Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS PSA Vehicle Operations Analysis

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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16. Abstract

The overall goal of this task was to identify issues and risks associated with a fully automated AHS vehicle. The primary issues that were addressed were related to vehicle-infrastructure functional decomosition, performance requirements, fail-safety and criticality, communications, self-monitoring and self-diagnosis technology, and overall vehicle management. specifically, this task had four primary objectives:

1. What new vehicle subsystems are required to meet the functional requirements of AHS including sensors, processing, and vehicle to vehicle communications and vehicle to infrastructure communications?
2. What subsystems have reliability issues that can have a significant impact on AHS operation and safety?
3. Can the reliability of these subsystems be improved through new design or redundancy?
4. Is it sufficient to perform subsystem checkout at start up or will a self diagnosis system offer greatly improve safety and fail-soft capability?
5. Will additional subsystem sensors be required?

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Contents

List of Figures

List of Tables

1.0 Executive Summary

This report documents the Rockwell Vehicle Operations Analysis task for the Precursor Systems Analysis of Automated Highway Systems study. The overall goal of the Rockwell Vehicle Operational Analysis study was to identify issues and risks associated with a fully automated AHS vehicle.

The Rockwell Science Center was responsible for overall project management of the study and for the primary technical focus of the study. PATH provided significant technical content to this study through a subcontract to Rockwell.

1.1 Study Objectives

The primary issues which were addressed were related to vehicle-infrastructure functional decomposition, performance requirements, fail-safety and criticality, communications, and self-monitoring and self-diagnosis technology. Specifically, this task had four primary objectives:

1. What new vehicle subsystems are required to meet the functional requirements of AHS, including sensors, processing, and vehicle-to-vehicle communications and vehicle-infrastructure communications?

2. What subsystems have reliability issues which can have a significant impact on AHS operation and safety?

3. Can the reliability of these subsystems be improved through new designs, use of redundancy, or application of new advances in self-monitoring technology?

4. Is it sufficient to perform subsystem checkout at start up, or will a self-monitoring self-diagnosis system offer greatly improved safety and fail-soft capability? Will additional subsystem sensors be required?

1.2 Technical Approach and Summary

Figure 1 presents an overview of the entire Rockwell Vehicle Operational Analysis effort and illustrates the relationship between the various tasks.

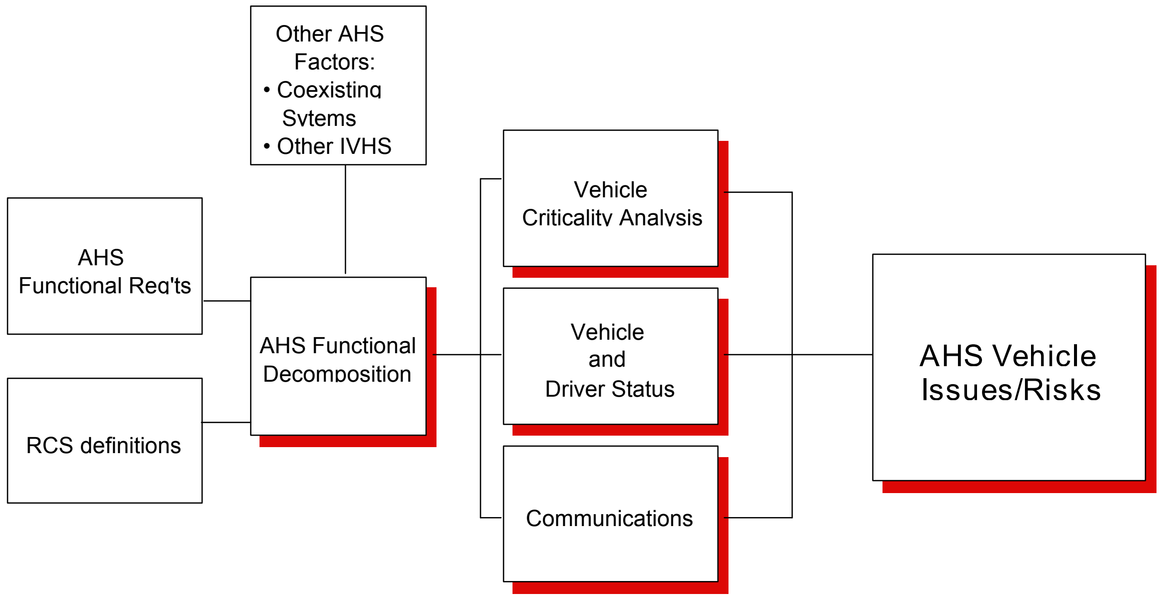

Figure 1. AHS Study Flow

The study started with the functional requirements task. Significant emphasis was placed on understanding the vehicle functional requirements and on understanding the implications of various schemes for vehicle-infrastructure functional decomposition. This effort formed the basis for the next step which was to analyze the fail-safety and criticality of the key vehicle functions and to identify those which must be considered the most safety critical for an AHS vehicle.

Six Representative System Configurations (RSCs) were defined representing different approaches to partitioning required AHS functions between the infrastructure and vehicle. From these six RSCs three were determined to represent the most promising approaches to vehicle-infrastructure partitioning. These six RSCs present a more detailed breakdown of vehicle functions than the vehicle or infrastructure weighted RSCs used in the other Rockwell PSA studies. Several levels of infrastructure or vehicle weighted functionality are introduced rather than the the two levels in the other studies. The difference between barrier and no barrier used in the other rockwell RSCs was less important in the approach used for the vehicle operations analysis.

Twenty-one Operational Functions were defined which cover all AHS operations. From these 21 operational functions three were selected for detailed criticality analysis. Safety critical paths were defined for each of the three key operational functions. Detailed quantitative safety critical analysis was performed on the key safety critical functions of lateral and longitudinal control. Finally, a qualitative safety critical/efficiency critical analysis was performed for each elemental functions.

The Communications task included the communications and information processing requirements to perform each of the critical AHS functions. In addition to defining the communications requirements, this task provided insights into the various vehicle-infrastructure functional decomposition approaches. This analysis illuminated communications and processing differences between the six RSCs and helped to identify potential issues with several of the RSCs.

1.3 Primary Assumptions

The study was performed with the following general guidelines and assumptions:

1. All RSCs implement a fully automated AHS. The study did not examine evolutionary concepts or concepts which did not provide a fully automated AHS.

2. The functional decomposition was to be technology independent. Those aspects of the analysis which examined functional decomposition, functional requirements, and criticality of functions did this in a technology independent way.

3. AHS could evolve in small steps through technology improvements without modifications to the functional decomposition or functional requirements.

1.4 Observations

The following observations and conclusions have been derived from this study:

1. Because of the significant communications requirements between the Coordination and Regulation layer for the Maneuver Planning function, it appears that the maneuver planning function of the Coordination layer should be done on the vehicle. This allows the coordination-regulation communications to be intra vehicle instead of infrastructure-vehicle communications.

Several recent analyses support vehicle based maneuver planning including spontaneous platooning and mixed mode AHS evolutionary concepts.

Additional analysis must be done to examine other issues related to performing the coordination function on the vehicle. Stability must be examined within the context of specific algorithm approaches across expected operating regimes. System level performance evaluation will require treatment of the AHS as a complex adaptive system whose behavior is determined by the interaction among semi-autonomous individual entities that communicate largely asynchronously and employ limited information bases.

2. It is important for vehicles in a platoon to maintain communications with the lead vehicle. It is possible to build accurate acceleration estimators to decrease the chances of collision but the problem of non-decreasing spacing errors down the string of vehicles can cause potential problems for sufficiently long platoons of vehicles.

3. The noise experienced in a platoon is a percentage of the target spacing. Hence spacing errors will be larger at larger target spacings. Vehicles following at larger spacing, albeit safer, will not necessarily result in the best form of control. Low gain controllers must be designed to ensure that small variations in spacing errors do not translate into high control effort and actuator saturation.

4. The effect of actuator limitations was studied but it was found that throttle actuators at least as fast as 150 ms are fast enough for the frequency and type of maneuvers that can be expected in automatic vehicle control on highways. Brake actuators slower than 150 ms can lead to poor tracking performance during high jerk deceleration maneuvers.

5. The communication function is critical for control of strings of vehicles based on the spacing distance control. Autonomous or time headway control approaches are more robust to losses of communication. With spacing control, if there is no communication, attenuation of errors down a string of vehicles cannot be guaranteed. The errors in tracking can be reduced,somewhat, through accurate estimators.

6. The closing rate function is by far the most important function for longitudinal control. Performance is greatly degraded in the absence of closing rate information. In addition, if communications are not working properly, potentially hazardous situations can arise due to large lags in accleration tracking. The degradation in performance without closing rate and communication information is true regardless of the control approach used. The closing rate function is safety critical.

7. Self-diagnosis and self-monitoring technology can have significant benefit to improving the safety of AHS. Additional study is needed to determine the best technology approach and whether it is best to have a centralized self-monitoring elemental function or to have a distributed monitoring capability with each element performing its own diagnostics, or a combination of both.

2.0 Introduction

This report documents the results of the Rockwell International Vehicle Operational Analysis task of the AHS Precursor Analysis. The goal of this study was to examine the issues and risks of a fully automated AHS vehicle. Because the AHS vehicle concept is still in the formative stages, the study emphasized functionality rather than specific technology or system implementations. The issues which were examined were, therefore, top level and technology independent. Future studies should focus on specific implementation approaches and refine the concepts outlined in this report.

The specific goals of this study were to analyze the following issues from a top level functional viewpoint.

1. What new vehicle subsystems are required to meet the functional requirements of AHS including sensors, processing, and vehicle to vehicle communications and vehicle to infrastructure communications.

2. What subsystems have reliability issues which can have a significant impact on AHS operation and safety.

3. Can the reliability of these subsystems be improved through new designs, technology or redundancy.

4. Is it sufficient to perform subsystem checkout at start up or will a self-monitoring self-diagnosis system offer greatly improved safety and fail-soft capability. Will additional subsystem sensors be required.

The overall study flow was illustrated in Figure 1 in the Executive Summary of this report. The key tasks which were performed during this study and which will be discussed in detail in this report are:

1. Top Level AHS functional model
2. AHS Control Architecture
3. Vehicle-infrastructure Functional Decomposition
4. Communications and Information Processing Requirements
5. Performance requirements, criticality and failure mode analysis
6. Self Monitoring and Self Diagnostic technology

Every task performed during this study assumed that the AHS vehicle would implement a fully automated AHS. No evolutionary concepts or RSCs were examined. The primary purpose of defining and analyzing several RSCs was to gain understanding into different functional approaches for AHS not to define an evolutionary path for AHS. Section 3 defines the RSCs used in the study. These RSCs offer more detailed definitions to the more general RSCs Rockwell has used for the other PSA tasks.

While the overall study is vehicle oriented, the functional analysis started with a top level examination of the overall AHS functional requirements because of the importance in considering the vehicle's relationship to the infrastructure and to the overall AHS. For example, the criticality of the communications links implemented on the vehicle greatly depends on whether the vehicle or infrastructure is responsible for planning a lane changing maneuver.

Thus, the requirements analysis presented in this report utilizes a broad top-down approach incorporating both infrastructure and vehicle considerations. The analysis starts with a concise set of overall highway goals independent of AHS and the top level mission oriented tasks necessary to realize these goals. The mission oriented tasks provide a consistent framework within which alternative approaches can be compared and AHS compared to non-AHS approaches. The mission oriented tasks are then subdivided into specific operational functions which must be able to be performed. Some of the operational functions are generic and apply to both AHS and non-AHS roadways, while others apply only to AHS. Again this framework provides a basis to understand, in detail, potential specific areas of improvement possible through AHS.

The lowest level functions which the requirements analysis examines are elemental functions. The elemental functions are the functional building blocks of AHS and describe the detailed functions necessary to provide the operational function capability. Section 4 presents the AHS functional model. This model was used to focus subsequent analyses and to help identify safety critical functions and AHS vehicle components.

Section 5 describes an AHS open layered control architecture. This architecture is a framework for implementing AHS. Each layer performs a unique and important AHS role and is defined and described in terms of the elemental functions which are performed within that layer.

The control architecture was used to partition elemental functions between the infrastructure and vehicle and to help define the six representative system configurations discussed in Section 3.

Section 6 presents the communications and information processing requirements analysis. This analysis developed top level communications requirements and illuminated differences in the six representative system configurations.

Section 7 presents the results of the criticality and failure mode analysis. This section includes detailed functional flow diagrams for three primary operational functions including safety critical paths. It also presents a detailed quantitative safety criticality analysis of the two primary safety critical operational functions - longitudinal and lateral control

Self-monitoring and self-diagnosis technology is discussed in section 8. The goal of this analysis is to understand the potential for this technology to predict impending failures before the actual occurrence. This could improve fail-safety even if reliability is not improved.

Finally, the primary conclusions of the study are presented in section 9.

3.0 Representative System Configurations

The Rockwell study approach uses two basic categories of Representative System Configurations - Infrastructure and Vehicle weighted. Within that context this section presents a description of six RSCs defined in terms of the AHS control layers discussed in the previous section and the associated elemental functions.

The six RSCs are illustrated in Figure 2. In the figure, the numbering of the RSCs is purely arbitrary and does not represent an evolutionary ordering or rank ordering of the RSCs. Each RSC has been conceived to be able to perform all of the required functions of a fully automated AHS. The various RSCs illustrate potential functional partitions between the infrastructure and vehicle. Tables 1, 2 and 3 present more detailed information on the six RSCs.

RSC #1 is predominately infrastructure weighted and RSC #6 is predominately vehicle weighted. Some functions such as the regulation layer and the actuation functions of the physical layer will always be contained within the vehicle. Also, some of the Network layer functions will always be accomplished by the infrastructure. The remaining functions can be reasonably partitioned between the infrastructure and the vehicle as illustrated.

Moving from RSC #1 each subsequent RSC represents a portion of the control functions shifted from the infrastructure to the vehicle. RSC #2 represents a functional partitioning where some of the coordination layer control functions such as maneuver coordination planning are performed on the vehicle rather than by the infrastructure.

RSC#3 continues with some of the Link layer control functions partitioned to the vehicle. RSC #3 represents a system with even more vehicle autonomy than RSC #2 with both maneuver planning and lane assignment and vehicle parameter monitoring performed by the vehicle. This RSC has significantly reduced communication requirements between the vehicle and the infrastructure compared to RSC #1, but adds the complexity of a self-organizing system with many elements capable of making decisions.

RSC#4 illustrates a functional partitioning with all of the coordination layer control functions performed on the vehicle. RSC #4 allows the entry/exit permission function to be made by the vehicle. This requires a complete and reliable self-diagnosis/self-monitoring system within the vehicle.

Continuing with RSC #5, the partitioning now includes all of the Link layer control functions performed by the vehicle. RSC #5 assumes the vehicle receives all information necessary to make decisions for incident management and establishing vehicle priorities.

And finally, the functional partitioning for RSC #6 includes the Link layer control functions performed by the vehicle. RSC #6 assumes the vehicles can effectively plan the individual vehicle routes.

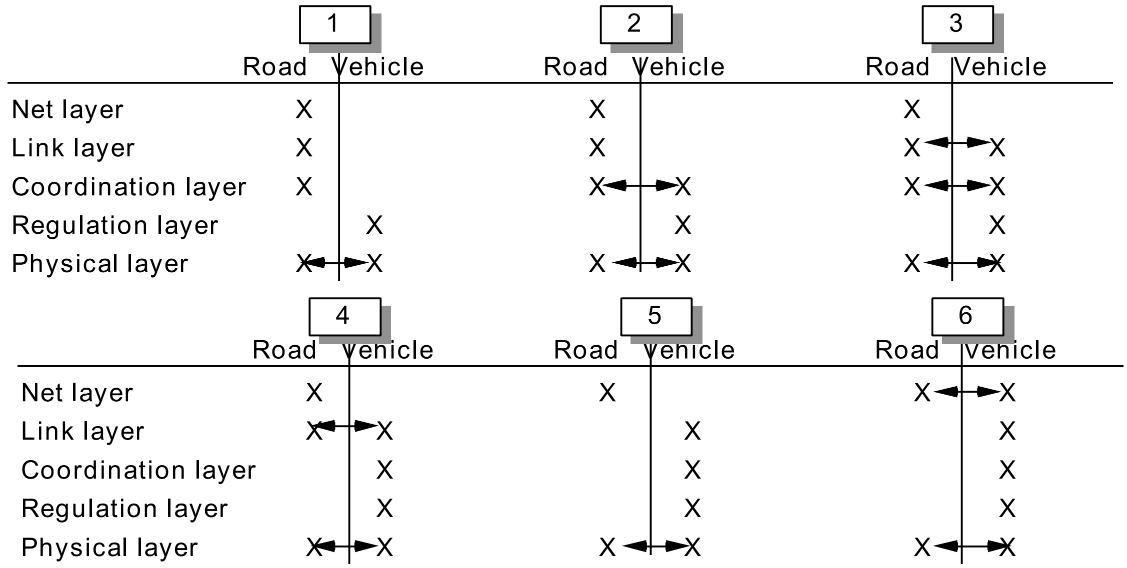

Figure 2. Functional partitioning between vehicle and infrastructure

A detailed breakdown of the elemental functions performed by the vehicle and by the infrastructure for each RSC is shown in Tables 1, 2 and 3.

