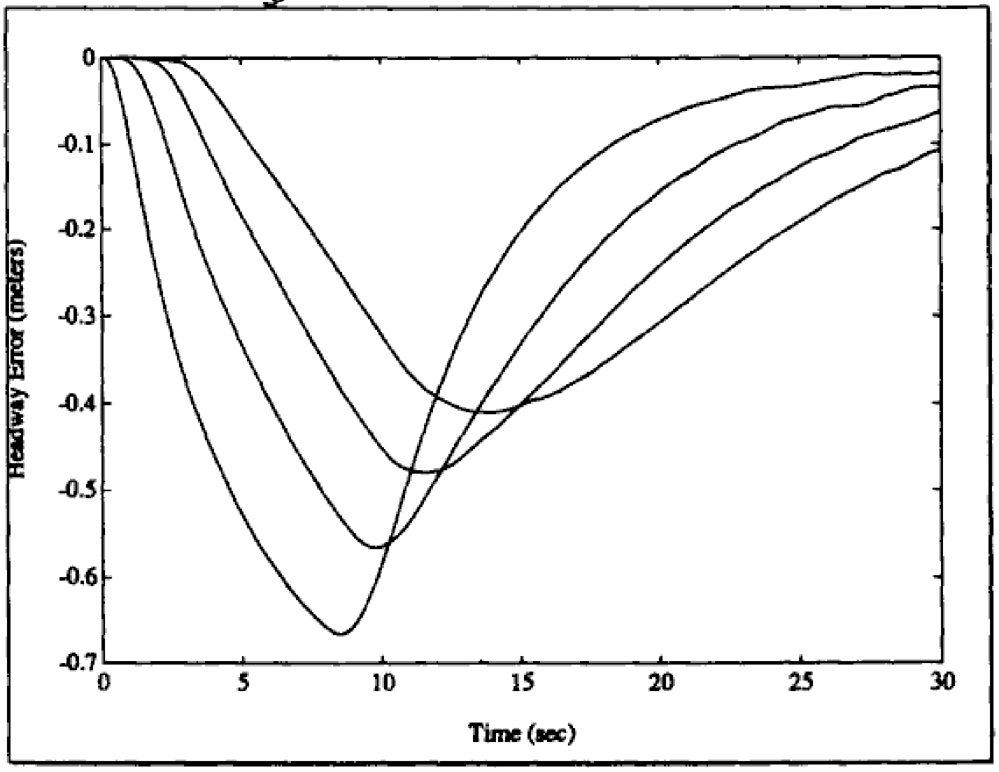


Figure 83. Case #19 Headway Error Plot

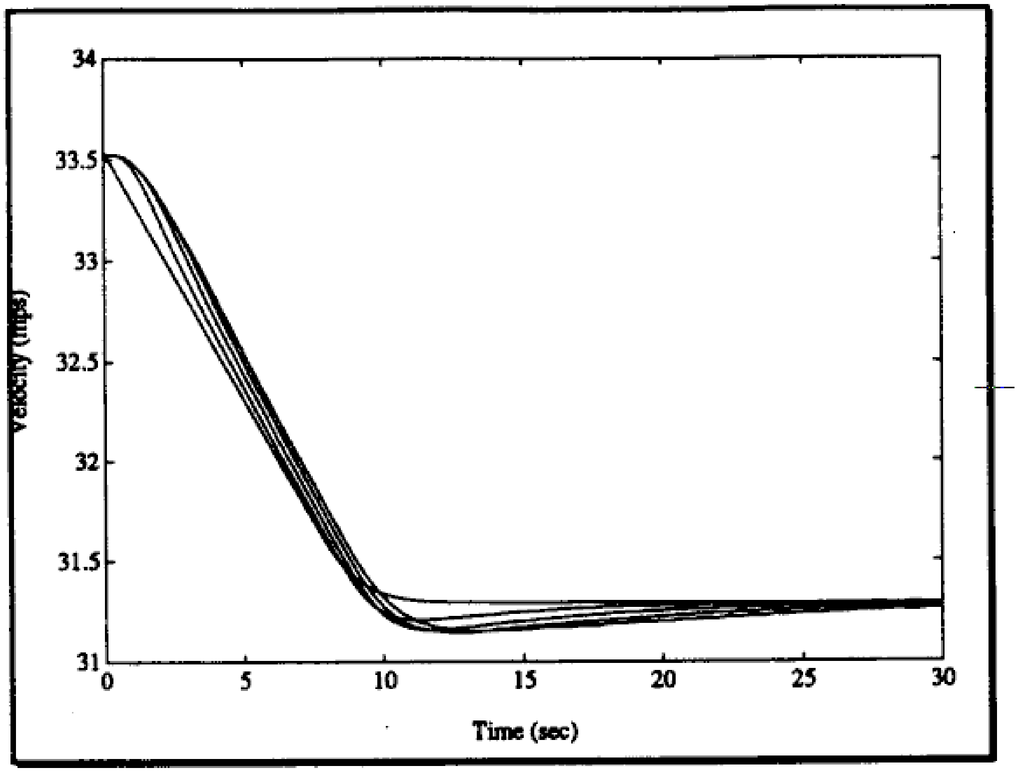


Figure 84. Case #19 Velocity Plot

B.20 Case 20.

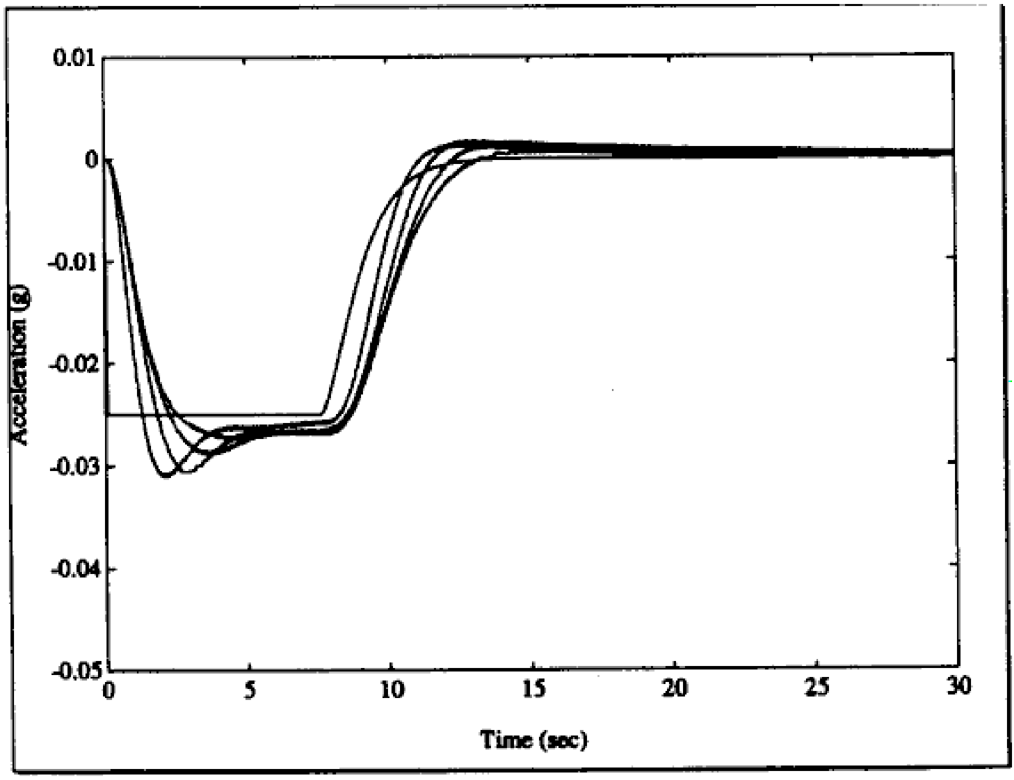


Figure 85. Case #20 Acceleration Plot

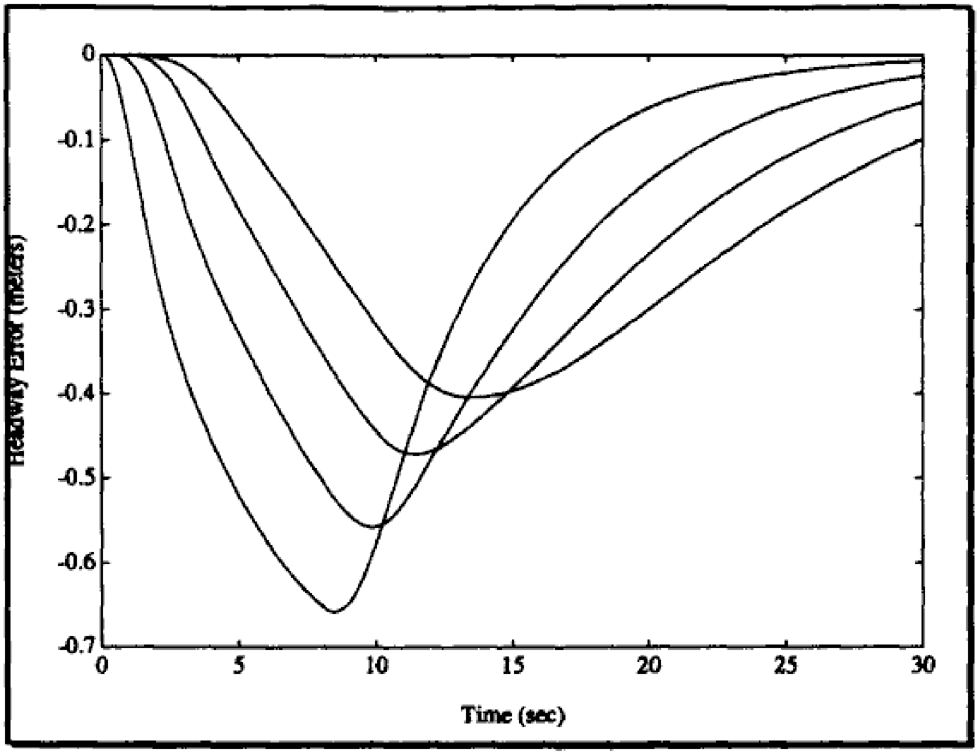


Figure 86. Case #20 Headway Error Plot

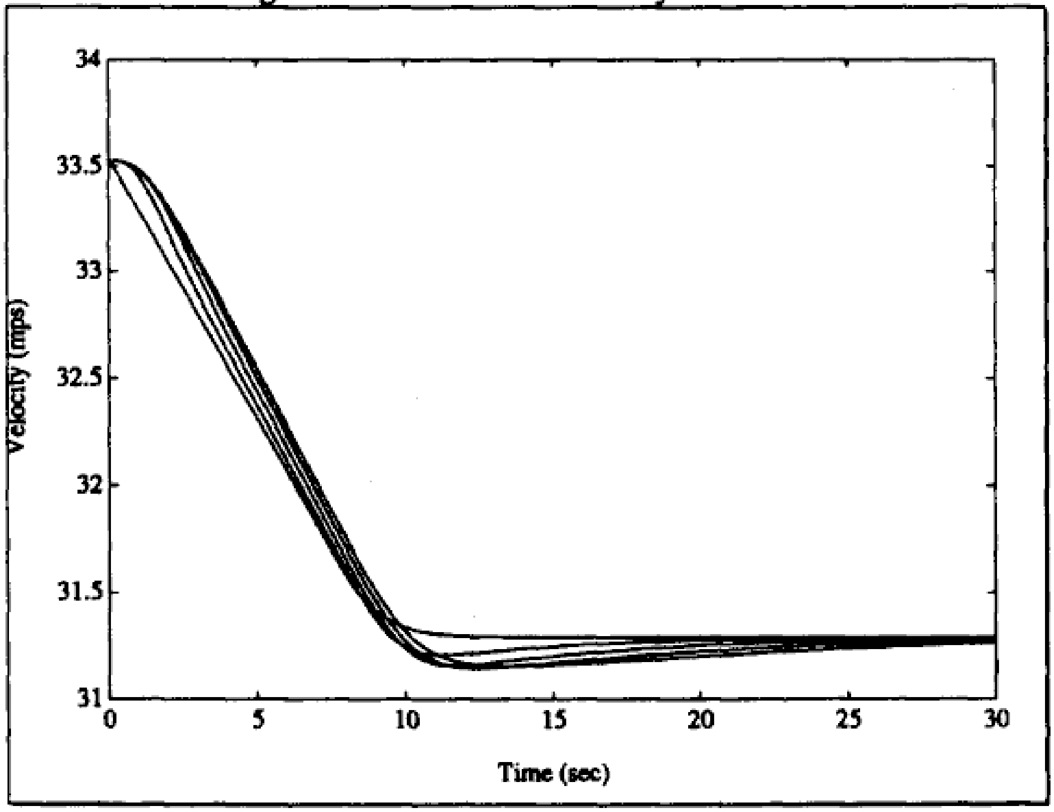


Figure 87. Case #20 Velocity Plot

B.21 Case 21.