Table 1. Functional Partitioning for RSC #1 and RSC #2

Control Layer	Elemental Function	RSC #1		RSC #2	
		Inf	Veh	Inf	Veh
Network Layer					
	Vehicle Identification	X		X	
	Monitor Traffic Condition	X		X	
	Route Recommendation	X		X	
Link Layer					
	Lane Assignment	X		X	
	Target Speed	X		X	
	Maximum Group Size	X		X	
	Minimal separations	X		X	
	Prioritize vehicle operation	X		X	
	Monitor regional traffic	X		X	
	Incident Management	X		X	
Coordination Layer					
	Issuing permission/rejection	X		X	
	Maneuver coordination planning	X			X
	Supervising sequence of maneuvers	X			X
	Monitoring road surface conditions/wx	X			X
Regulation Layer					
	Steering control command		X		X
	Speed regulation command		X		X
	Braking Command		X		X
	Vehicle monitoring & failure det/diag		X		X
	Trip progress monitoring		X		X
Physical Layer					
	Sensing-States of vehicle	X	X	X	X
	Sensing- Condition of vehicle		X		X
	Sensing- Info about infrastructure	X		X	
	Sensing- Weather conditions	X		X	
	Sensing- traffic signal/sign info	X		X	
	Actuation		X		X
	Human-Machine Interface		X		X
	Information links	X	X	X	X
	Secondary Functions		X		X

Table 2. Functional Partitioning for RSC #3 and RSC #4

Control Layer	**Elemental Function**	**RSC #3**		**RSC #4**	
		Inf	**Veh**	**Inf**	**Veh**
Network Layer					
	Vehicle Identification	X		X	
	Monitor Traffic Condition	X		X	
	Route Recommendation	X		X	
Link Layer					
	Lane Assignment	X	X	X	X
	Target Speed	X	X	X	X
	Maximum Group Size	X		X	
	Minimal separations	X	X	X	X
	Prioritize vehicle operation	X		X	
	Monitor regional traffic	X		X	
	Incident Management	X		X	
Coordination Layer					
	Issuing permission/rejection	X			X
	Maneuver coordination planning		X		X
	Supervising sequence of maneuvers		X		X
	Monitoring road surface conditions/wx		X		X
Regulation Layer					
	Steering control command		X		X
	Speed regulation command		X		X
	Braking Command		X		X
	Vehicle monitoring & failure det/diag		X		X
	Trip progress monitoring		X		X
Physical Layer					
	Sensing-States of vehicle	X	X		X
	Sensing- Condition of vehicle		X		X
	Sensing- Info about infrastructure	X	X		X
	Sensing- Weather conditions	X	X	X	X
	Sensing- traffic signal/sign info	X		X	X
	Actuation		X		X
	Human-Machine Interface		X		X
	Information links	X	X	X	X
	Secondary Functions		X		X

Table 3. Functional Partitioning for RSC #5 and RSC #6

Control Layer	Elemental Function	RSC #5 Inf	RSC #5 Veh	RSC #6 Inf	RSC #6 Veh
Network Layer					
	Vehicle Identification	X		X	
	Monitor Traffic Condition	X		X	
	Route Recommendation	X			X
Link Layer					
	Lane Assignment		X		X
	Target Speed		X		X
	Maximum Group Size		X		X
	Minimal separations		X		X
	Prioritize vehicle operation		X		X
	Monitor regional traffic		X		X
	Incident Management		X		X
Coordination Layer					
	Issuing permission/rejection		X		X
	Maneuver coordination planning		X		X
	Supervising sequence of maneuvers		X		X
	Monitoring road surface conditions/wx		X		X
Regulation Layer					
	Steering control command		X		X
	Speed regulation command		X		X
	Braking Command		X		X
	Vehicle monitoring & failure det/diag		X		X
	Trip progress monitoring		X		X
Physical Layer					
	Sensing-States of vehicle		X		X
	Sensing- Condition of vehicle		X		X
	Sensing- Info about infrastructure		X		X
	Sensing- Weather conditions		X		X
	Sensing- traffic signal/sign info		X		X
	Actuation		X		X
	Human-Machine Interface		X		X
	Information links	X	X	X	X
	Secondary Functions		X		X

4.0 Top-level AHS Functional Breakdown

This section presents a complete top-down functional approach for both AHS and non-AHS highway systems. The overall top-down approach is illustrated in Figure3. The top-down approach presents AHS goals, mission oriented tasks, operational functions, and at the lowest level, elemental functions.

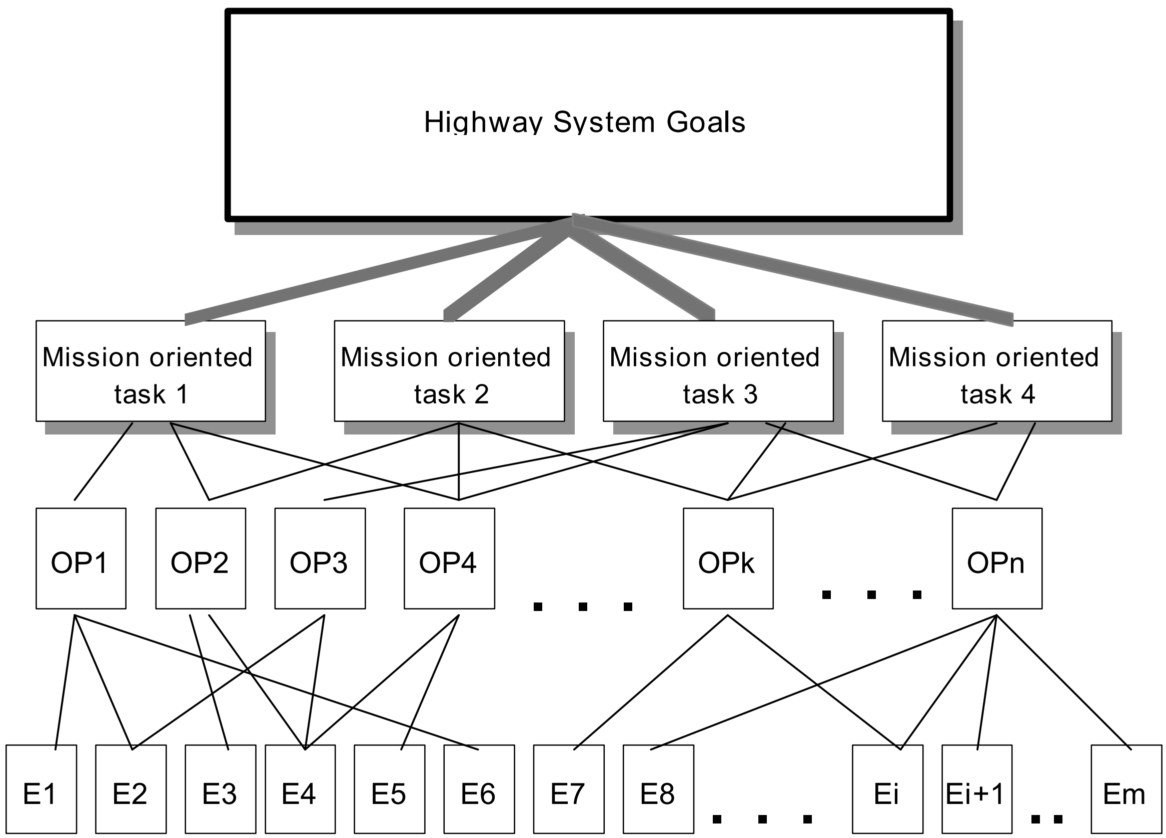

Figure 3. Top-level Functional Diagram

4.1 Highway System Goals

The purpose of any highway system is to provide a method for a person to take a trip from one point to another with fair access by all who want to use it. The trip should be able to occur at any time with any random starting point and destination point.

In addition to providing a means of travel the highway system should minimize the costs associated with the trip as much as possible. The associated costs can be measured in terms of:

1. Time - measured in both absolute delay and predictability or expected variance. Both aspects of the time measurement are important. It is important to take a trip with minimum time, but it is also important to reliably bound the range of the predicted trip duration.

2. Safety risk and liability - this includes both real and perceived risks.

3. Environmental damage - this includes the damage from building the highway and pollution due to traffic.

4. Effort - measured in term of required manual control, discomfort, lack of capability for handicapped.

5. Infrastructure and vehicle capital and operating costs such as tolls, dollar costs of land acquistion and construction, etc.

These highway goals are the objectives of any highway system. What sets AHS apart from current generation highways, is not that it has different top level system goals, it is that the vision for minimizing these costs is so much more significant. Throughout the remainder of this report, the cost reduction advantages of certain AHS functions and capabilities will be detailed and highlighted. This approach will help ensure that the evolving AHS concept will meet its goals.

Conventional freeway systems accomplish their goals largely by means of drivers manually performing required tasks according to prescribed rules of the road and through vigilant maintenance and monitoring of their own vehicles. The AHS will achieve the additional goals primarily by automating many of these functions currently performed manually. This automation is manifested primarily by added sensors and processors that can perform situation assessment and decision-making that result in automatic command generation for the actuators. The actuators are expected to be essentially conventional. For example, the vehicles will not have an especially higher braking capability in a physical/mechanical sense, although it will have passed a test to ensure it satisfies a minimal such expected capability. The vehicle may have superior braking due to added information about the road conditions, and may have advance warning that allows braking to begin earlier than in a conventional freeway situation.

The introduction of AHS may enable new operations to be used such as platooning and path planning on an aggregated scale. Also, several operations will have to be added for interfacing the AHS with conventional systems. These include: the capability to transition between manual and automated modes, check-in and check-out operations, and possibly maneuvers between an automated lane and a transition lane. Conventional operations which can be automated include: lane holding, longitudinal control (throttle and brake), and possibly lane changing.

4.2 Mission Oriented Tasks

Every highway system whether AHS or non-AHS requires specific mission oriented tasks be performed. These mission oriented tasks are directed toward meeting the goals of the highway system. Again, as with the overall goals, what differentiates AHS from non-AHS highways is not the specific mission oriented task, but the degree to which they reduce the costs associated with a trip.

The Mission Oriented Tasks can be divided into four categories:

1. Move toward destination

2. Incident avoidance and management
3. Resolve contention for shared resources (efficiently)
4. Enter and exit the system

4.2.1 Move Toward Destination - This task is directed toward realizing the goal of moving the vehicle from the starting point to the destination. It involves two sub tasks:

1. Provide motive force to propel the vehicle.

2. Steer toward destination, guidance:
   - know which direction the destination is and determine the route
   - make the proper turns at the appropriate junctions (switch point)

4.2.2 Incident Avoidance and Management - This task involves creating a safe and reliable highway system and is directed toward minimizing the associated safety and reliability costs. It includes three sub-tasks:

1. Maintain safe distances and speeds in both longitudinal and lateral directions
   - stay on the roadway by following the road geometry
   - maintain a safe distance between the vehicle and all fixed and moving objects

2. Be predictable to other drivers and vehicles
   - stay in the lane
   - the vehicle should signal intentions to change traveling conditions; the infrastructure should provide signal control and signing

3. Invoke emergency procedures if the situation warrants it. This sub task should minimize the impact of an incident on overall AHS safety and efficiency.
   - reevaluate destination for possible change or re-routing
   - send mayday message for help to be dispatched
   - alert upstream traffic of an incident so that traffic can take appropriate actions to minimize the impact

4.2.3 Resolve Contention for Shared Resources (efficiently) - This mission oriented task provides efficiency when several vehicles are traveling in close proximity with each other. It is directed toward improving the time required to travel without any sacrifice in safety. It involves four sub tasks:

1. Perform coordinated maneuvers such as lane changing, in association with the other vehicles which might be impacted. This involves sensing, evaluation, planning, and maneuver performance.

2. Balance traffic over roadways to improve overall traffic flow.
   - route selection based on congestion
   - adjust target speeds for congestion control
   - lane selection for load balancing

3. Make efficient use of roads to increase traffic density.
   - stay with lanes for better lateral packing

- platooning to increase density

4. Adjust and control entry of new vehicles to the system for flow control

4.2.4 Enter and Exit the System - This task is directed toward improving the safety of the AHS by controlling which vehicles enter the highway system and the transitions from manual to automatic control and back to manual. It contains three sub tasks:

1. Vehicle check in to ensure that the vehicle is performing all of the required AHS functions.

2. Transition from manual to automated mode - this must ensure that the vehicle is ready and able to take control from the driver and the driver is ready to relinquish control.

3. Transition from automated to manual mode - this must ensure that the driver is ready and able to take control of the vehicle.

4.3 Operational Functions

Each of the mission oriented tasks is realized through a series of operational functions. These functions represent the next lower level in the functional block diagram illustrated in Figure3. The operational functions are not unique to a specific task and the same operational function can be required in the performance of more than one task. In this section the operational functions are presented by mission oriented task. The operational functions are based on work performed by PATH and Honeywell under the Human Factors study. The next section presents complete list of the operational functions along with a detailed definition.

The operational functions are the functions that implement operational events under both normal and abnormal conditions. The abnormal conditions may include accident conditions in which a vehicle is required to perform emergency maneuvers to avoid an accident or to minimize the consequence of an accident, incident conditions in which a vehicle is instructed to change lanes or routes to avoid congestion, and failure conditions in which hazard reduction control is needed to prevent a vehicle from encountering hazards.

The operational functions are defined in such a way that (a) they are not affected by the physical implementation of the system, (b) they are observable by humans, and (c) more than one operational function can occur simultaneously. For example, two operational functions named lane-tracking and velocity regulation can accomplish an operational event“lane flow,” which involves controlling a vehicle to follow a traffic lane and adjusting the velocity of the vehicle to match a target speed.

Table 4 presents the Operation Functions included in the AHS functional definitions.

Table 4. Identified AHS Operational Functions

OP1	Vehicle check-in
OP2	Entering the system
OP3	Transition from human to automatic control
OP4	Destination/Route selection
OP5	Velocity regulation
OP6	Spacing regulation
OP7	Longitudinal position regulation
OP8	Lateral lane position regulation
OP9	Steering for lane-changing
OP10	Maneuvering coordination management
OP11	Maneuver coordination under abnormal conditions
OP12	Pause
OP13	Steering to avoid collision
OP14	Human backup for non recoverable failures
OP15	Exit from the system
OP16	Normal transition from automatic to manual control
OP17	Condition monitoring (vehicle)
OP18	Condition monitoring (roadway & environment)
OP19	Driver check-out
OP20	Route monitoring
OP21	Provide human interface

4.3.1 Operational Function Mapping

This section presents the mapping of the operational functions required for each mission oriented task.

Move Toward Destination - The operational functions for this mission oriented task are:

- OP4 Route selection
- OP9 Steering for lane-changing

Incident Avoidance and Management - The operational functions are:

- OP5 Velocity regulation
- OP6 Spacing regulation
- OP7 Longitudinal position
- OP8 Lateral lane position regulation
- OP9 Steering for lane-changing
- OP11 Maneuver coordination under abnormal conditions
- OP12 Pause
- OP13 Steering to avoid collision
- OP10 Maneuver coordination management under incident conditions
- OP14 Human backup for non recoverable failures

Resolve Contention for Shared Resources (efficiently) - The operational functions are:

- OP4 Route selection
- OP5 Velocity regulation
- OP7 Longitudinal position regulation
- OP8 Lateral lane position regulation
- OP9 Steering for lane-changing
- OP10 Maneuvering coordination management under normal conditions

Enter and Exit the System - The operational functions are:

- OP1 Vehicle check-in
- OP2 Entering the system
- OP3 Transition from human to automatic control
- OP15 Exit to a transition lane
- OP16 Normal transition from automatic to manual control

The next section presents the definitions of all of the Operational Functions contained in the four mission oriented tasks.