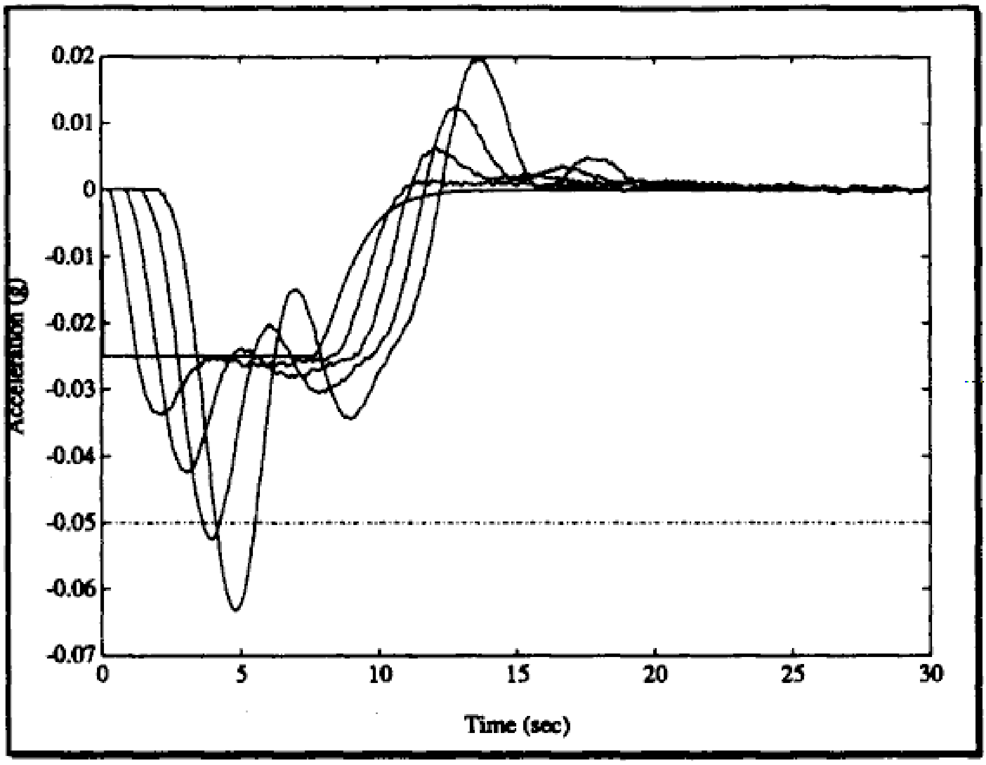


Figure 88. Case #21 Acceleration Plot

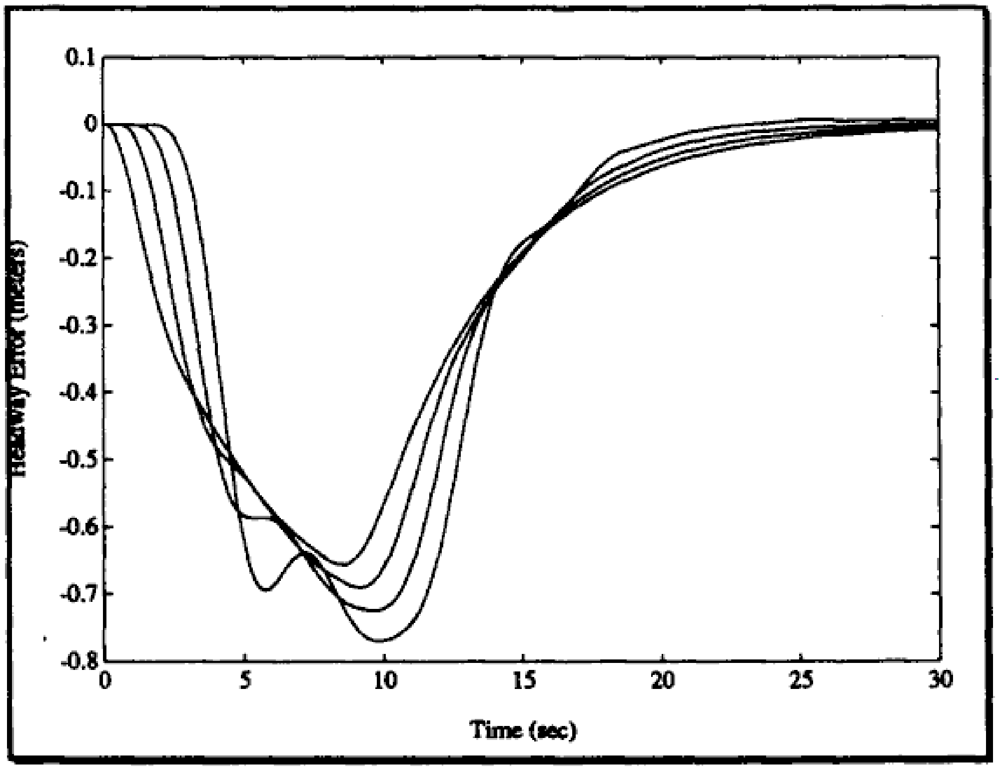


Figure 89. Case #21 Headway Error Plot

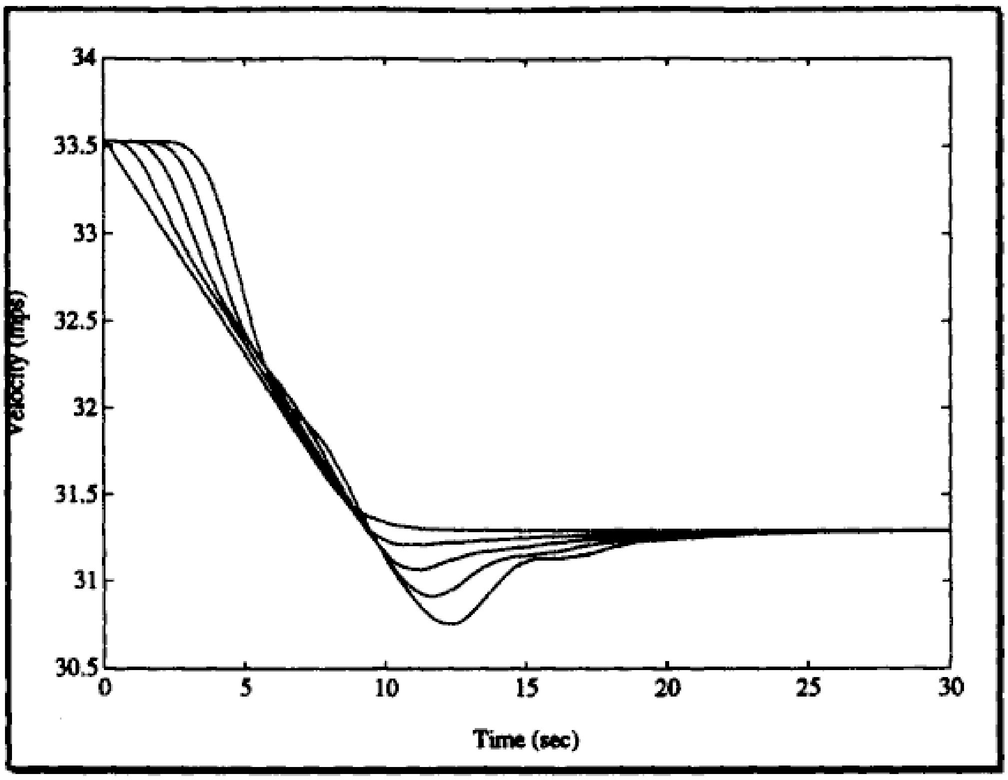


Figure 90. Case #21 Velocity Plot

B.22 Case 22.