4.3.2 AHS Operational Functions Definitions

This section presents detailed definitions of each of these Operational Functions.

OP1 Vehicle check-in: Vehicle check-in is performed before the vehicle enters the automated highway by a combination of roadside and on-vehicle systems. The check-in process may include both static inspection and dynamic testing of the vehicle to ensure that its safety-critical components function as specified. Only those that pass the inspection are issued permission to enter.

OP2 Entering the system: The vehicle is driven manually onto the on-ramp or the transition lane following instructions provided by the system. If an on-ramp is directly connected to the inspection station, the automated control system guides the vehicle to the on-ramp.

OP3 Transition from human to automatic control: Manual control is released after the automated control system has reliably taken over the control tasks. In the transition process, the driver is instructed to release manual control in a given sequence.

OP4 Destination/Route Selection: Route selection can take place before or when the vehicle enters the AHS network and during the trip, upon approval by the system. The driver inputs the origin, destination, and designated locations along the route. The system recommends a route according to the request and the traffic conditions. Alternative routes may also be recommended upon request. During the trip, the system may provide updated route recommendations should an incident be detected on the selected route. The driver has the responsibility of finalizing the route selection.

OP5 Velocity regulation: Velocity regulation will be performed to cause the vehicle to match a nominal speed or commanded speed profile. The nominal speed is set by the system abased on the speed limit, road surface, and traffic condition. The commanded speed profile is given when a coordination maneuver such as lane-changing is performed.

OP6 Spacing regulation: Spacing regulation is enacted when there is a vehicle within range in front of the controlled vehicle and a minimum target separation has been given. A target separation represents the minimum allowed separation between vehicles.

OP7 Longitudinal position regulation: The longitudinal position regulation is performed to cause a vehicle to keep a spacing greater than an instructed minimal distance from a specific geometric location for a given period of time in order for another vehicle to accomplish a location constrained lane-changing maneuver.

OP8 Lateral lane postition regulation: The lane-tracking operation is performed to keep the vehicle within a traffic lane. Lane-tracking allows the system to follow a reference line installed in the center or on the edge of a traffic lane to within a given tolerance.

OP9 Steering for lane-changing: The lane-changing operation is performed according to a new lane assignment. The new lane-assignment can be given when there is a request for lane-changing, or at locations where two lanes combine into one or one traffic lane separates into two lanes.

OP10 Maneuvering coordination management: Maneuvering coordination management provides instructions to vehicles for coordinating lane-change, merging, and any other maneuvers that require close coordination with neighboring vehicles. In a system with platoons, maneuvering coordination management is also responsible for forming, joining, and splitting groups of vehicles.

OP11 Maneuver coordination under abnormal conditions: Providing the required actions to minimize the impact on safety and overall traffic flow. The actions could include warning other vehicles, removing a failed vehicle, re-routing other vehicles, and adjusting traffic flow speed and entry to AHS.

OP12 Pause: The vehicle is led to a pause or stop mode when a system failure is detected and continued operation may induce a critical hazard.

OP13 Steering to avoid collision: Steering to avoid collision will be performed when: a) the closing rate to a neighboring vehicle/obstacle is such that a collision cannot be avoided by decelerating at the vehicle's maximal deceleration rate and b) a neighboring lane is available for an immediate lane-changing operation. This operation differs from a normal lane change in two ways. First, the vehicle may not actually complete a lane change to avoid the collision, but may move partially out of its lane. Second, if there are more than two lanes and a second vehicle is driving alongside the endangered vehicle, a coordinated steering maneuver by both vehicles may be the only way for the endangered vehicle to avoid a crash.

OP14 Human backup for non recoverable failures: Human backup may be allowed in the system when a non-recoverable failure may potentially induce a hazard and the human backup may eliminate or reduce the consequences of an accident.

OP15 Exit to a transition lane: In this operation, the vehicle will be guided to a transition lane near the exit.

OP16 Normal transition from automatic to manual control: The normal transition from automatic control to manual control will take place after the vehicle enters the exit area or transition lane.

OP17 Condition monitoring (vehicle): Monitoring the condition of the vehcile and all of its subsystems.

OP18 Condition monitoring (roadway & environment): Monitoring the condition of the infrastructure and the environment.

OP19 Driver check-out: Determine the status of the driver to take over manual control of the vehicle.

OP20 Route Monitoring: Monitor the position of the vehicle along the selected route.

OP21 Provide human interface: Provide all neessary interfaces to the driver including warning systems and displays.

4.3.3 Selected Operational Function Case Studies

Three representative Operational Functions have been selected for in-depth analysis during the remainder of the Vehicle Operational Analysis studies. Specifically, one important operational function was selected from each of the first three mission oriented tasks. This will provide a meaningful balance between performing an in-depth analysis and the need to examine a broad range of issues.

1. Move Toward Destination:
   Steering for lane-changing (lateral control)
2. Incident Avoidance and Management:
   Spacing regulation (longitudinal control)
3. Resolve Contention for Shared Resources:

Maneuvering coordination management (information flow)

Steering for lane-changing and Spacing regulation are key AHS operational functions and are critical toward achieving many of the top level AHS goals. Maneuvering coordination management places emphasis on the communication links and will identify communication related issues.

5.0 AHS Control Architecture

The AHS architecture presented in this section is based on work performed by PATH and refined by PATH and Honeywell under the Human Factors study. This AHS architectureis an open layered control architecture and includes five layers. This approach was selected because it is has several important features which are important to this study:

1. Technology independent. It is independent of the implementation technologies which may be used. The goal of this analysis is to examine issues related to AHS and not to design specific implementation approaches.
2. Vehicle/infrastructure partition independent. It does not specify whether the infrastructure or the vehicle performs and of the control functions. This enabled the study to examine several different vehicle/infrastructure functional partitioning approaches.
3. Unique elemental function mapping. A unique mapping of the elemental functions into each of the control layers is possible. This provides an effective method of assessing the impact on overall system performance of changes in an elemental function.

5.1 Control Layers

Figure 4 illustrates the five control layers of the AHS architecture.

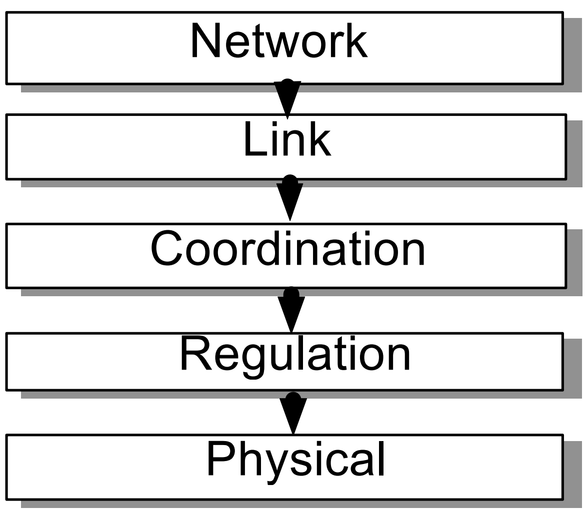

Figure 4. Functional layers within the AHS architecture

All of the architectures and functional partitioning described in this section assume a fully functional AHS. Each conceptual representative system configuration has essentially the same inherent capability. The purpose of examining several functional partitions between the vehicle and the infrastructure was to develop a reasonable set of vehicle based functions which could be examined in detail during the remainder of the study.

The basic responsibilities of each layer is outlined below.

1. Network layer: overall route selection and overall flow control

The network layer is responsible for route and flow control within a network. Based on the nature of an inquiry, the network layer can provide either information reflecting the traffic conditions on a specific route or route recommendations designed to achieve a desired traffic flow. The vehicle operator finalizes the route selection and informs the network of his/her selected route.

2. Link layer: path and lane selection and local congestion control

Each route in the automated highway network can be subdivided into sections, defined as links. The link layer is responsible for path and congestion control within individual links on the assigned route. The link layer may select a lane for each vehicle, sets target speeds for vehicles or platoons for each section of the route, and manipulates platoon size (when relevant) depending on the flow. It may also prioritize the vehicle's operation during cooperative maneuvers and manage incident responses.

3. Coordination layer: coordination between vehicles

The coordination layer is responsible for microscopic management of a subsection within a link. The coordination layer inspects and monitors vehicles and traffic flows, issues permission/rejection, and coordinates complicated maneuvers under both normal and incident conditions. The coordination layer also provides information regarding the road surface conditions and weather, and sets minimal separations. In a system with platoons, the coordination layer is also responsible for joining and splitting platoons.

4. Regulation layer: individual vehicle control and actuator control commands

The regulation layer carries out the directions of the coordination layer. It tracks target speeds, maintains separations between vehicles and between platoons, and provides commands to perform steering and speed control for maintaining the lateral position of the vehicle and the longitudinal separation between vehicles. It also provides commands to implement lane-changing, merging, and splitting/joining a platoon. The regulation layer is also responsible for monitoring vehicle conditions and for on-board failure detection/diagnosis.

5. Physical layer: vehicle actuation and sensors

The physical layer includes the actuation and sensing devices that actually carry out the control commands of the regulation layer and feed information back to it. The physical layer is also responsible for human-machine interaction.

Each control layer in the layered AHS architecture is builds on a lower functional layer and performs and performs a well defined and unique traffic management or vehicle control task with minimal support from other layers. While inputs and information is received from other functional layers, the specific management or control task is performed predominately within the layer.

The building blocks of each of the control layers in this architecture are groups of elemental functions. Elemental functions pertain to sensing, monitoring, decision making, and actuation.

A complete list of the elemental functions contained within each control layer and their definitions is presented in the following section.

5.2 Elemental Function Definitions

AHS Elemental functions

The IVHS architecture includes five layers: the Network layer (responsible for route and flow control), the Link layer (responsible for path and congestion control), the Coordination layer (responsible for vehicle maneuver coordination), the Regulation layer (responsible for vehicle maneuver control command), and the Physical layer (responsible forsensing and vehicle actuation). The operations that must be performed by human operators are specified as essential human functions. The layered architecture is defined in such a way that each control layer is built on top of the lower functional layer and accomplishes a unique traffic management or vehicle control task with minimal support from other layers. Corresponding to the layered architecture, the elemental functions are grouped into five hierarchical layers, each of which possesses a set of elemental functions dealing with sensing, monitoring, decision making, and actuation. Appendix A presents a complete list, by control layer, of the elemental functions.

6.0 Communications and Information Processing Requirements

This section discusses the Communications and Information Processing requirements for each of the five control layers. These requirements are used to better understand the differences between the six RSCs defined in Section 3. Each RSC represents a different partitioning of the required functions between the infrastructure and the vehicle.

6.1 Information Flow Requirements

Before it is possible to understand the communications and processing requirement, it is important to understand what information must flow between each of the layers. Figures5 and 6 illustrate this information flow.

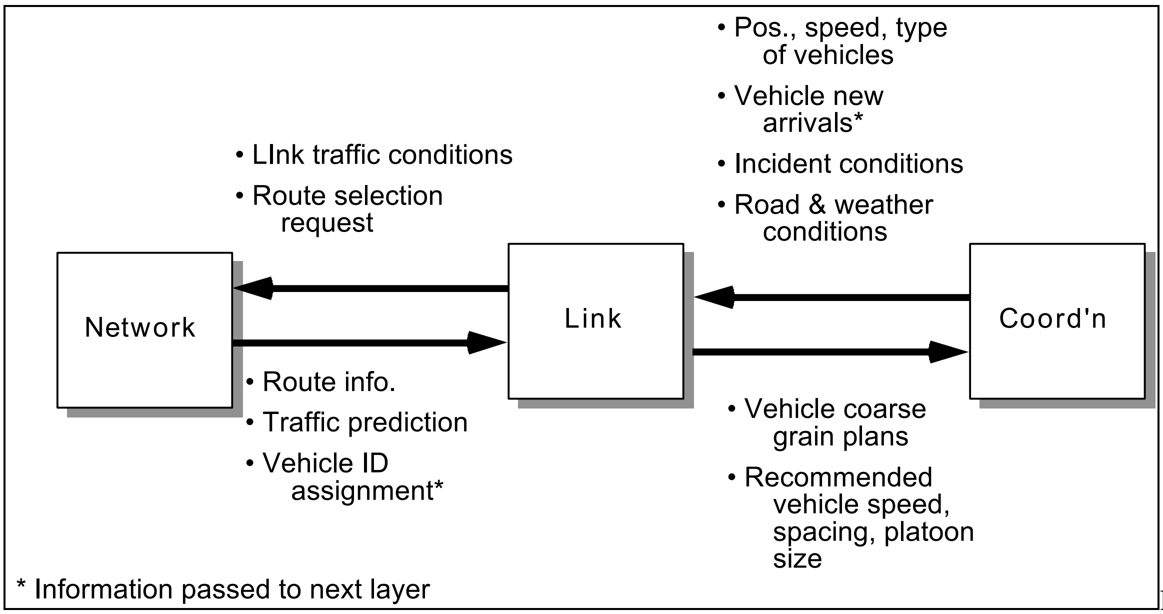

Figure 5. Information Flow

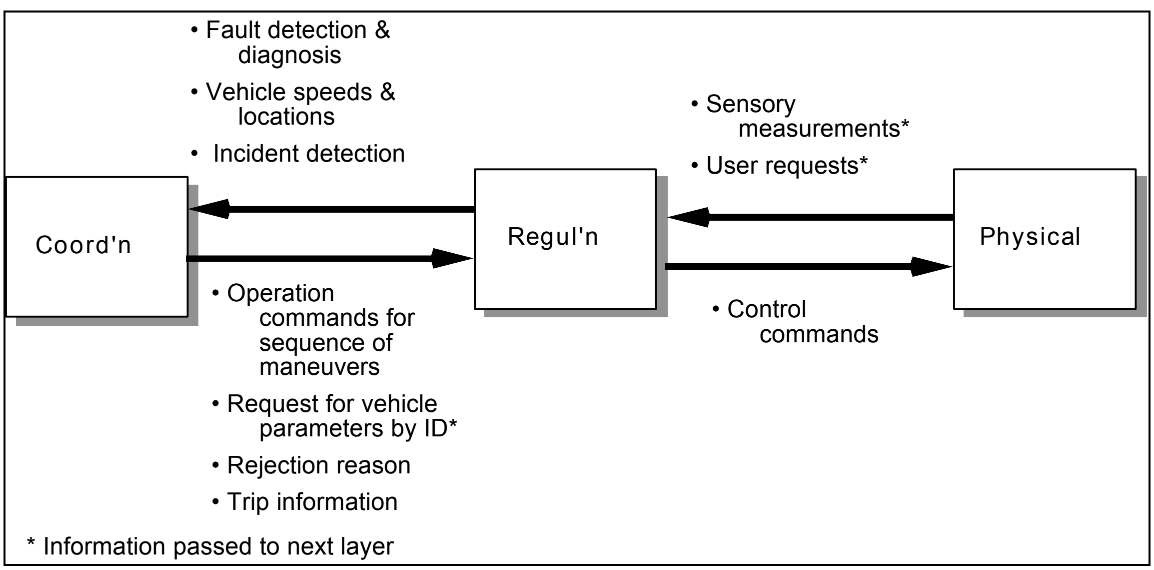

Figure 6. Information Flow

The Network layer communicates general route information and predictions of traffic conditions to the Link layer. In addition, the Network assigns an ID to each vehicle as it enters the AHS. This ID is also transmitted to the Link layer.

In return, the Link layer transmits traffic conditions within the link to the Network layer for the Network to use in developing overall traffic predictions. The Link layer also communicates requests for route selection for a specific vehicle up to the Network.

The information the Link layer communicates to the Coordination layer includes coarse grain plans for each vehicle, specifying lane assignments and recommended vehicle speed, intervehicle spacing, and maximum platoon size. These parameters are recommendations rather than requirements and can be changed by the Coordination layer if local changes in conditions warrant.

The Coordination layer communicates several types of information to the Link layer. The position, speed, and type of each vehicle within the local sector is transmitted, and used by the Link layer to update vehicle position maps for processing the optimizing lane assignment algorithms. Also, the Coordination layer communicates information on new vehicles entering the system. This information is used by the Link layer and re-transmitted to the Network layer for the Network layer to assign an ID to the new vehicle. The Coordination layer also communicates local road and weather conditions and incident or hazard conditions which currently exist.

The Coordination layer maintains complete position and speed information on every vehicle within its sector. The information is used to update a vehicle map and is obtained from the Regulation layer via a request for a specific vehicles position and speed. All lane changing is planned by the Coordination layer. The plan includes a detailed X,Y,T trajectory for each maneuvering vehicle and neighboring vehicles.