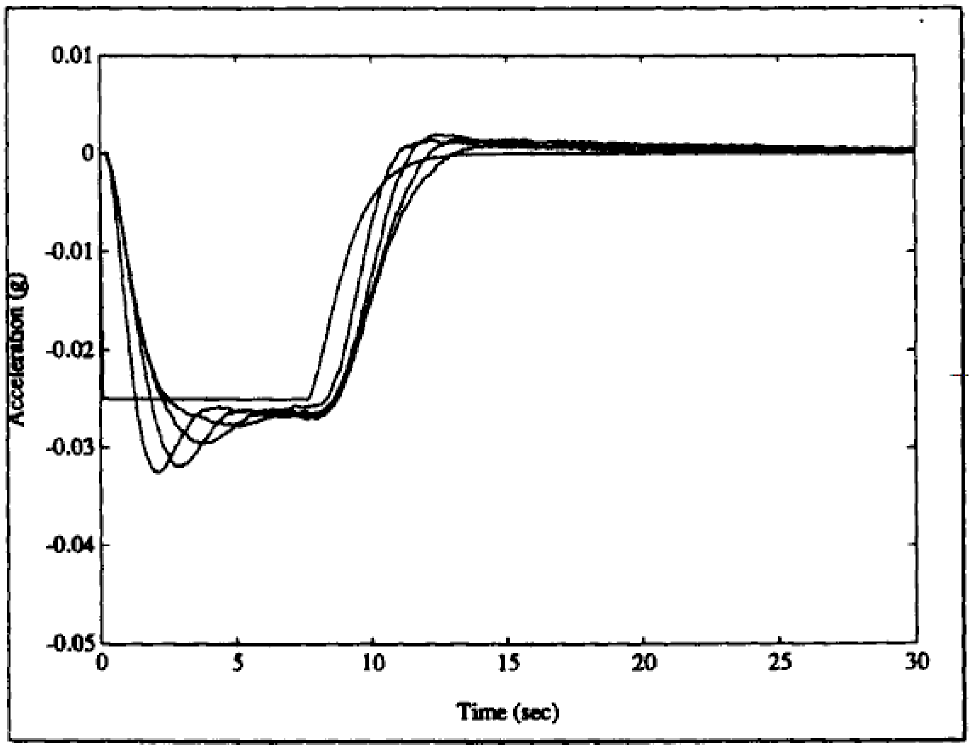


Figure 91. Case #22 Acceleration Plot

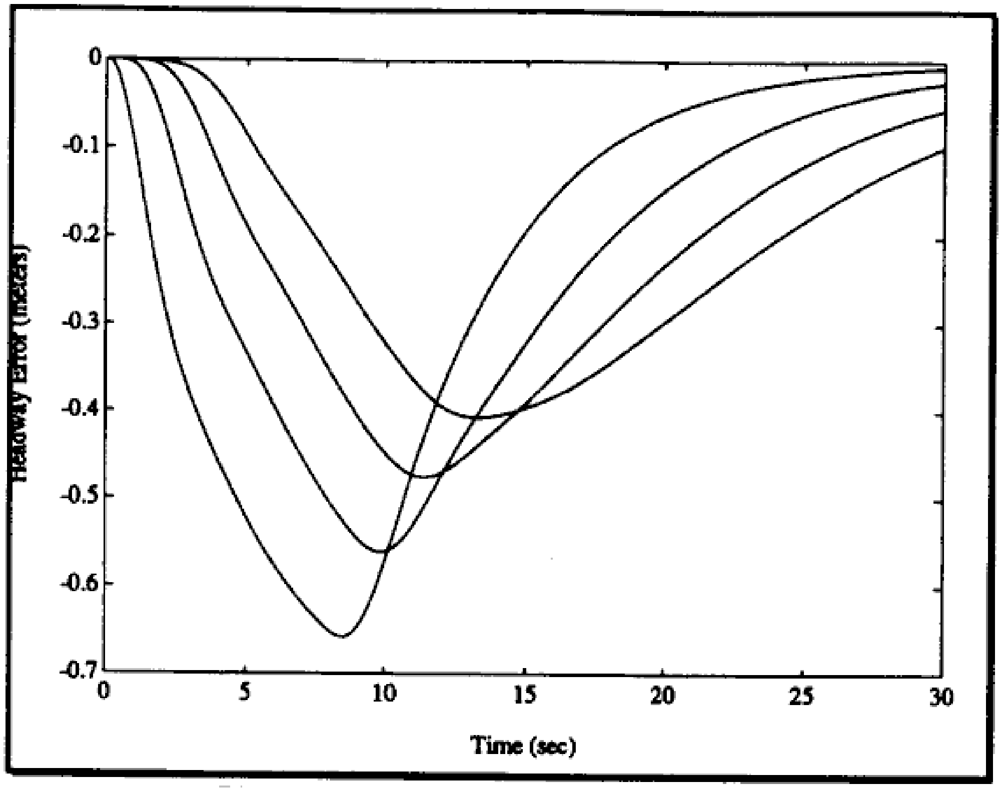


Figure 92. Case #22 Headway Error Plot

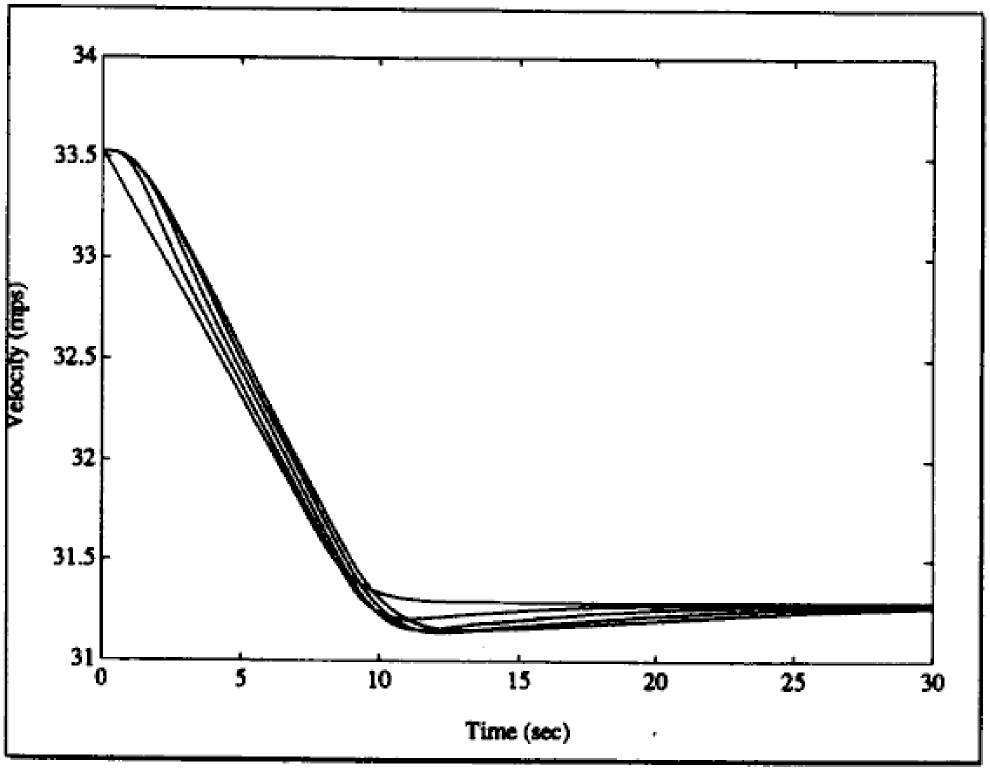
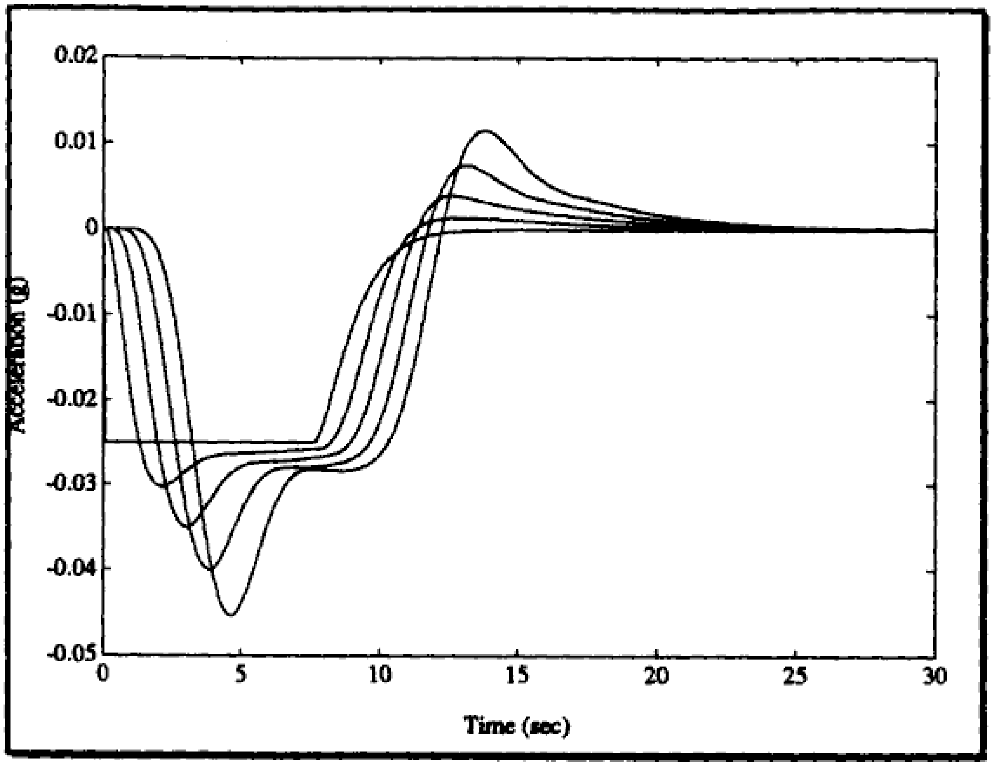


Figure 93. Case #22 Velocity Plot

B.23 Case 23.



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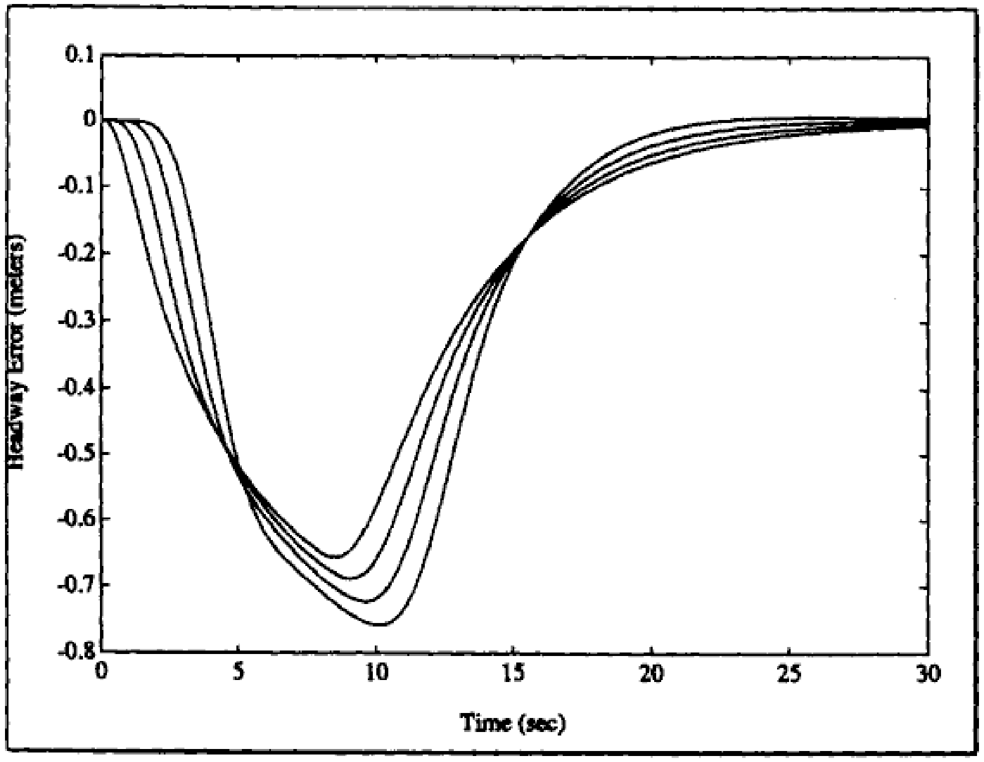