The Coordination layer has responsibility for permitting or rejecting a vehicle from entering the AHS. If a vehicle is rejected, the reason for the rejection is communicated to the Regulation layer for eventual communication to the driver. Overall trip progress for each vehicle is maintained by the Coordination layer and trip information updates are transmitted to the Regulation layer.

The Regulation layer immediately communicates to the Coordination layer variances to the planned maneuver. This includes fault detection and diagnosis for any subsystems used for the maneuver and incident detection. Either of these events can preclude the maneuver from occurring and requires the Coordination layer to re-plan the maneuver with updated variance information. The Regulation layer also transmits the individual vehicle's current position and speed when requested by the Coordination layer.

The Regulation layer uses the planned maneuver trajectory from the coordination layer and develops steering and braking control commands for the actuators. These control commands are transmitted to the actuators in the Physical layer.

In addition to the actuators, the Physical layer includes all of the sensors required for AHS. The sensory information obtained by the Physical layer is communicated to the Regulation layer. The Physical layer also includes the driver, and driver requests are communicated to the Regulation layer for re-transmission to higher layers in the control architecture.

6.2 Information Processing Requirements

This section presents the information processing requirements for each of the control layers.

6.2.1 Information Processing Requirements by Control Layer

Figures 7 and 8 present the information processing requirement for each of the control layers. The processing requirements are summarized separately for each elemental function within the layer. The requirements are assigned a low, medium, or high descriptor. These are intended as a relative measure of the computational intensity required to perform the functions. The following guidelines will help to define these measures.

1. Low:
   - Essentially trivial calculation
   - Can easily be performed in background on processor used for other elemental functions
   - Minor cost impact

2. Medium:
   - Requirement within the state of the art for processors within the size and cost constraints for the application
   - Moderate cost impact

3. High:
   - Requirement not currently within the state of the art for processors of the required size and cost constraints
   - Should be viewed as a technical issue
   - Due to the rapidly advancing performance of processors, could be attainable for AHS
   - Unknown cost impact

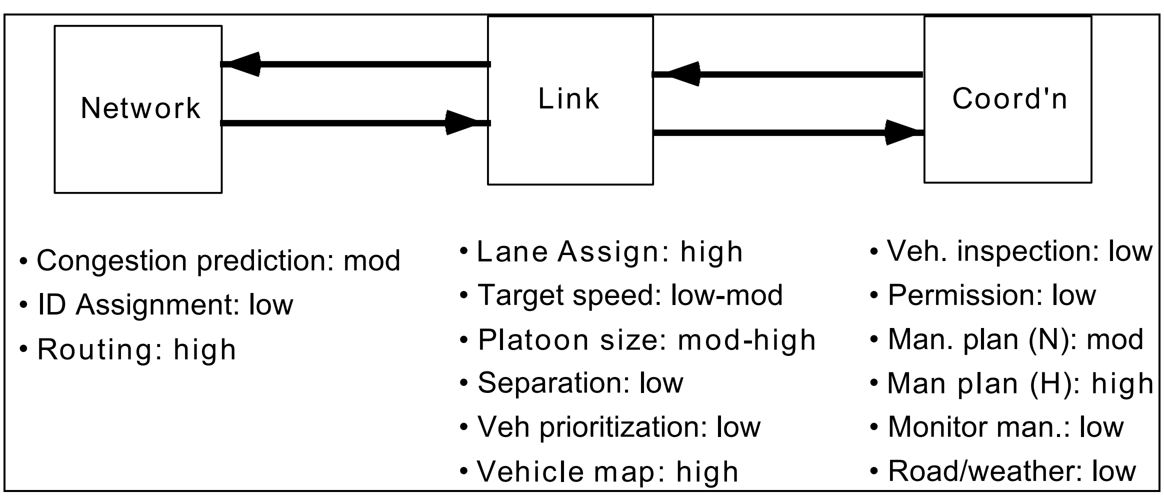

Figure 7. Processing requirements

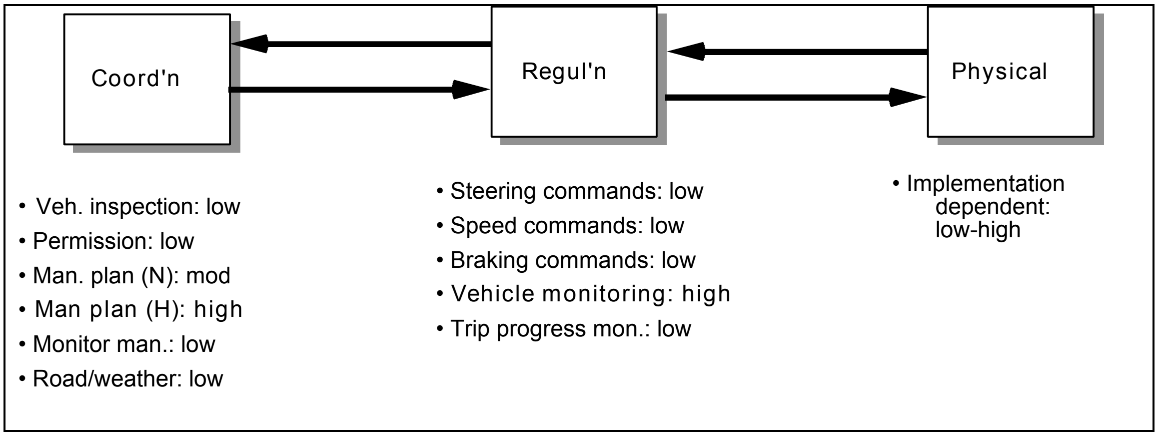

Figure 8. Processing requirements

<u>Network Layer</u>
The critical processing requirement for the Network layer is the routing elemental function. The function involves assembling information on all vehicle positions and speed within the Network and performing a large scale optimization on the data. The optimization will maximize the flow of vehicles through the Network based on a measure such as the number of vehicles or the value of the vehicles. The computational intensity can vary greatly depending on the details used in the optimization algorithms.

<u>Link Layer</u>
The Link layer has several elemental functions with high processing requirements. The lane assignment function is a similar optimization function to the routing function in the Network layer. The processing requirement depends on the number of lanes in the line as well as the density of vehicles. Obviously, if there is only one lane, the processing requirement becomes low, and if there are many lanes, the optimization problem is significant.

Platoon size again is an optimization problem but of a somewhat smaller size. Again, the problem is one of maximizing traffic flow and yet accommodating the required lane changes.

The vehicle map function requires fairly significant processing because it maintains a file on every vehicle within the link and frequently updates and correlates new information as it is received.

<u>Coordination layer</u>
The primary processing function in the Coordination layer is the maneuver planning under hazard conditions. This requirement is driven by the required calculations and the very short time allowed for the calculations to be performed. The time element is the primary difference between the processing requirement for the maneuver planning under normal conditions and under hazard conditions.

<u>Regulation layer</u>
The vehicle monitoring function continuously monitors a physical function and detects transient anomalies. This monitoring function is performed in real time within the vehicle and requires significant signal processing. It is possible that the sensor in the Physical layer perform its own monitoring and thus the processing requirement is relegated to the Physical layer.

Physical layer

The processing requirement for each of the sensors in the AHS will vary significantly depending on the type of sensor and how "smart" the sensor is. For example, a high resolution imaging sensor will require significantly more processing than a sensor monitoring the tire pressure.

6.2.2 Information Processing Requirements by Elemental Function

This section presents an outline of the information processing requirements for each of the elemental functions in the Network, Link, and Coordination Layers.

N1. Monitoring traffic conditions and predicting congestion.

Inputs:
- External sources such as highway patrol, sporting event administrators.
- Reports from individual vehicles (e.g. via mobile phone) that “short-circuit” thelink layer.
- Updates: event-based. Timeliness: worst case is major incident, which should be reported as a network layer event within minutes (faster at link layer)
- Congestion reports from link layer. Continuous updates; timeliness within minutes.
- Historical databases. Non-real time.

Processing:

Implementation-dependent - generally moderate processing

Outputs:
- Predicted traffic loads used by N3. Timeliness: minutes.
- Predicted traffic loads used by L1, L2, L3, possibly L4

N2. Vehicle ID Assignment.

Inputs:
- Existence of vehicle at AHS entry. Event-based. Timeliness on the order ofcheck-in time, possibly down to a few seconds
- Possible additional vehicle-specific data, including permanent (e.g., size of vehicle) and trip-dependent (e.g., number of occupants (for HOV priority), gross weight).
- This information may be encoded into the ID for use in other functions such asL5.

Processing:
- Minimal: Simple bookkeeping once inputs are available.
- Need capability to de-assign IDs as vehicles leave system so that they may be reused, in order to limit the ID size.

Outputs:
- Assigned ID sent to vehicle.
- Performed when vehicle checks into AHS.
- Size: dependent on mechanization and use. Bounded above by a permanentunique identifier for every vehicle (approximately 30 bits). Since this identifier will be used extensively, an efficient (small) ID is desirable.

N3. Routing.

Inputs:

- Specific destination for the individual vehicle/user. This is to be provided at the moment of entering the system. Timeliness: of the order of check-in, (perhaps 10 seconds).
- Information on traffic conditions throughout the network.

Processing:

The routing function can demand a fairly large amount of processing, depending on the complexity incorporated in the algorithm.

Outputs:

Planned route, either for the entire trip or a portion of a trip if routing updates are used. This is used to effect switch point maneuvers, as well as to inform the driver/occupants.

L1. Lane Assignment.

Inputs:

- Position and speed information for each vehicle in the link. These are provided from link level sensors and by sensors at the lower layers relayed through the coordination layer. Additional information may include details on each vehicle's characteristics such as vehicle type (e.g., truck with low accel/decel capability), priority (e.g., HOV or emergency vehicle), etc. that could influence lane assignments.
- New vehicle arrivals and vehicles exiting within the link.
- Vehicle ID for each vehicle in the link, so that a lane change command may be issued to an individual vehicle.
- Congestion levels for adjacent downstream link(s). These are provided by estimates generated by the network layer (using knowledge of user destination plans etc.), and by the downstream links themselves.
- Incident information for this link and adjacent downstream link(s). This is provided by the network layer (using knowledge of user destination plans etc.), and by the downstream links themselves.
- Routing information from N3 regarding each vehicle's next link (if there is a switch alternative) or whether the vehicle's destination is within this link.
- Road and weather conditions.
- Historical estimates of anticipated new arrivals within the link (at entrance ramps; probably only one per link by definition).
- Static knowledge of the geometry within the link and adjacent downstream links

Processing:

- Lane assignment decisions for congestion control is coupled heavily with other congestion control functions, specifically L3, L4, and L2, and therefore the processing load should be considered as a whole. Depending on the quality of the process, the computational load could be significant.
- Lane assignment decisions for routing purposes should be integrated with the congestion control aspects, but is otherwise straightforward.

Outputs:

- Notification to the coordination layer of the decision for the need for a lane change within the link together with approximate spacing and timing and any associated hard constraints (such as physical barriers).

- The flow of vehicles per lane is perhaps 7000 veh/hour, times the number of lanes (say 5) gives the rate of lane assignments per link. Each message is quite small, say 3 bits (8 lanes).

L2. Target Speed.

Inputs:
- Estimated congestion levels for this and adjacent links from the network layer L1. Includes predictions of new arrival rates.
- Congestion level for this link from link layer sensors L6.
- Road and weather conditions from C5.
- Geometry of link and adjacent downstream links (static database).

Processing:
Small to moderate; likely coupled with L3, L4, possibly L1.

Outputs:
Recommended target speeds for use by coordination layer normal maneuver planning C3.1, which is assumed to include normal cruising conditions as well as lane changing etc.

L3. Maximum group (platoon) size.

Inputs:
- Regional traffic load.
- Distribution of vehicles with exit (destinations) within this link.
- Expected arrival rates of new vehicles to this link.

Processing:
Small to moderate.

Outputs:
The maximum platoon size is provided to the coordination layer for maneuver coordination planning C3.1, specifically, for maneuvers involving the creation and dissolution of platoons.

L4. Minimal separations.

Inputs:
- Roadway and weather conditions (i.e., traction and visibility).
- Road geometry (static database).
- Own vehicle's deceleration capability.
- Lead vehicle's deceleration capability.
- If platooned, platoon's deceleration capability.

Processing:
Small.

Outputs:
- Separation between single vehicle and preceding vehicle if singlet
- Separation between platoon leader and preceding vehicle if platooned

L5. Prioritizing vehicle operations.

Inputs:
Vehicle characteristics: ambulance, fire engine, HOV, etc.

Processing:
Small.

Outputs:
An encoding of those characteristics.

L6. Regional traffic conditions monitoring and incident management.

Inputs:
- Link layer sensors for vehicle flow and incident detection (video cameras, inductive loops, etc.).
- Flow and incident detection information from in-link vehicles.
- Knowledge of appropriate resources to alert under different incident conditions.

Processing:
- Normal traffic congestion estimation and reporting: small.
- Incident detection: small using reactive design, large if expert system.
- Incident diagnosis and determination of appropriate response: moderate.
- Planning for diversion around incident; coupled with lane change planning L1: moderate.
- Planning for emergency vehicle ingress/egress; coupled with lane change planning L1: moderate.

Outputs:
- Normal congestion reporting, used by network layer N1 and N3, and by link layer L1, L2, L3, and L4.
- Notification of incident to adjacent links (link neighborhood = “region”), and to network layer N1 and N3.
- Emergency response requests to resources via network layer.
- Plans for normal vehicles to divert around incident to coordination layer C3.1.
- Plans for emergency vehicles to/from incident to coordination layer C3.1.

C1. Vehicle inspection and monitoring.

Inputs:
Sensor inputs from R4.

Processing:
Small.

Outputs:
If vehicle fault is detected as present or imminent, notification is provided to C3.2

C2. Issuing permission/rejection.

Inputs:
- Health and status of the vehicle.
- Driver condition and license status.
- Destination.

Processing:
Small; presumable most tests are continuously and reliably performed on the vehicle, and only reporting is required for the most part.

Outputs:
- Notification to the vehicle of rejection so that it may perform maneuver through proper rejection path.
- Notification to driver of reasons for rejection.
- If vehicle is permitted entry, notification is given to link layer to initiate merge planning procedure L1.

C3.1. Normal maneuver coordination planning.

Inputs:
Approximate plan for maneuver from link layer L1.

Processing:
Moderate.

Outputs:
Planned maneuver trajectory, X,Y,T coordinates of the vehicle.

C3.2. Maneuvering coordination planning for hazardous conditions.

Inputs:
- Information on hazard condition.
- Information from Link layer on vehicle speeds and positions.

Processing:
Moderate.

Outputs:
Planned vehicle trajectory: X, Y, T coordinates.

C4. Supervising the sequence of coordinated maneuvers.

Inputs:
- Planned X, Y, T maneuver.
- Actual X, Y, T of the vehicle maneuver.

Processing:
Small.

Outputs:
If comparison is not within tolerance, alert maneuver coordination function for reprogram

C5. Monitoring road surface conditions and weather.

Inputs:
Sensor measurements.

Processing:
Small.

Outputs:
Information on surface conditions.