Figure 95. Case #23 Headway Error Plot

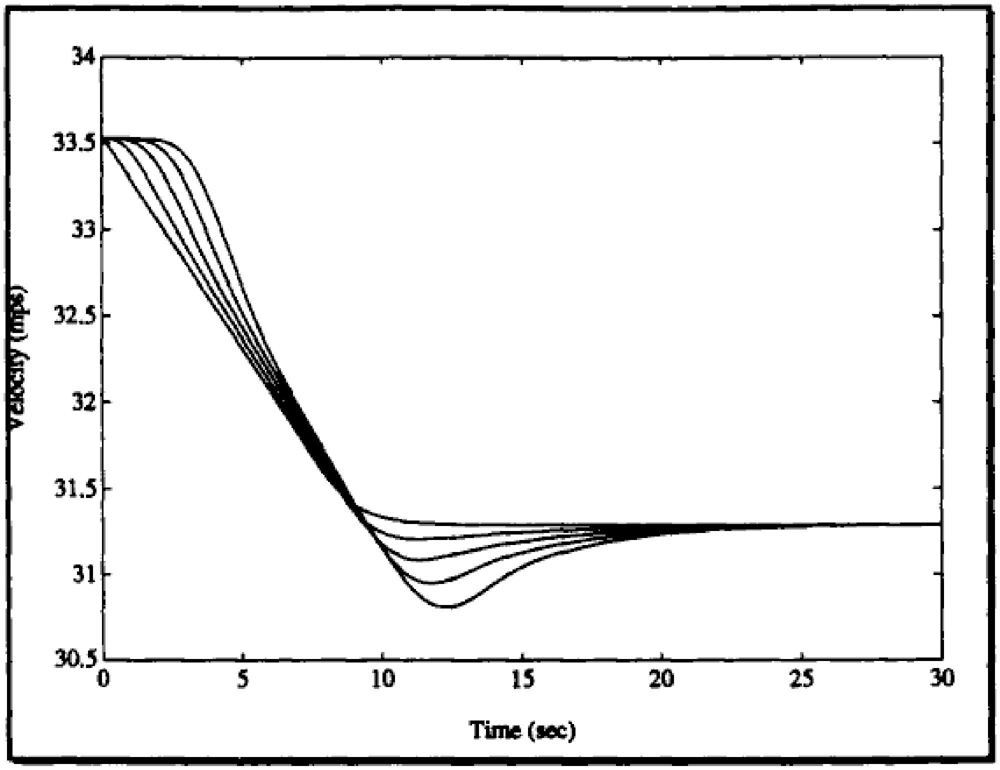

Figure 96. Case #23 Velocity Plot

B.24 Case 24.

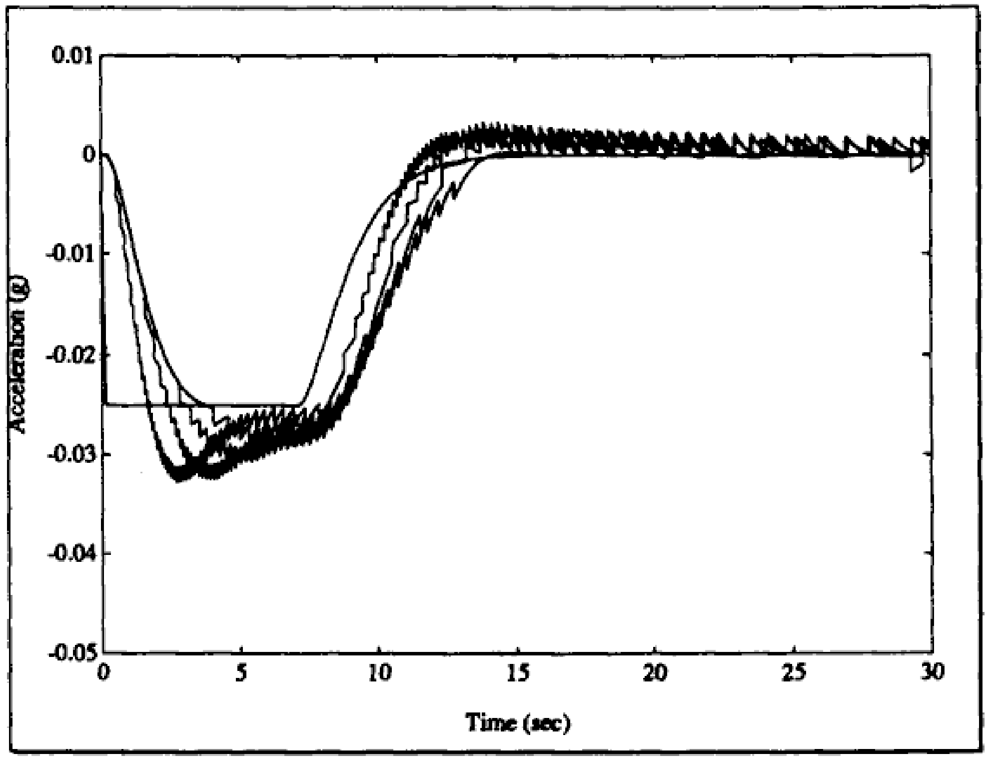

Figure 97. Case #24 Acceleration Plot

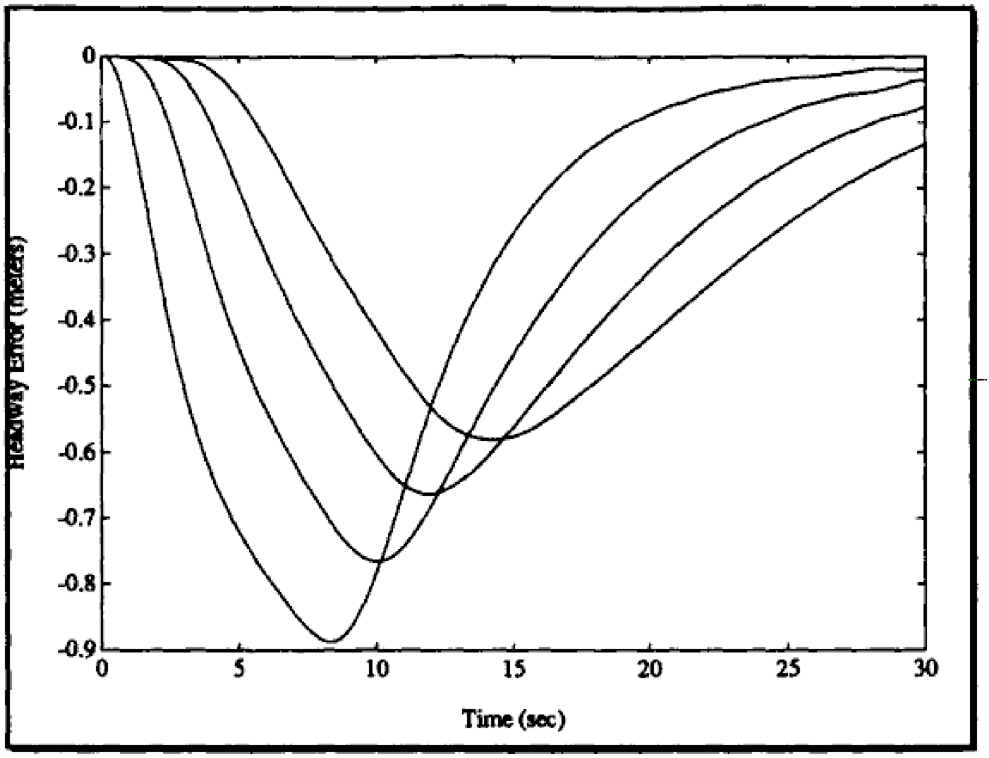

Figure 98. Case #24 Headway Error Plot

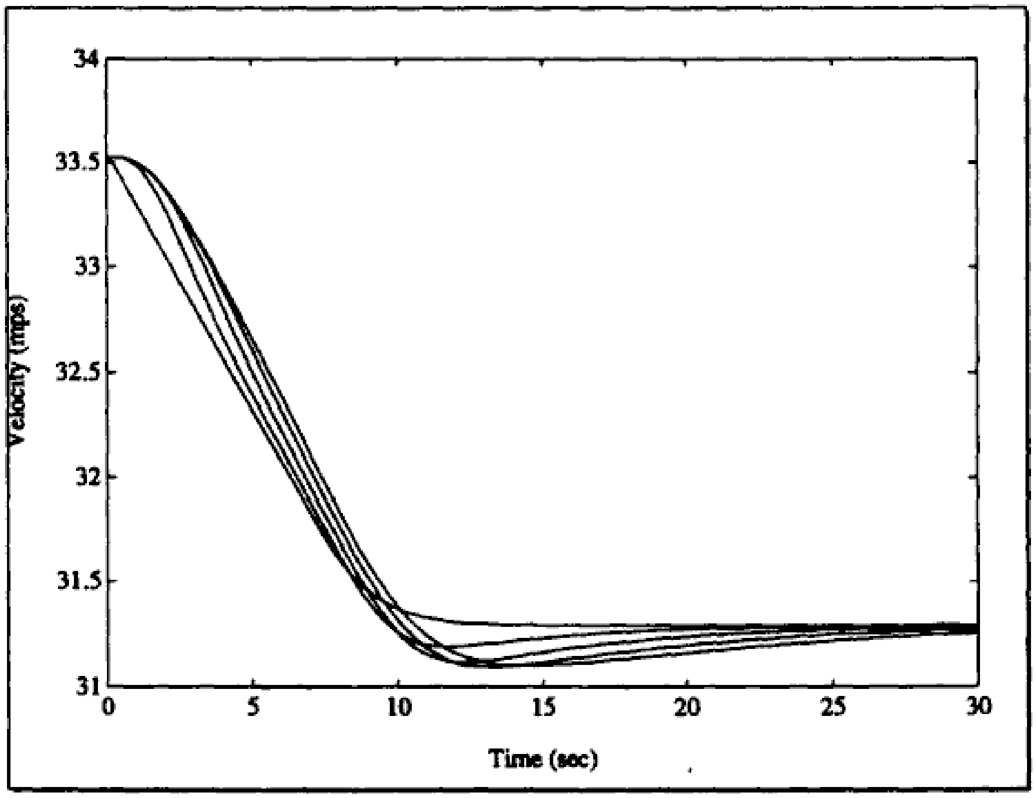

Figure 99. Case #24 Velocity Plot

B.25 Case 25.