6.3 Communication Requirements

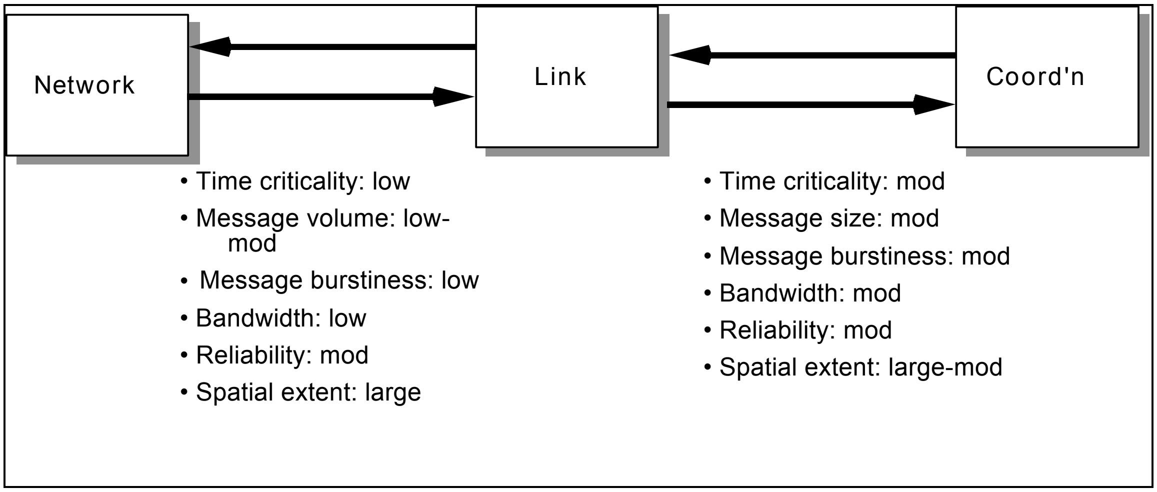

Figure 9. Communications requirements

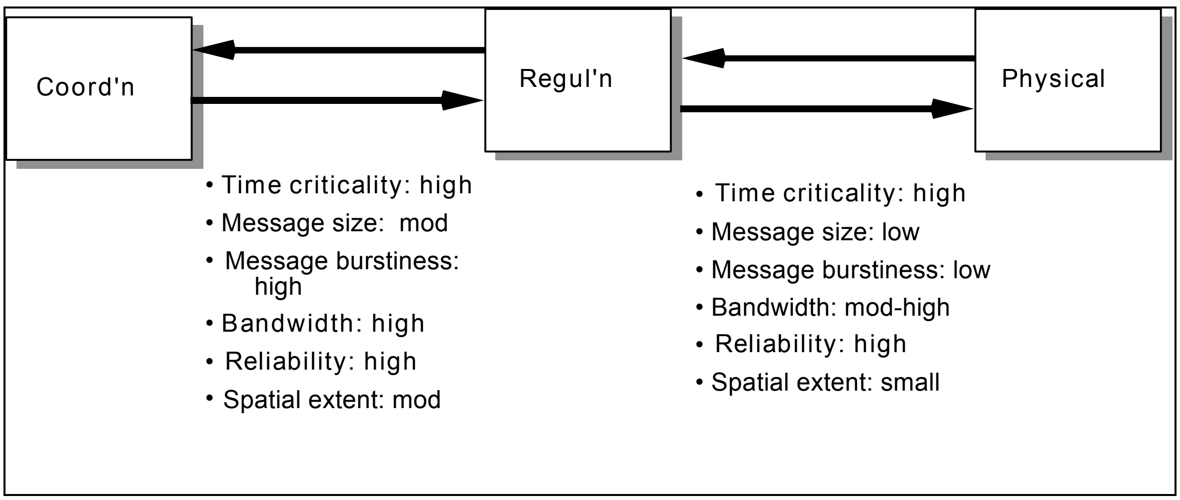

Figure 10. Communications requirements

The communication requirements between each of the layers are illustrated in Figures9 and 10. The communications requirements are subjectively evaluated in six categories:

1. Time Criticality: Given that a message is created at the source, what is the maximum tolerable delay until the intended recipient receives the message.

2. Message size: Average bits per message.

3. Burstiness: Describes how the messages are distributed over time. Low burstiness indicates generally uniform, continuous message generation, while high burstiness indicates a sporadic, non-continuous message generation process.

4. Bandwidth: Volume of messages per second offered for transmission (by the source). Measured in bits/sec.

5. Reliability: Measure of the criticality of the message being received correctly.

6. Spatial extent: Distance over which the communication must occur.

Network -Link layers
The overall communications requirements between the Network and Link layers is low. The messages are basically continuous with low message volume and low time criticality.

Link - Coordination layers
The communications requirements between the Link layer and the Coordination layer is moderate. The primary factor for the communication requirement is the updates for each vehicle's speed and position for the Link layer to maintain the vehicle map. These updates are periodic and could be on demand from the Link layer. The message volume for each update is relatively small.

Coordination - Regulation layers
This communication link must fulfill high communications requirements. The Regulation layer must send regular updates on the results of the maneuvers that the vehicle is attempting to carry out. Fairly continuous re-programming and updated trajectories are transmitted to the Regulation layer. All messages are time critical, moderate size, and must be reliably received.

Regulation - Physical layers
The time criticality of this communication link is high. Sensor actuator faults must be rapidly detected. Because of the extreme safety critical nature of this communication link, the reliability of accurately receiving each message must be very high.

6.4 Communications and Processing Requirements Conclusions

Section 3 presented six Representative System Configurations based on different approaches to partitioning the required AHS functions between the infrastructure and vehicle. Based on this analysis the following observations can be made.

1. Because of the significant communications requirements between the Coordination and Regulation layers for the Maneuver planning function, it appears that the maneuver planning function of the Coordination layer should be done on the vehicle. This allows the coordination-regulation communications to be intra-vehicle instead of infrastructure-vehicle communications.

Additional analysis must be done to examine other issues related to performing the coordination function on the vehicle. When the maneuver planning function is performed on the vehicle, the AHS becomes equivalent to a system with many elements, each responding to relatively local conditons with a similar set of rules. A major issue which should be studied is the overall stability of a self-organizing complex system of this nature.

2. Because of the information processing requirements, it appears that the Link Layer functions should be performed by the infrastructure rather than the vehicle. Additional analyses is required to examine in more detail specific optimization algorithms and the associated processing requirements.

3. Because of these observations, the vehicle - infrastructure partitioning represented by RSCs #2,3, and 4 in tables 1 and 2 appear to be the most promising partitioning approaches.

6.5 Examples of Vehicle Based Maneuver Planning

Several analyses have illustrated the feasibility and desireability of performing the maneuver planning function on the vehicle rather than the infrastructure. Two of the supporting analyses are summarized.

6.5.1 Spontaneous Platooning

J. Agre and L. Clare of Rockwell International quantitatively simulated and examined the notion of spontaneous platooning. In their paper they presented a simple set of rules that each automated vehicle continuously applies using only its locally collected information, and showed that platoons are formed and dissolved in a completely distributed manner, i.e., no central control is present. This concept, called Spontaneous Platooning, has been tested and validated utilizing a microscopic simulation model of a freeway segment with on- and off-ramps and associated vehicle-following, merging, exiting, and lane-changing rules. Numerous scenarios have been simulated, and demonstrate the self-organization of vehicles to platoon or deplatoon adaptively with traffic demand. An example case is described in their paper in which vehicles enter and exit in nonplatooned mode, and yet steady state flows of up to 7200 vehicles/hour/lane are achieved.

6.5.2 Alternative AHS Evolution

Jerry Ward, in his paper “An Hypothesized Evolution of an Automated Highway System”, describes an evolution for AHS which involves several stages of vehicle automation. This alternative AHS deployment plan achieves the ultimate AHS goal in a sequential manner by deploying intermediate steps which take into consideration the number of cars equipped with the required automated equipment. This deployment concept supports a gradual and non-disruptive transition to completely automated lanes by first providing improvements in safety and efficiency in mixed traffic which involves automated and non-automated vehicles. At such time when sufficient vehicles are equipped for AHS operation, dedicated AHS highway lanes can be introduced and the ultimate AHS performance goals realized.

An important aspect of this evolution is AHS and non-AHS vehicles will be on the same road simultaneously until such time as most cars are equipped with AHS equipment. Because of this type of mixed mode traffic, the maneuver planning function will be done on the vehicle with relatively little input from the infrastructure.

Three possible stages of automation might be

1. Automatic braking - invisible to the driver and used in an emergency to avoid a hazard condition. Based on sensors contained on the vehicle.

2. Automatic inter-vehicle spacing control - automatic throttle control and automatic braking in non-emergency conditions. This is based on sensors contained on the vehicle and does not

require any infrastructure communications. Used by the automated vehicle driver when desired as an “Intelligent Cruise Control” to maintain a constant distance to the vehicle in front.

3. Automatic lane holding - maintain position within the lane. This can be accomplished with limited infrastructure modifications which could include magnetic nails in the middle of the lane as in the PATH concept or specially painted lines for vision sensors. The combination of automatic lane holding plus automatic inter-vehicle spacing control achieves a significant degree of the automation goal of AHS and has been referred to as “Automatic Cruise Control”.

7.0 Criticality and Failure Mode Analysis

This section summarizes the results of the criticality and failure mode analysis. The operational and elemental functions referred to in this section are those presented in Section 5. Several aspects of the criticality of AHS vehicle functions were examined ranging from high level qualitative judgements of each of the elemental functions to detailed quantitative safety critical analyses.

Section 7.1 describes the three operational functions which have been selected for in-depth criticality analysis. Functional flow diagrams and critical paths for each of these three operational functions are presented in Section 7.2. Section 7.3 presents detailed quantitative criticality analysis of the two primary safety critical operational functions, longitudinal and lateral control. Minimum performance and critical fault estimates for each of the elemental functions contained in the operational functional flow diagrams are presented in section 7.4. Finally, section 7.5 presents a qualitative assessment of elemental function criticality for each elemental function.

7.1 Selected Operational Function Case Studies

Three representative Operational Functions have been selected for in-depth analysis during the remainder of the Vehicle Operational Analysis studies. Specifically, one important operational function was selected from each of the first three mission oriented tasks. This will provide a meaningful balance between performing an in-depth analysis and the need to examine a broad range of issues.

1. Move Toward Destination:
   Steering for lane-changing (lateral control)
2. Incident Avoidance and Management:
   Spacing regulation (longitudinal control)
3. Resolve Contention for Shared Resources:
   Maneuvering coordination management (information flow)

Steering for lane-changing and Spacing regulation are key AHS operational functions and are critical toward achieving many of the top level AHS goals. Maneuvering coordination management places emphasis on the communication links and will identify communication related issues.

7.2 Functional flow diagrams and critical paths

7.2.1 Steering for Lane Changing

Figure 11 presents the functional flow diagram for the Steering for Lane Changing operational function. This function starts with information on the distance and closing rate to the neighboring vehicle, the turning parameters of the controlled vehicle, and the longitudinal position of the controlled vehicle relative to the road geometry. This information is communicated to the steering regulation function which determines an updated steering command which is communicated to the steering actuators. Once the steering command has been completed, updated controlled vehicle parameters are again measured and communicated to the steering regulation function and the process is repeated.

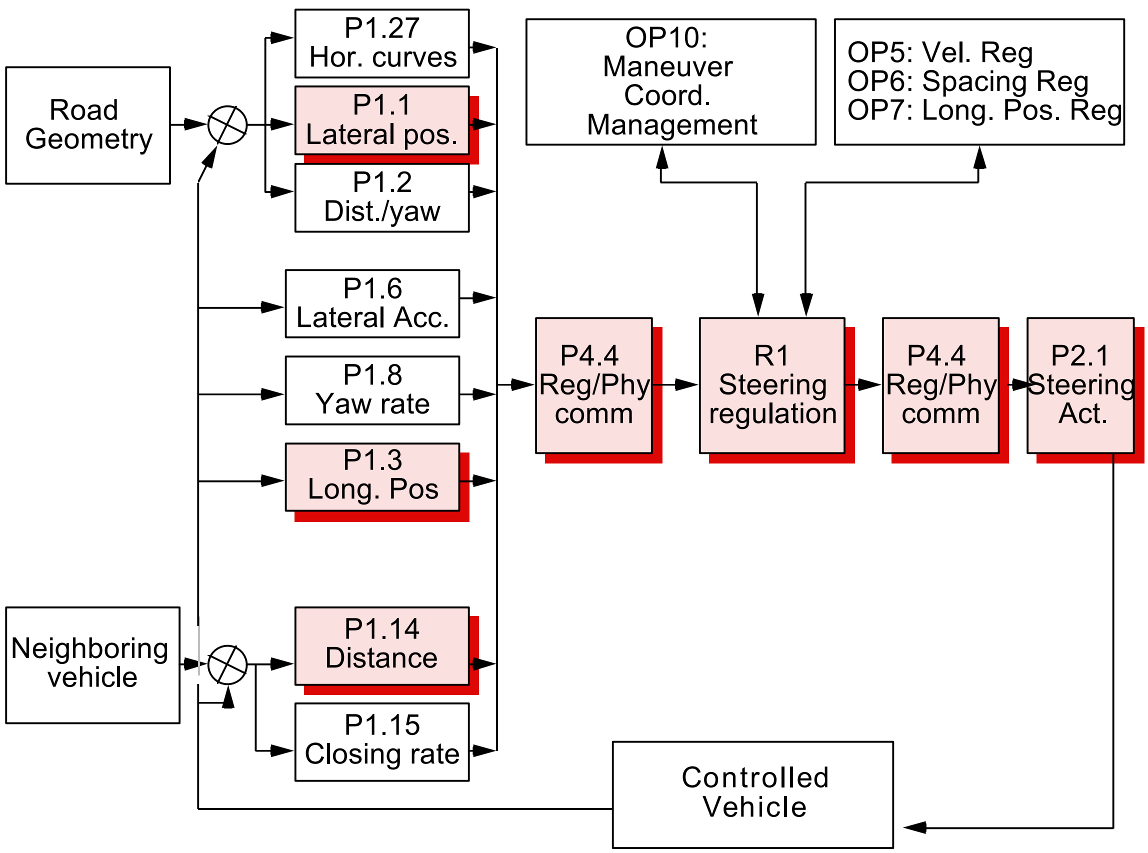

Figure 11. Steering for Lane Changing Functional Flow Diagram

The key inputs into the whole process are the outputs from the following operational functions:

OP10: Maneuver coordination Management - Defines the lane changing trajectory.

OP5: Velocity regulation - Controls the speed of the vehicle.

OP6: Spacing regulation - Controls the spacing between vehicles.

OP7: Longitudinal Position regulation - Maintains a minimum distance from an object.

The safety critical elemental functions are identified by the shadowed boxes. Together these elemental functions define a safety critical path for the operational function. In general, the safety critical path consists of those elemental functions associated with the distance between the controlled vehicle and object which could cause a hazard condition.

7.2.2 Spacing regulation

Figure 12 illustrates the functional flow diagram for the spacing regulation operational function. The important control vehicle parameters which are measured are

1. Distance to the frontal vehicle.
2. Closing rate to the frontal vehicle.
3. Longitudinal acceleration.
4. Velocity.

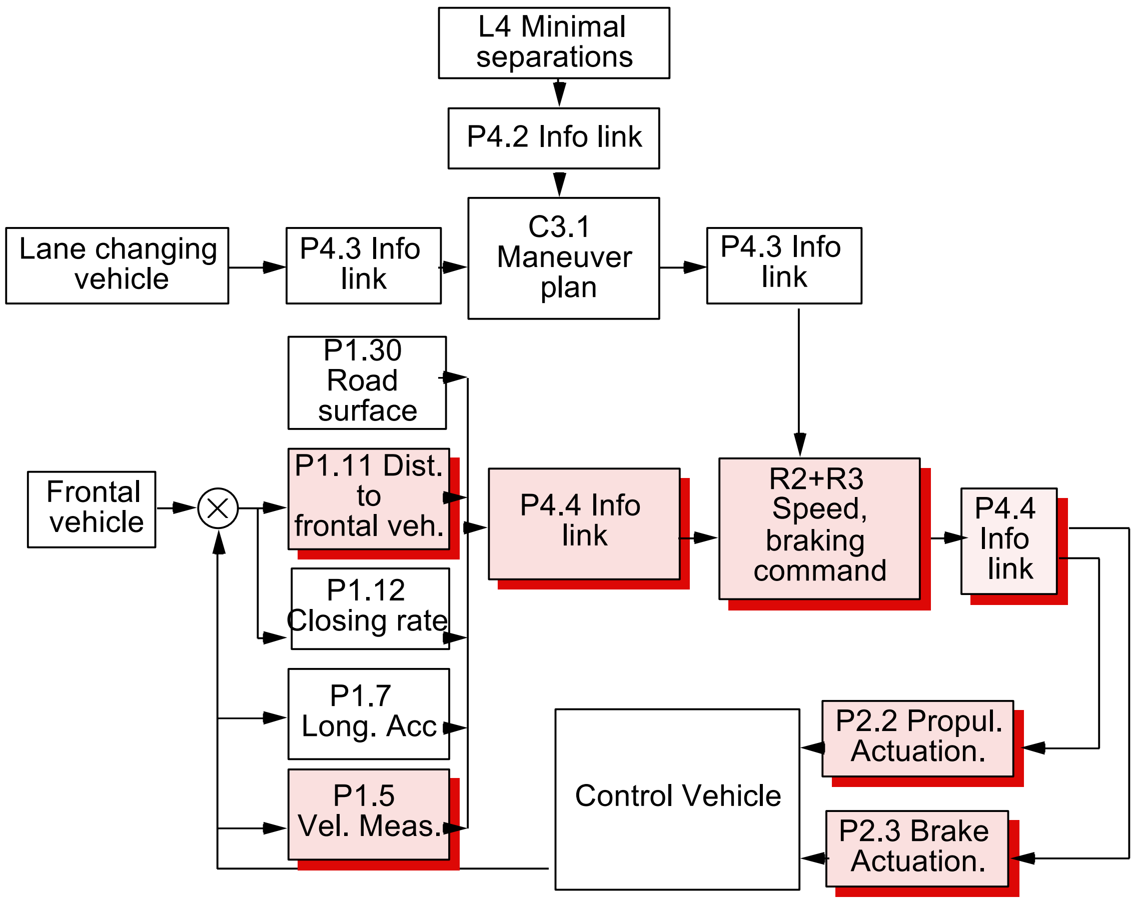

Figure 12. Spacing Regulation Functional Flow Diagram

This information together with the minimal separations and the maneuver coordination information on any lane changing vehicle determines an updated target path for the controlled vehicle. This is communicated to the speed and braking command elemental functions of the Regulation layer.

The target path braking and speed commands are communicated to the propulsion and brake actuators of the Physical layer. Once the commands have been completed, updated controlled vehicle parameters are measured and the process is repeated.

The shadowed boxes indicate the safety critical path for this operational function. The elemental functions within the critical path are related to maintaining a safe distance to the frontal vehicle.

7.2.3 Maneuvering coordination management

The Maneuvering coordination management operational function uses the following information on each vehicle which may be affected or involved in the lane changing maneuver:

1. Longitudinal position.
2. Lane.
3. Velocity.

This information is communicated to the coordination management planning operational functions to plan the lane changing maneuver trajectory.

The critical path for this operational function includes all of the elemental functions measuring the required input information. If any of the information is measured incorrectly, a hazard condition could develop.

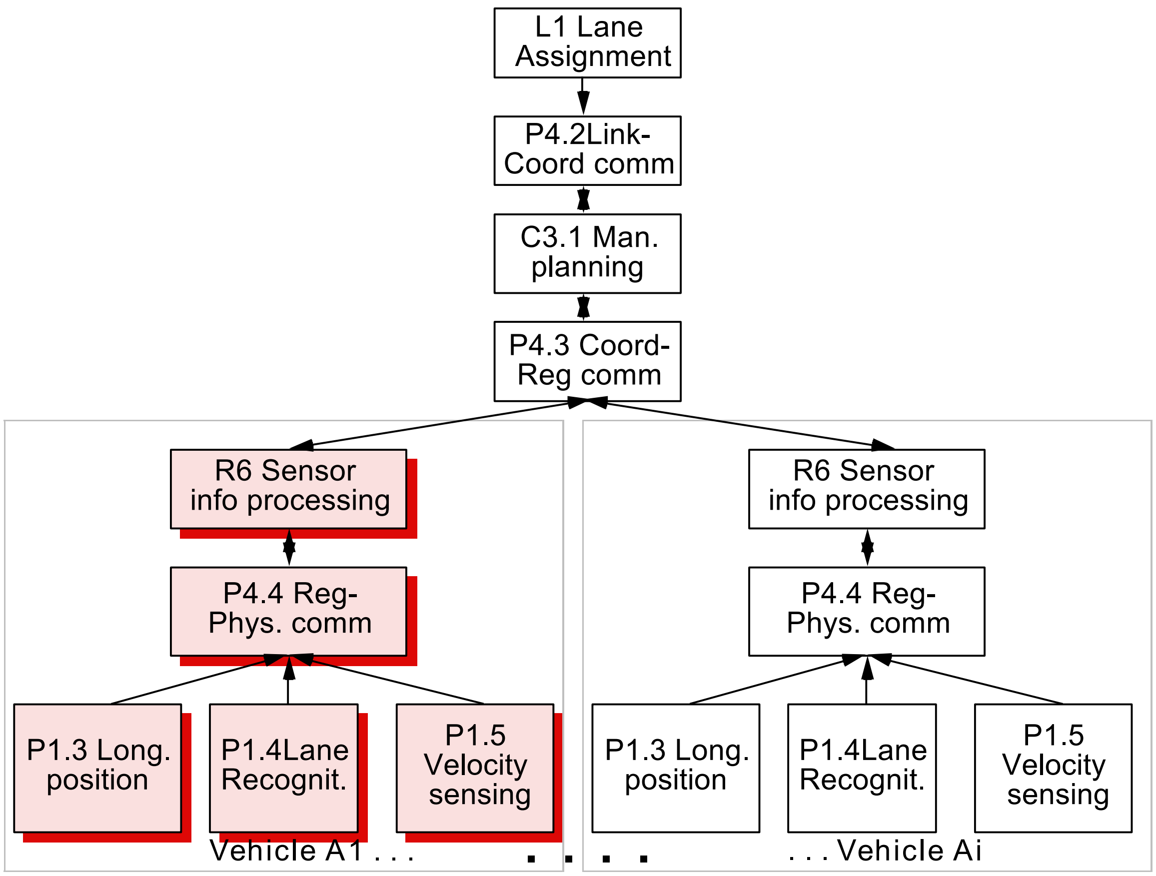

Figure 13. Maneuvering Coordination Management Functional Flow Diagram

7.3 Safety Criticality in Longitudinal and Lateral Control

This section quantitatively examines the safety critical issues related to the two primary safety related operational functions, longitudinal and lateral control. The basic approach is to parameterize key performance factors to identify safe operating conditions. Issues related to the effects of actuator bandwidth limitations, sensor noise and reduced information sets available for control on system performance are examined. It must be stressed that the results described in this section deal with criticality of functions, that is on safety (i.e., crash avoidance and system stability) rather than on passenger ride comfort issues.

7.3.1 Evaluating Criticality of Functions

First the limits of safe performance must be defined. It is possible that a vehicle operation might stray into unsafe regimes without compromizing system stability and vice versa. With this in mind two measures of evaluating criticality of functions based on control errors are defined.

1. The entire platoon system must be stable: The vehicle spacing errors must converge to zero.

e_i is the error (spacing error between vehicles or lateral displacement).

- The system is stable if for every $\varepsilon > 0$ there exists some $\delta_i > 0$ such that

$$\|\varepsilon_i(t_0)\| < \delta_i \Rightarrow \|\varepsilon_i(t_0)\| < \varepsilon \qquad \forall t_0$$

- In addition we require that there exists some $\delta_i > 0$ such that e_i 0 as t (More realistically there must exist some T (>t_0) such that

$$\|\varepsilon(t_0)\| \in B(0,\gamma) \qquad \forall t > (t_0 + T)$$

where γ is sufficiently small. The above requirement is purely a stability requirement that ensures a conservative upper bound on the system error and ensures that it goes to zero.

It is clear from the above that it is possible to violate safety requirements without compromizing system stability. Hence the additional requirement for safety criticality is given as follows.

2. Errors must at all times be within a maximum bound $e_{max,i}$

Longitudinal control: $e_{max,i}$ is dependent on crash avoidance requirements, i.e., it is equal to the stabilizing distance, d_i.

$$|e_{ix}(t)| \le \|e_{ix}\|_\infty < e_{max,t}$$

$$d_i = \frac{(v_{ix} - v_{i-1,x})^2}{2\, a_{max,i}}$$

It ensures that if the relative velocity between the controlled vehicle and its preceding one is non-zero, there is sufficient time for an emergency maneuver that avoids a vehicle crash. Hence e_{max} is dependent on the maximum acceleration and decleration capabilities of the vehicle.

Lateral Control: $e_{max,i}$ is the maximum lateral deviation that can be read off the sensing range for lateral deviation measurement.

The above requirements can be collapsed into 1 by requiring that

$$\delta x \leq e_{max,i} \quad \forall t$$

The vehicle models that were used in this analysis have been validated through extensive experimental work performed in the preceding years. Descriptions of the lateral and longitudinal vehicle control models are contained in Appendices B and C.

7.3.2 Longitudinal Vehicle Control Criticality Analysis

Longitudinal vehicle control involves design of controllers that ensure stable vehicle operation through all possible longitudinal vehicle maneuvers. There are three main modes of operations of the vehicle.

- Group mode: The vehicle is a member of a group of vehicles and the control objective is maintaining intervehicle spacing of sp_{des} during all maneuvers of the lead vehicle.

- Velocity regulation mode: The vehicle is either a free agent or a lead car of a platoon. The objective of vehicle control is to maintain a constant vehicle velocity.

- Transition mode : The vehicle/mini platoon is in the process of merging with a platoon ahead to form a single larger platoon or splitting from a larger platoon to form smaller platoons or for exit from AHS.

In the platooning mode the controller must also ensure that the error does not propagate down a string of vehicles. In transition maneuvers the controller must be designed to ensure smooth variation of control inputs.

It must be noted that an alternate approach to vehicle control is to regulate the time headway between succeeding vehicles of the platoon. This analysis emphasizes the constant spacing distance approach.

A model used for longitudinal vehicle control must capture the dynamics between the throttle and the observable parameter, the vehicle velocity. With this objective in mind a 6 state vehicle model was developed for a 5.0 liter, 8 cylinder FWS, RWD Lincoln Town car. The model is based on steady state engine maps. It includes two engine and four transmission states. A brief discussion of the model is contained in Appendix B.

The analysis uses the performance of a group of 10 cars as the simulation basis of study. The basic model only serves to highlight the degradation of system performance under non-ideal conditions. At the beginning of the simulation all vehicles are travelling at 25m/sec and the separation between succeeding cars of the platoon is equal to sp_{des}. The lead car of the platoon then follows a harsh deceleration and acceleration profile as shown in Figure 14. The variables of interest are:

1. Vehicle velocities, V_i (for i^{th} vehicle)
2. Vehicle accelerations, a_i
3. Spacing errors between vehicles, $e_i = x_i - x_{i-1} - sp_{des,i}$
4. Actual/stabilizing distance

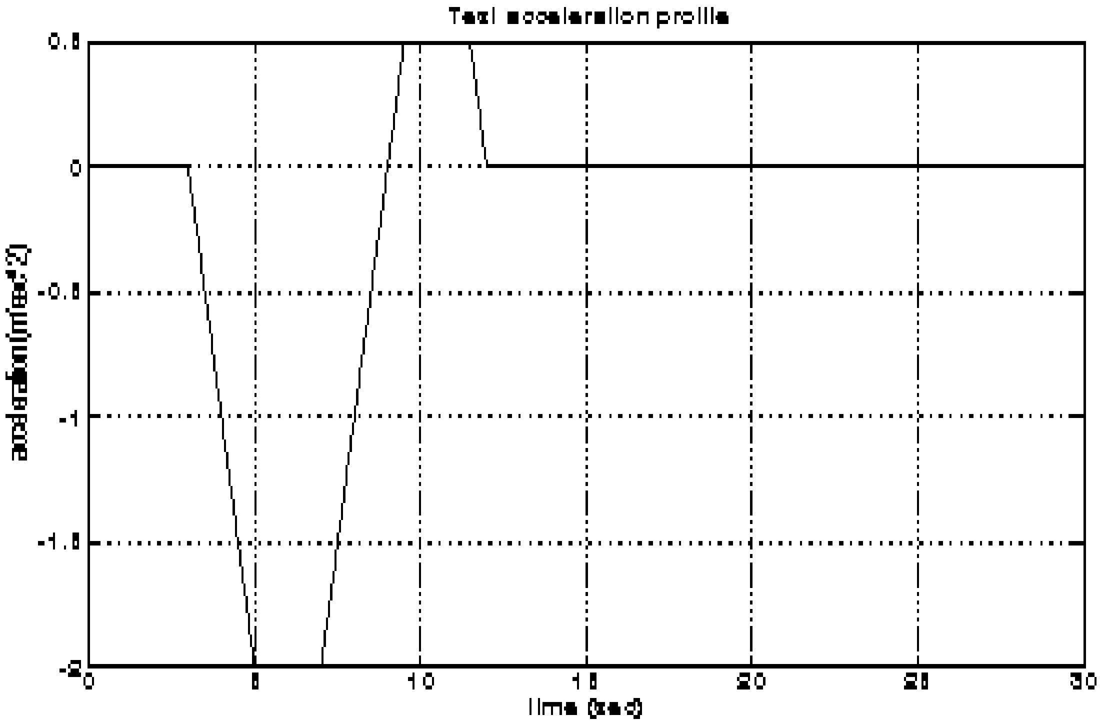

Figure 14. Lead Car Acceleration Profile

Assumptions for Baseline model

The baseline simulation scenario is an ideal case scenario with the following assumptions:

- Controller sampling time is 50ms.
- A spacing sensor provides inter-vehicle spacing measurement, $x_i - x_{i-1}$.
- A closing rate sensor provides relative vehicle velocity measurement, $v_i - v_{i-1}$.
- A communication link is used to transmit lead vehicle a_l, v_l, x_l and preceding vehicle a_{i-1}, v_{i-1}, x_{i-1} information.
- Sensor sampling time is 50ms and sensor readings are noise free.
- Throttle actuator has a 450/sec saturation rate and the braking actuator is modeled as a first order lag with time constant of 75 ms.
- Controller uses preceding as well as lead vehicle information.

Full Information Control

The first sets of simulations assume full information availability for control, i.e., lead and preceding vehicle acceleration information in addition to the spacing and closing rate information. Figure 16 shows vehicle velocity variations while Figure 15 shows the variation of vehicle acceleration. The plots show very good tracking. The velocity and acceleration of vehicles increase slightly down the string of vehicles. The controller has been designed to ensure attenuation of errors down the string of vehicles. This is seen in Figure 17 which shows the variation of the spacing errors of the platoon.