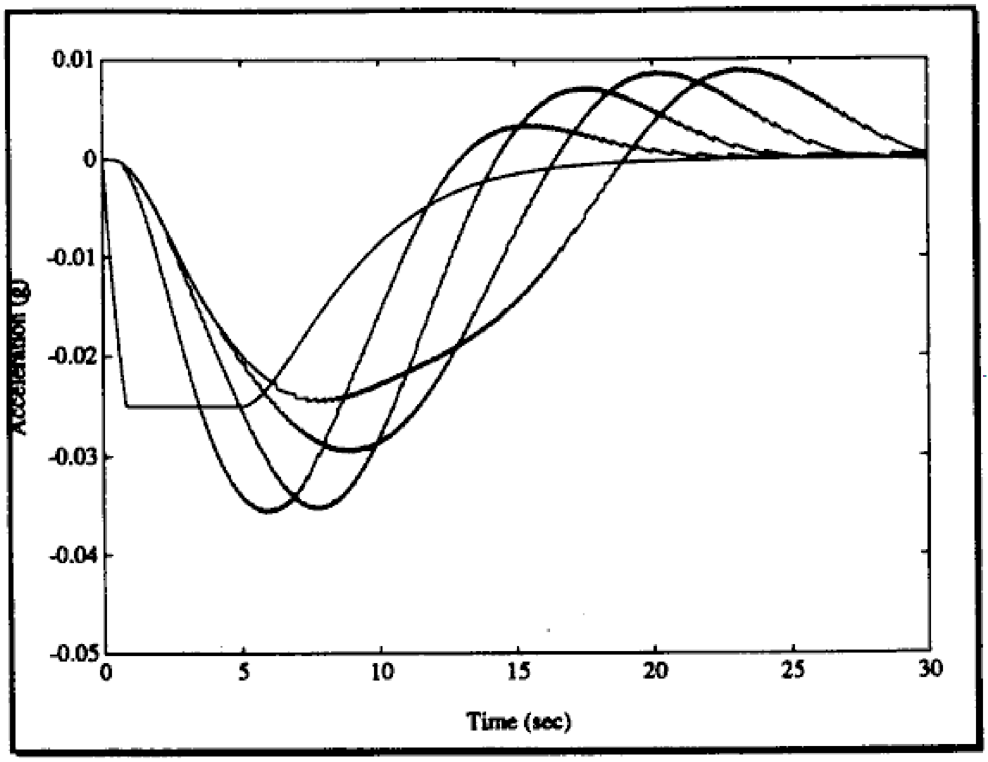

Figure 100. Case #25 Acceleration Plot

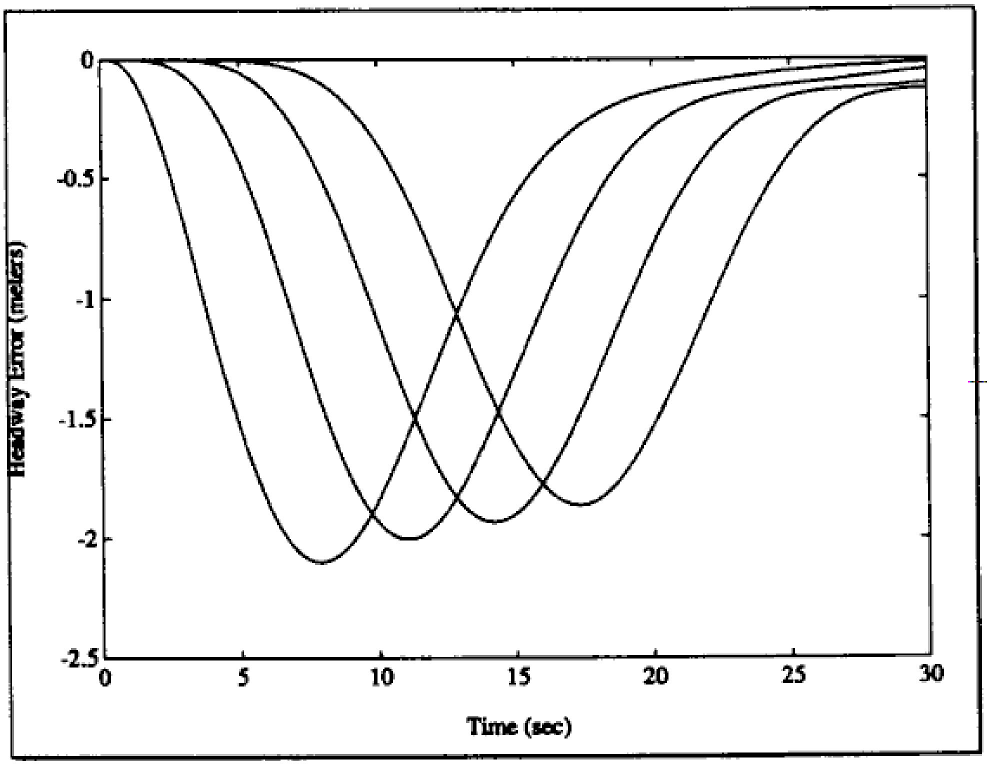

Figure 101. Case #25 Headway Error Plot

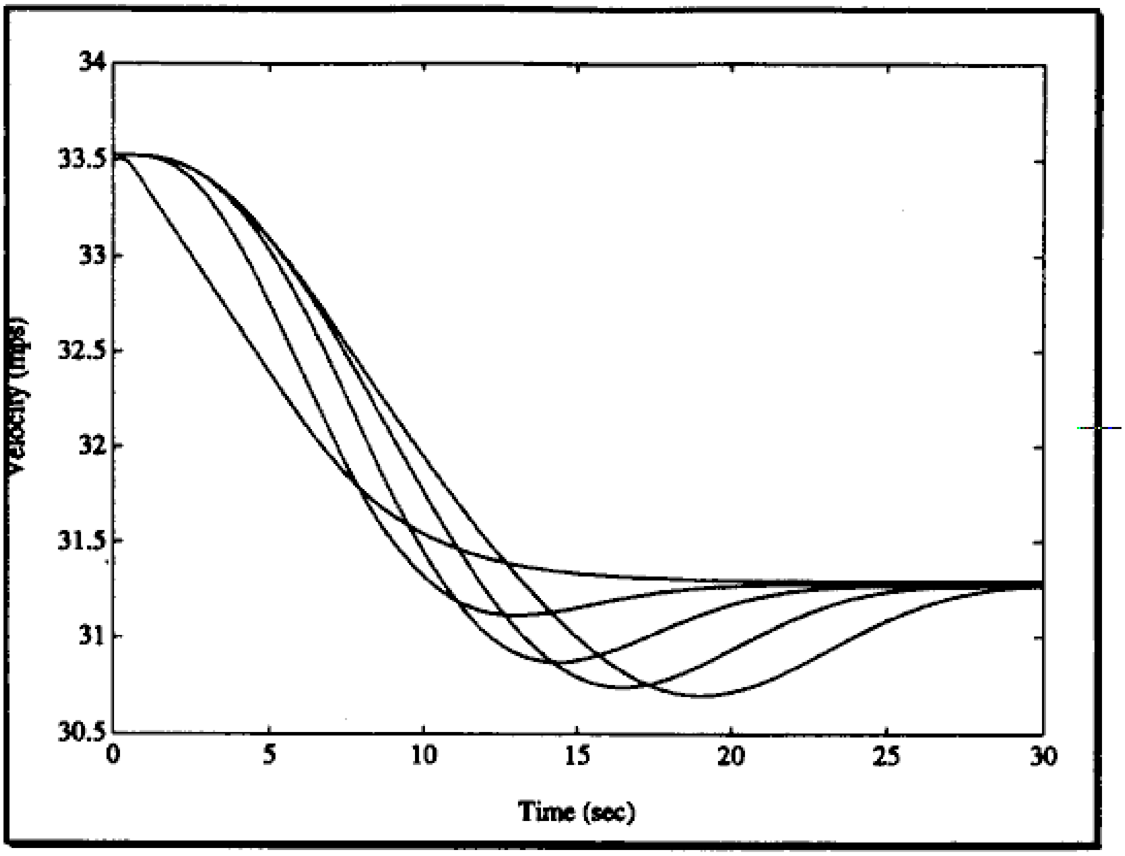

Figure 102. Case #25 Velocity Plot

Appendix C. Summary of Identified Issues

Document	§ Ref.	Issue Summary Statement
MDFRD	2.4.1.1	Throttle actuation bandwidth and latency requirements need some quantitative backup that doesn't exist.
MDFRD	2.4.1.2	Throttle excursions need to be an important measure in control system design for energy efficiency
MDFRD	2.4.2.1	When it comes to assuring safe responses to failure conditions, what is appropriate under what conditions? Standards may need to be created for basic vehicle control (independent of vehicle performance specifics) similar to those that exist for aircraft flight control.
MDFRD	2.4.3.1	Should the steering be physically decoupled from the steering wheel during automated operation?
MDFRD	2.4.3.2	Standards should to be established defining stability, control, and failure mode requirements and limitations before designs move to the system deployment phase.
MDFRD	2.4.3.3	A tension exists between safety limits and performance. Safety limits are imposed to prevent inducing loss of control, but the more stringent the limits, the less control authority is available.
MDFRD	2.4.3.4	According to sources in the automotive industry, skid compensation is not being contemplated for future. However, it may become a requirement for systems implementing automatic obstacle avoidance because of the possibility of abrupt maneuvering. If so, it will require careful relaxation of steering limits imposed for safety reasons.
MDFRD	2A.4.1	Under unusual or emergency conditions, the tendency will be for the operator to attempt to wrest control from the system. Because of the high density of traffic and short reaction times in some operating modes, the consequences of inappropriate action might be not only to endanger the driver and occupants of a given vehicle, but to endanger nearby vehicles as well.
MDFRD	2.4.4.2	Automatic control under high performance, safety-critical conditions requires fault/tolerance to a level not expected in manual systems. A large body of knowledge in redundancy management exists, but solutions are frequently expensive, requiring additional equipment for sensing, processing, and actuation.
MDFRD	3.3.1	Does certification for AHS operation require the presence of automatic transmissions?

Document	§ Ref.	Issue Summary Statement
MDFRD	3.3.2	How and under what conditions does the system permit user takeover of steering control?
MDFRD	3.3.3	By what strategies will the AHS most effectively manage vehicle emissions?
MDFRD	3.3.4	What is the proper fail-safe protocol for steering actuation?
MDFRD	3.3.5	No requirements exist for maximum acceptable latency between occurrence of a failure and operator notification.
MDFRD	3.3.6	Specification of lateral acceleration limits for other than dry pavement conditions complicates the issue because of the wide variety of environmental conditions. Sensing traction-reducing conditions in all but very coarse ways is beyond current state of the art.
MDFRD	3.3.7	Derived steering angle limits may generate a requirement for relatively high precision on steering position feedback signals.
MDFRD	4.4.1	Safety standards need to be developed covering coordination and coupling of controls.
MDFRD	4.4.2	Deceleration performance limits of each vehicle in a platoon must be communicated to all vehicles forward of that vehicle when closely-spaced following is engaged.
MDFRD	4.4.3	Relative deceleration performance capability and imputed limits create complex liability assignment issues in closely-spaced platooning.
MDFRD	4.4.4	Headway requirements are dominated by latency under emergency stop maneuvers. Latencies will have to be very low to avoid impact during maximum deceleration maneuvers.
MDFRD	4.4.5	Ability to detect and avoid moving obstacles is beyond the current state of the art and should not be a requirement.
MDFRD	4.4.6	Sensor resolution and update rates for vision-based obstacle detection remain the most demanding technology deficits today. Solutions are achievable, but the cost remains prohibitive.
MDFRD	5.7.1.1	Variations in vehicle performance may make it imperative that the performance of vehicles behind are considered in executing control actions. Failure to do so may create dangerous situations. such as braking too hard with a heavy truck immediately behind.
MDFRD	5.7.1.2	Will long strings of vehicles in platoons exacerbate the problems of ingesting the fumes of vehicles to the front?

Document	§ Ref.	Issue Summary Statement
MDFRD	5.7.1.3	Close following may reduce air flow through engine compartments, aggravating heat rejection problems, particularly for air-conditioned vehicles
MDFRD	5.7.1.4	The risk of injury or damage to property is greatly increased if bumpers are at incompatible heights in close following situations.
MDFRD	5.7.2.1	In the presence of tracking errors, vehicle following alone may cause growing offset errors as each vehicle going around the turn exhibits successively greater offset from the lane center
MDFRD	5.7.2.2	Vehicle following without independent verification can cause a following vehicle to inappropriately follow a failing lead vehicle. This may give rise to a new class of tort litigation - the "you led me astray" case.
MDFRD	5.7.2.3	Concepts dependent on forward-looking sensors for determining lane position are incompatible with close vehicle following. Lane acquisition when changing modes may be hindered by obscuration by preceding vehicles.
MDFRD	5.7.3.1	Generalized obstacle avoidance is currently limited by obstacle detection sensor performance. AHS concepts will likely have to work within the constraint of an inability to detect and avoid flotsam or holes on the highway until sensor capability improves within a reasonable cost profile.
MDFRD	5.7.3.2	Lateral acceleration profiles permissible for emergency maneuvering will have to take worst-case traction conditions into account, or a highly reliable means of detecting traction conditions will have to be present in the system concept.
MDFRD	5.7.3.3	The authority of the vehicle to execute obstacle avoidance needs to be kept low to avoid the possibility of loss of control, but doing so increases the look-ahead requirement.
MDFRD	5.7.3.4	Sudden lane changes are likely to alarm the operator and may induce him to try to intervene. How to notify him under duress that the system is functioning properly is a difficult human factors issue.
MDFRD	6.4.1.1	In order to be able to assure entry for vehicles queued up for entry at a given point, it will likely be necessary to limit platoon length to assure sufficient opportunities for entry under high density conditions.
MDFRD	6.4.1.2	Assuming that platoon length is limited as in §6.4.1.1, intervehicle communication or platoon coordination will be mandatory to assure vehicles do not form platoons of arbitrary length.

Document	§ Ref.	Issue Summary Statement
MDFRD	6.4.1.4	Operator comfort testing has exclusively focused on the vehicles ahead and not on the presence of vehicles behind.
MDFRD	6.4.2.1	Can a vehicle safely depart the highway from within a platoon without change in speed or separation distance?
MDFRD	6.4.2.2	15 Extra Space Required In Front and/or Behind During Exit? If so, how much?
MDFRD	6.4.2.3	Modeling needs to be done to determine traffic flow impact of opening space for disengagement from platoons
MDFRD	6.4.2.4	If a vehicle is exiting from the middle of the platoon, all vehicles in that platoon need to be advised of the condition. The transients and required maneuvers will most likely require some anticipation to coordinate properly.
MDFRD	6.4.2.5	If vehicles are to exit platoons at speed with no increase in spacing, does that mean that manual exit from platoons or from the AHS while in a platoon are prohibited?
MDFRD	6.4.3.l	Under small headway conditions, each vehicle must be capable of distinguishing between failure and intentional emergency exit by the vehicle in front of it within a very short time interval.
MDFRD	6.4.3.2	Extensive analysis will be required to determine the kinds of emergency (off-nominal) conditions the AHS must be capable of responding to and the right protocols for response to those conditions. This analysis will have to documented as standards that form the basis for limiting product liability.
MDFRD	7.4.1.1	Safe queuing~space is needed for entry that does not interfere with exit and entry abort queues and traffic patterns.
MDFRD	7A.1.2	Synchronizing speed and position to enter a hole can severely constrains longitudinal performance requirements.
MDFRD	7A.1.3	Should the transition from manual to automatic mode occur before entry or once in the AHS lane? The trade is between system complexity and do-ability.
MDFRD	7.4.1 A	Assuming physical barriers and limited access, should vehicle certification occur on the fly before or within the confines of the entry zone?
MDFRD	7.5.1.5	If there is no physical separation between the AHS and non-automated lanes, where does certification take place?
MDFRD	7.4.2.1	The system must provide an effectively unlimited capacity to leave the system.