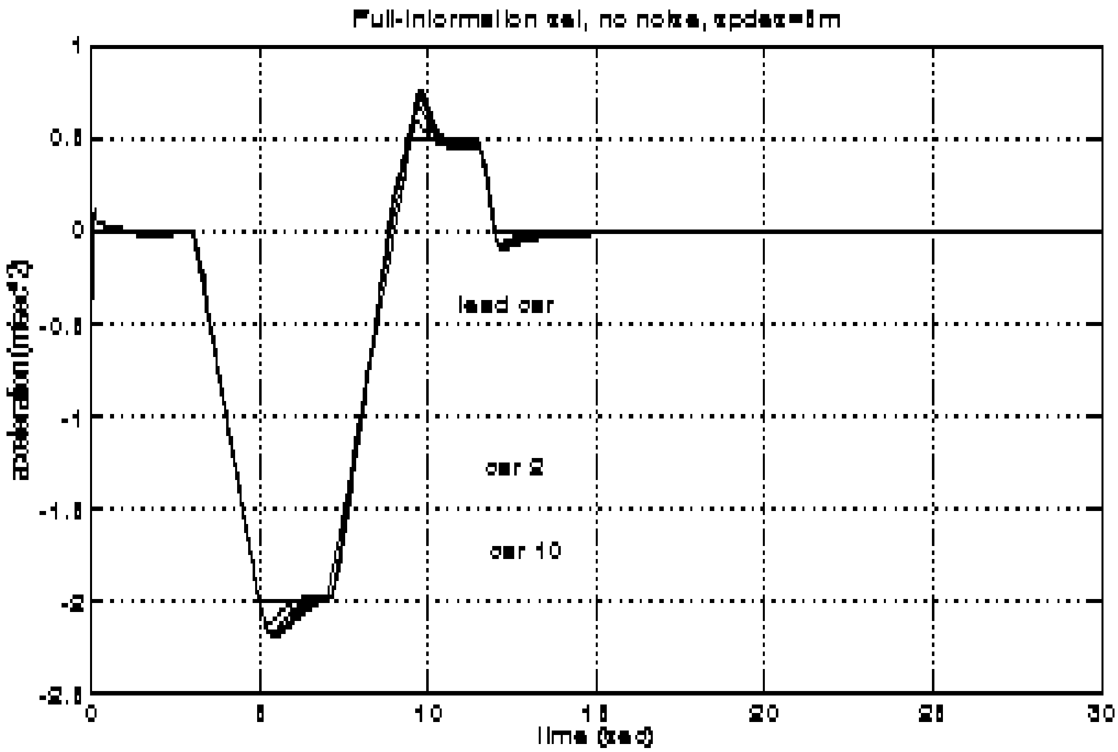

Figure 15. Baseline Simulation, no noise, full information - Velocity

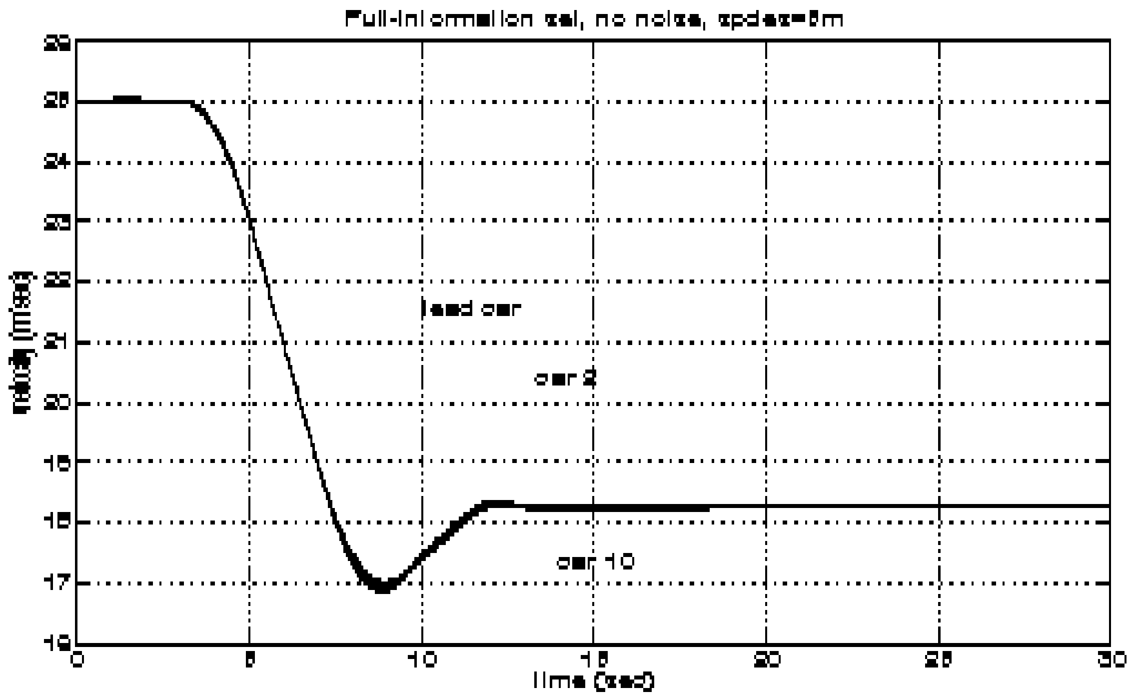

Figure 16. Baseline Simulation, no noise, full information - Acceleration

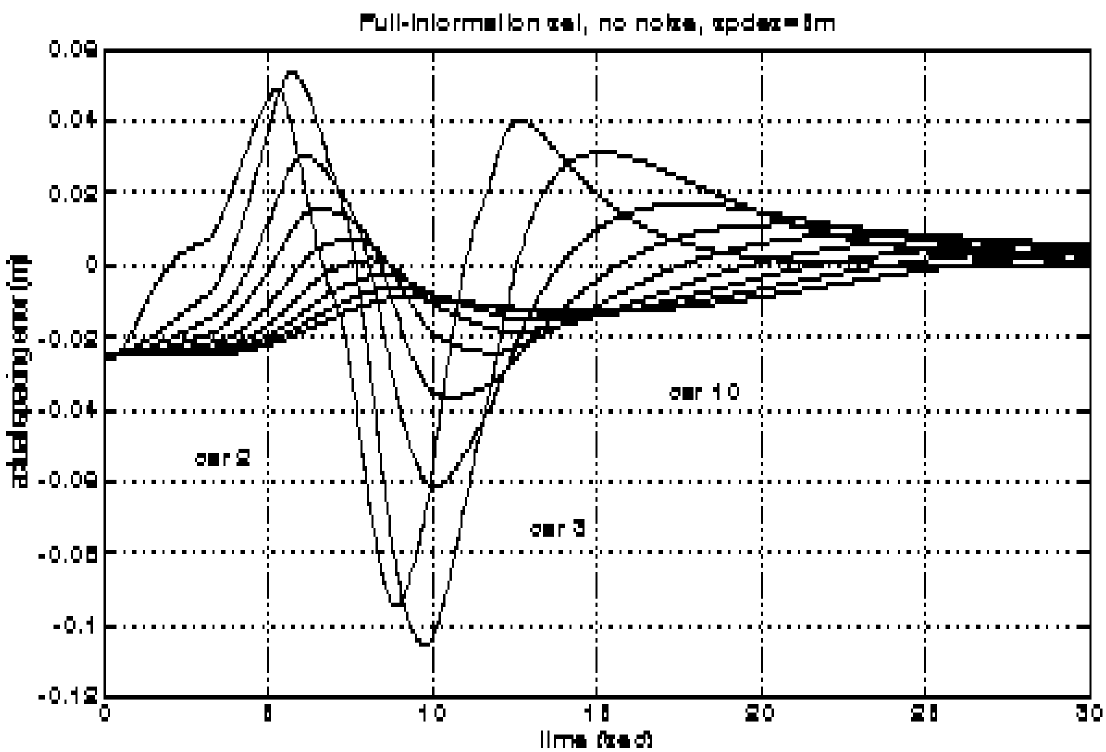

Figure 17. Baseline Simulation, no noise, full information - Spacing Errors

In order to observe the effect of noise in sensor channels on system performance a 5 % uniformly distributed noise was injected into the spacing sensor readings. This is equivalent to accurate sensor information at low spacings with readings becoming progressively worse at larger spacings.

Figures 18 and 19 are velocity and acceleration plots at desired spacing, sp_{des} = 1m, and indicate good tracking despite the presence of noise. This set of simulations is with full information availability for control.

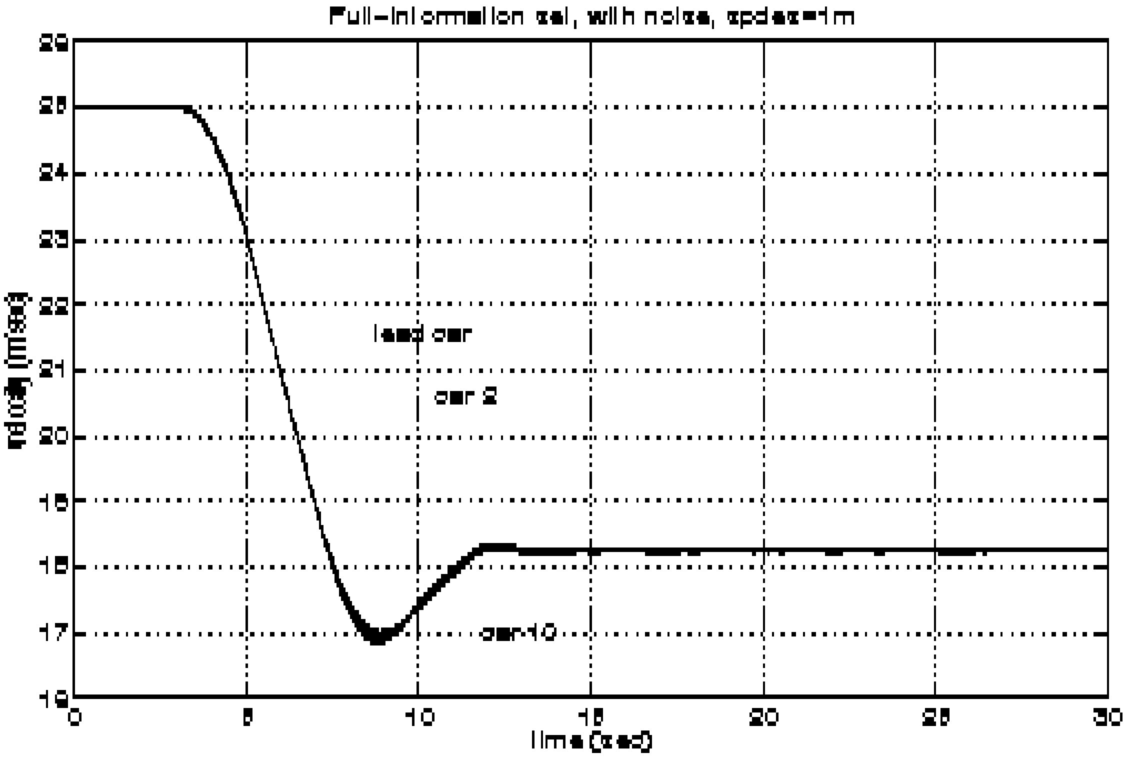

Figure 18. Velocity profiles with noise sp_{des} = 1m - Velocity

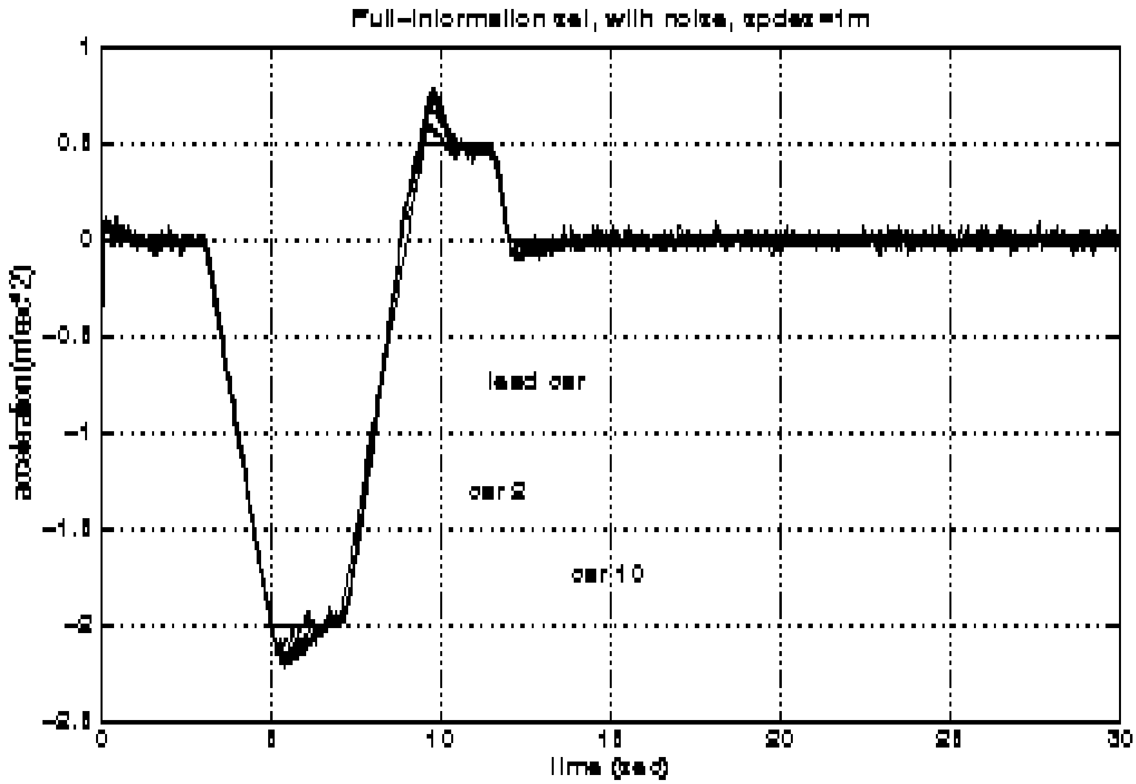

Figure 19. Acceleration profiles with noise sp_{des} = 1m - Acceleration

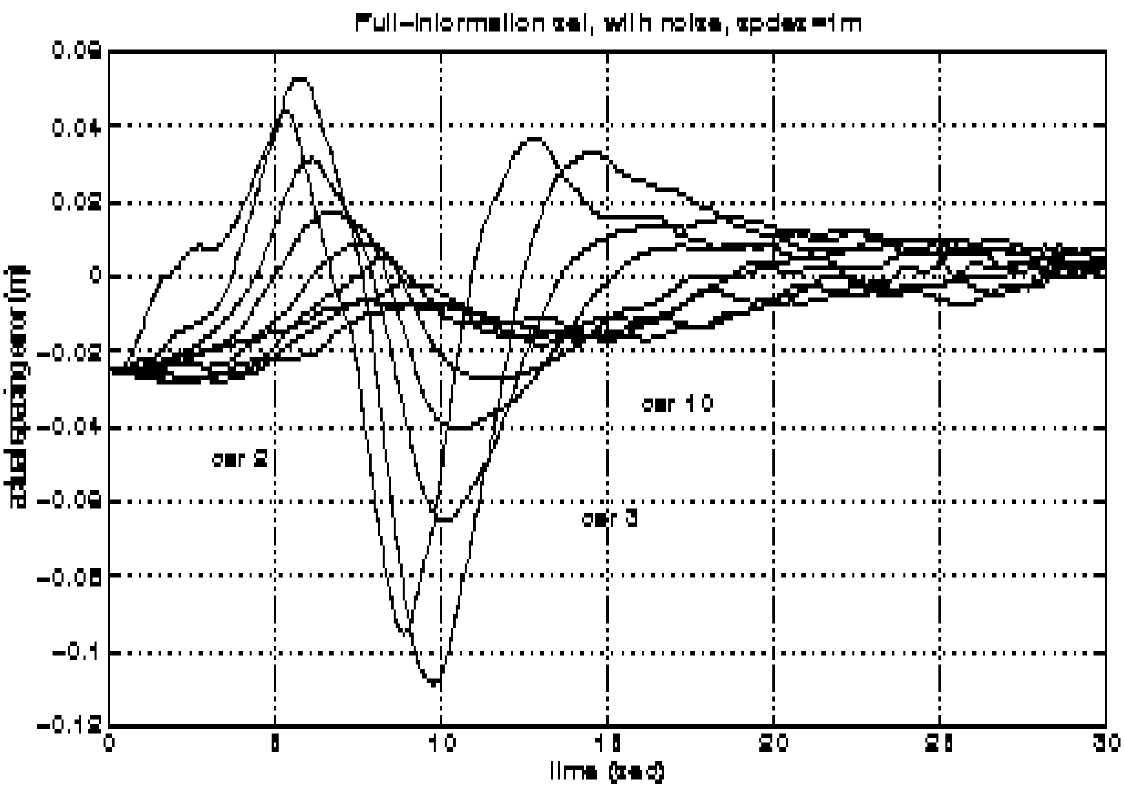

Figure 20. Spacing Error profiles with noise sp_{des} = 1m

Figure 20 shows the variation of the spacing errors of all the vehicles in the 10 vehicle platoon. For the desired spacing of 1m, the attenuation of errors is still seen since the noise level is sufficiently small. At larger spacings, the noise being a percentage of the target spacing, the noise level is high enough to obscure the attenuating effects of the controller. Figures 21, 22, and 23 show the comparison of the spacing errors of the 2nd, 3rd and 10th cars of the platoon respectively for various desired spacings.