Document	§ Ref. m	Issue Summary Statement
MDFRD	7.4.2.3	if exit is to be done under automatic control, one reliability issue is how to handle the case of communications failure in the checkout mechanism?
MDFRD	7.4.3.1	How much of a safety zone is required for emergency exit situations with respect to other vehicles or objects in adjacent lanes approaching from behind?
SCDD	2.5.1	State of the art image processing techniques are not very robust with respect to environmental effects such as rain, snow, nighttime lighting, changes in pavement coloration, etc. Considerable research and development may be needed to assure adequate safety.
SCDD	2.5.2	Image-based sensing is subject to deregulation when lenses or windows covering the optics become dirty, coated, or speckled with water droplets.
SCDD	2.5.3	The problems of operating in close following conditions include the possibility of obscuring critical sensing modes by the vehicle in front, depending on sensor configuration. However, even with optimal placement, it is not likely that the automated system can match the performance of human operators capable of looking through the windows of the car in front to see what is happening beyond.
SCDD	3.5.1	Flow-based platoon length optimization may adversely impact traffic flow under high-density conditions because of the need to dynamically change formations along the length of the highway.
SCDD	3.5.2	Transient dynamics for the full closed-loop system under emergency conditions will be a driver on sensor update rate requirements, field of view requirements, or both.
SCDD	3.5.3	This concept provides for improving performance through communicating velocity. Which velocity state is communicated is an issue with profound implications for aggregate system stability and complexity.
SCDD	3.5.4	When performing stereo correlation on point sources, the presence of other point sources in the field of view can create ambiguities that are difficult to resolve without continuous tracking of the sources. By contrast, whole-scene stereo has sufficient other cues to resolve such ambiguities. This issue is particularly acute if the sensor are not covering the same fields of view.
SCDD	4.5.1	Lateral position sensing using out~of-lane infrastructure elements may limit AHS implementation to no more than two adjacent lanes.

Document	§ Ref.	Issue Summary Statement
SCDD	4.5.3	One shortcoming of this is that the lane tracking accuracy is dependent upon the combination of barrier and vehicle accuracy. What would an accident in the adjacent manual lane (or an incident in the AHS lane) do to the barrier accuracy?
SCDD	5.5.1	Boundary conditions across the segments must be managed to prevent discontinuities leading to performance-reducing state changes.
SCDD	5.5.2	This concept relies on the use of infrastructure-based coordination for maintaining vehicle spacing. There is little provision for incident detection and reaction without bi-directional communication between infrastructure and vehicles and significant processing burden to maintain track histories of all vehicles in a given segment.
SCDD	5.5.3	Reflections from other vehicles may create timing ambiguities leading to accuracy problems. The extent of this effect is a function of frequencies selected for the RF beacons. Unfortunately, the frequencies needed for resolving position with sufficient precision are the frequencies at which RF travels only in unobstructed line-of-sight paths and also reflects well from metallic objects (such as vehicles).
SCDD	6.5.1	Use of an active lateral control reference probably mandates a fully redundant, fail-safe lateral control system.
SCDD	6.5.2	Fewer requirements for a guideway-powered highway are quite high under heavy loads and also highly variable, braking design and installation of a power distribution network potentially quite expensive.
SCDD	6.5.3	Experience shows that the most efficient linear motor applications are those for which speeds exceed 150 mph.
SCDD	6.5.4	The more efficient configurations of linear motors require an electrical pickup for the vehicle. negating the physical advantages of linear motors.
SCDD	6.5.5	Efficiency of the inductive motor is partially a function of the width of the coils, but more coil width reduces the ability to discriminate lateral position.
SCDD	6.5.6	For a flat-bed coil configuration in the center of the roadway, vertical tolerances along the roadway length will be critical, and normal road wear and seasonal heaving of the roadway will be a problem.

Document	§ Ref.	Issue Summary Statement
SCDD	6.5.9	Electromagnetic field "slip" translates into heat building up in the coils that must be dissipated.
SCDD	6.5.10	Power drawn from the infrastructure will need to be metered on the vehicle and use data downloaded at checkout time. This requirement will add to the cost and complexity of the vehicle.
SCDD	6.5.11	Constant exposure to electromagnetic fields has been an environmental concern in recent years, particularly for individuals residing near high-voltage transmission lines. The intensity of fields from linear induction motors is potentially higher, and the health and environmental effects are not known.
SCDD	6.5.12	The use of radar for obstacle and collision detection has been pioneered in the aviation industry, but the techniques used there do not translate easily to the ground environment. Achieving reliable, fail-safe obstacle detection with non-imaging devices will require substantial research and development activity.
SCDD	7.5.1	Because of the use of centrally-supplied power, a means of metering power draw during AHS operations that is tamper-proof is required to permit fair and accurate billing.
SCDD	7.5.2	A disincentive for poor maintenance needs to be included in the system definition for AHS users under this concept to minimize the impact of failures on the general public.
SCDD	7.5.3	The design of open-air direct connect power pickup mechanisms is very difficult in areas where there is significant snowfall or heavy rains.
SCDD	7.5.4	The magnitude of power required for an entire urban area and the infrastructure it implies in power generation and distribution is quite substantial.
SCDD	7.5.5	Making a lane change under emergency conditions will mean that the vehicle will have to be able to exit the guideway at any point along the way. ~ in turn, will require that power strips or contacts cannot impede lateral movement of the vehicle, at least in one direction..
SCDD	7.5.6	Since the system is centrally powered, the effects of power loss to the system will be potentially catastrophic. At a minimum, all traffic will come to a halt unless sufficient fail-operational design elements and/or degraded mode operations are designed into the system.

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SCDD	7.5.8	The wear associated with sliding contact electrical pickup under very high usage expected of the AHS may result in unacceptably high preventive maintenance requirements.
SCDD	8.1.1.1.1	If barriers are used, then to create the buffer spaces needed for safety, and to allow for queuing of cars trying to merge into dense traffic, a dedicated entry/acceleration lane will be required. Without such a lane, the entering vehicle would have to be fully synchronized with AHS traffic while traveling in the non-AHS lanes prior to the entry point. If AHS lanes are permitted to run at higher speeds, this will not be legally possible.
SCDD	8.1.1.1.2	If barriers are used, then each barrier break will have to be equipped with energy absorbing configurations to prevent fatalities from hitting the leading edge at high speed, increasing the construction and maintenance cost of the interchange.
SCDD	8.1.1.1.3	If barriers are used, then rush hour traffic may cause backup in the entry/acceleration lane as vehicle desiring to enter wait for an opening. The slipover into the non-AHS lanes could induce a slowdown there as well. This slowdown could be potentially dangerous in that it occurs in the "high speed lane" of the non AHS traffic. Lane layout designs and regulations must be specified to avoid this problem.
SCDD	8.1.1.2	Barriers create a real estate problem to provide for failures. It is axiomatic that vehicles will fail and will become unable to move under their own power. When this occurs, there must be some place for the vehicle to coast to a stop.
SCDD	8.1.2	String stability a phenomenon applicable to more than just the 'platooning' scenario.
SCED	5.1	There are a number of concepts under consideration at various institutions around the country that require the use of infrastructure-supplied power. However, we believe that centrally-supplied power is only superficially attractive and that deeper analysis provides compelling arguments against its use.
SCED	5.2	Unless the basic underlying concept of an AHS at large is completely change (unlikely), a concept must have some level of inter-vehicle communications to be viable. The two primary reasons for this are 1) assuring string stability in the close vehicle following mode, and 2) providing intent information so that the right actions are taken under exception conditions.

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