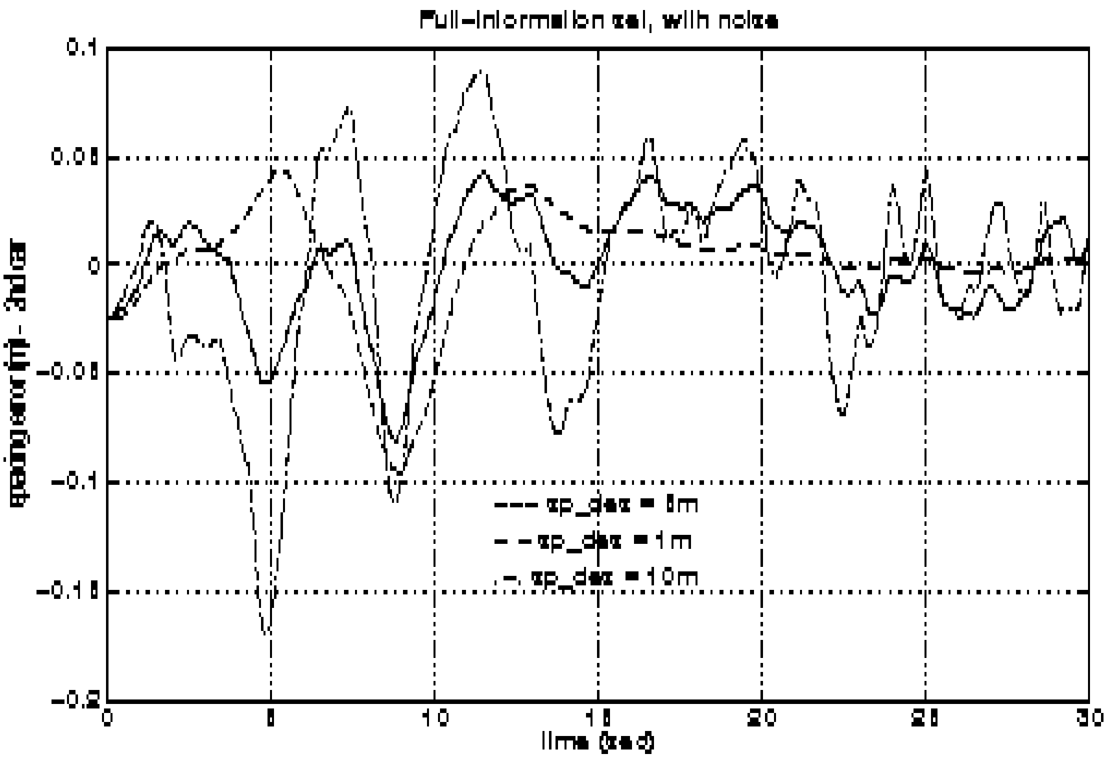

Figure 21. Spacing Error - 2nd vehicle, full information set

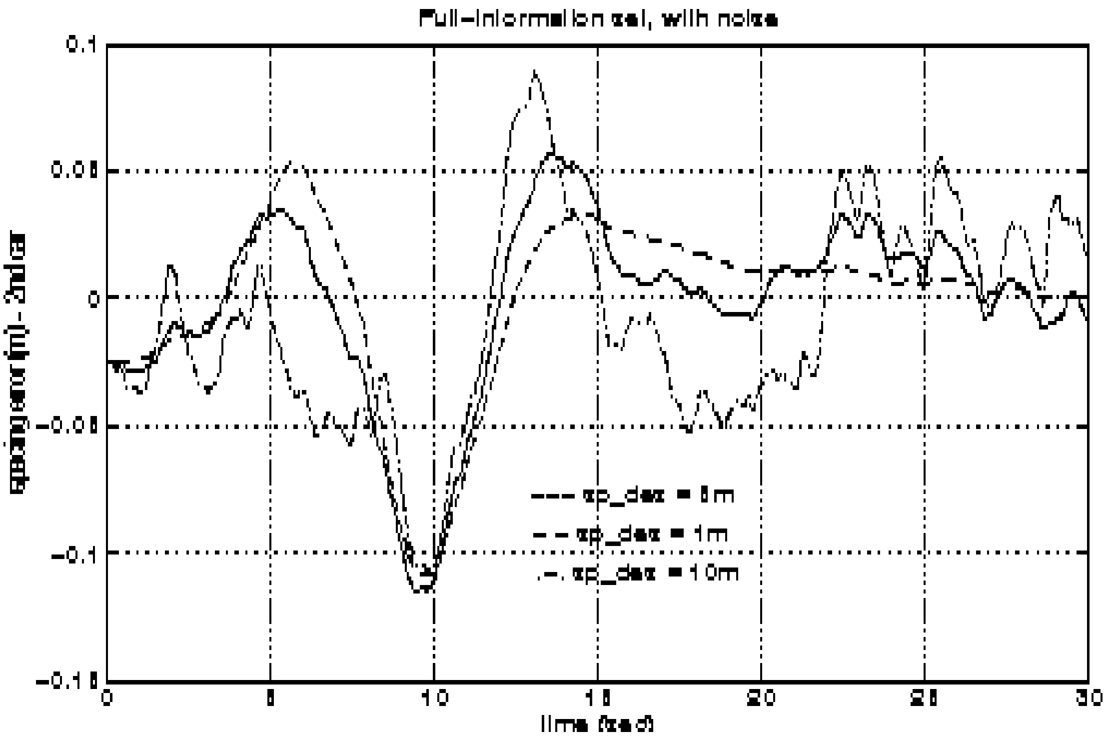

Figure 22. Spacing Error - 3rd vehicle, full information set

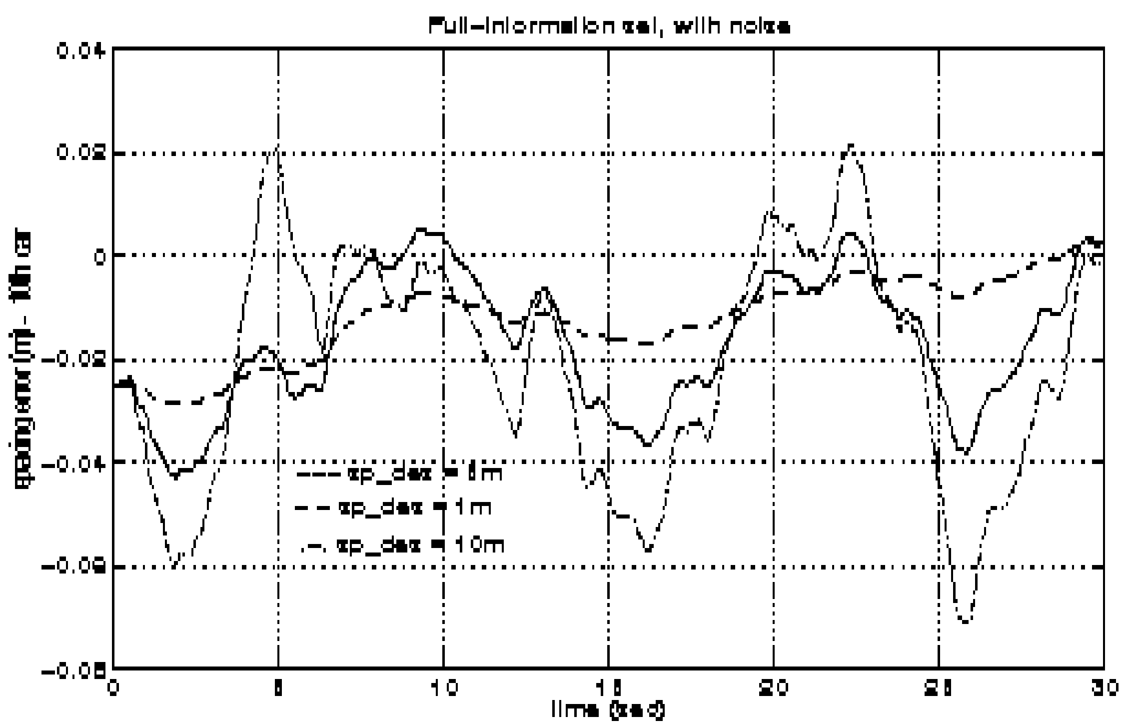

Figure 23. Spacing Error - 10th vehicle, full information set

With increased target spacing, as expected, we have larger spacing errors for each vehicle. At lower desired spacings the system can tolerate a higher percentage of noise without onset of actuator saturation or instability.

Control Without Communication

Without communication, lead car information is not available for control. Prior studies have shown that lead car information is necessary for error attenuation down a string of vehicles. Hence we must expect the spacing errors of subsequent vehicles to be at least as high as those of the immediately preceding vehicles.

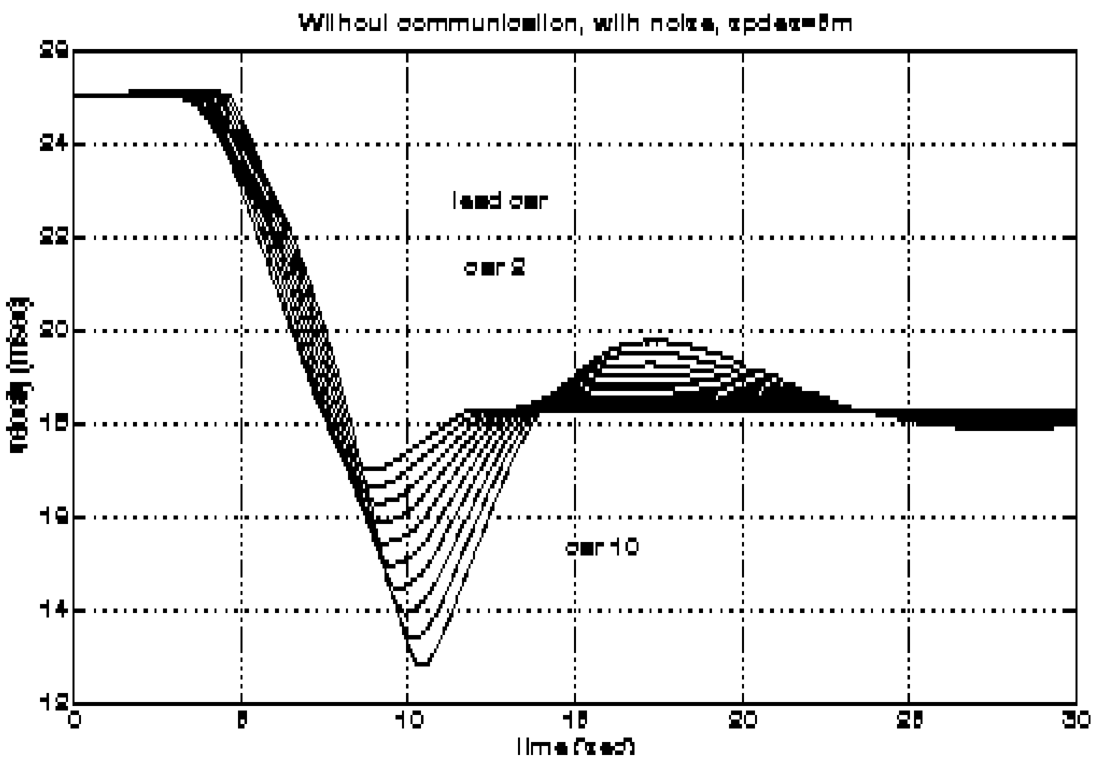

Figure 24. Velocity profiles, sp_{des} = 5m - no communication

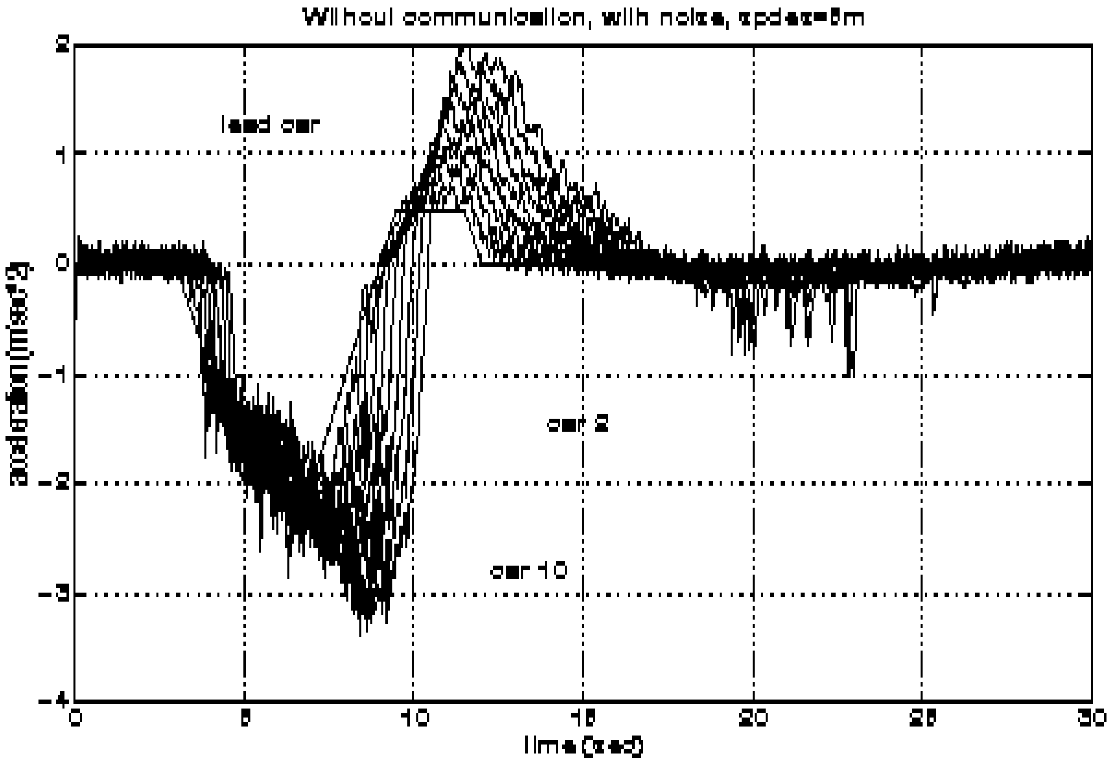

Figure 25. Acceleration profiles, sp_{des} = 5m - no communication

Preceding car acceleration is also transmitted via the communication link. Without a communication link this must be estimated. With the availability of closing rate information and the controlled vehicle (i^{th}) acceleration from on-board accelerometers, the preceding vehicle's acceleration can be estimated through numerical difference equation methods. A butterworth filter (5 Hz cutoff) is used to filter out the high frequency components.

The velocity (Figure 24) and acceleration (Figure 25) show the degraded tracking performance. The reason for the lag in the velocity and communication profiles is because of the estimation of lead and preceding vehicle accelerations. The overshoots in the acceleration profiles are greater toward the end of the string of vehicles.

The importance of communication for control can be seen in the plot showing the variation of the spacing errors of the vehicles. The spacing error becomes larger down the string of vehicles. This is a direct effect of not communicating lead vehicle acceleration. The effect of no communication is detrimental to accurate platoon following. It is possible to build accurate acceleration estimators to decrease the chances of collision but the problem of non-decreasing spacing errors down the string of vehicles can cause potential problems for sufficiently long platoon of vehicles.

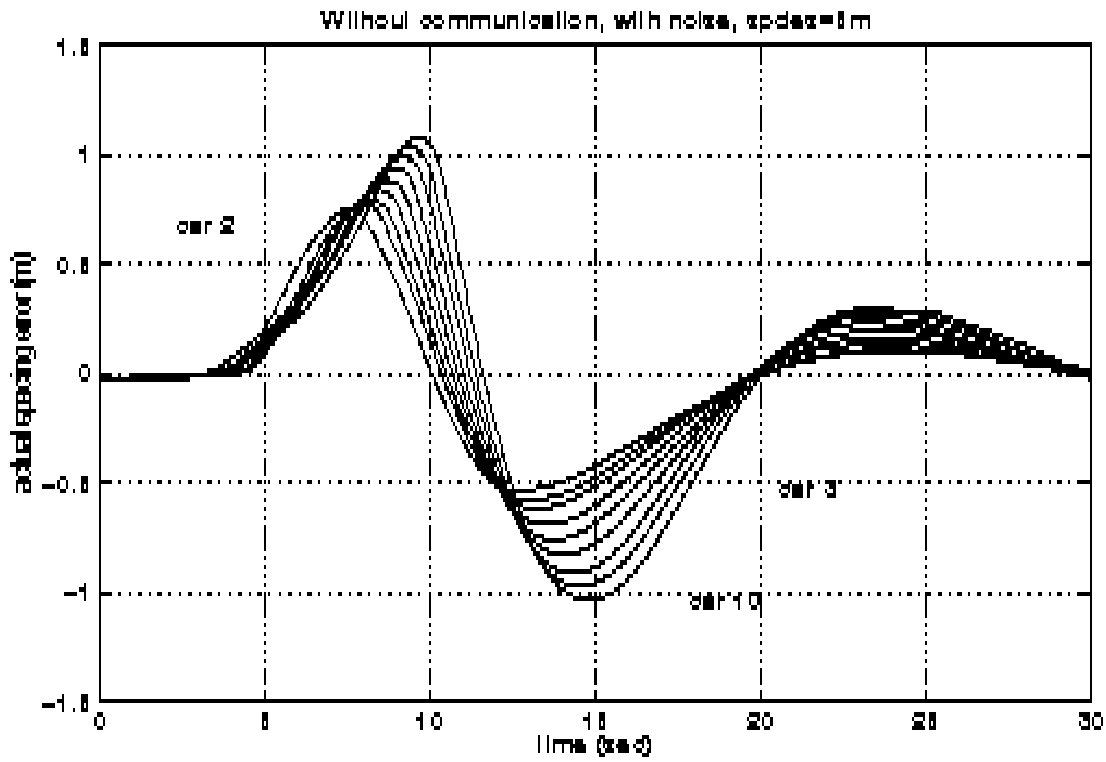

Figure 26. Acceleration profiles, sp_{des} = 5m - no communication

Control Without Communication and Closing Rate

The worst case scenario is one of control without closing rate information or communication between vehicles. The absence of closing rate in addition to communication means that we have no accurate way to estimate the acceleration of the immediately preceding vehicle. In effect, either an accurate estimator must be built by differentiating the spacing sensor information twice or we must perform vehicle control assuming zero lead and preceding car accelerations. The fact that vehicle acceleration is obtained through a double integration means sufficintly slow response of succeeding vehicles to lead and preceding vehicle accelerations. Hence it is likely to have very poor acceleration and velocity tracking.

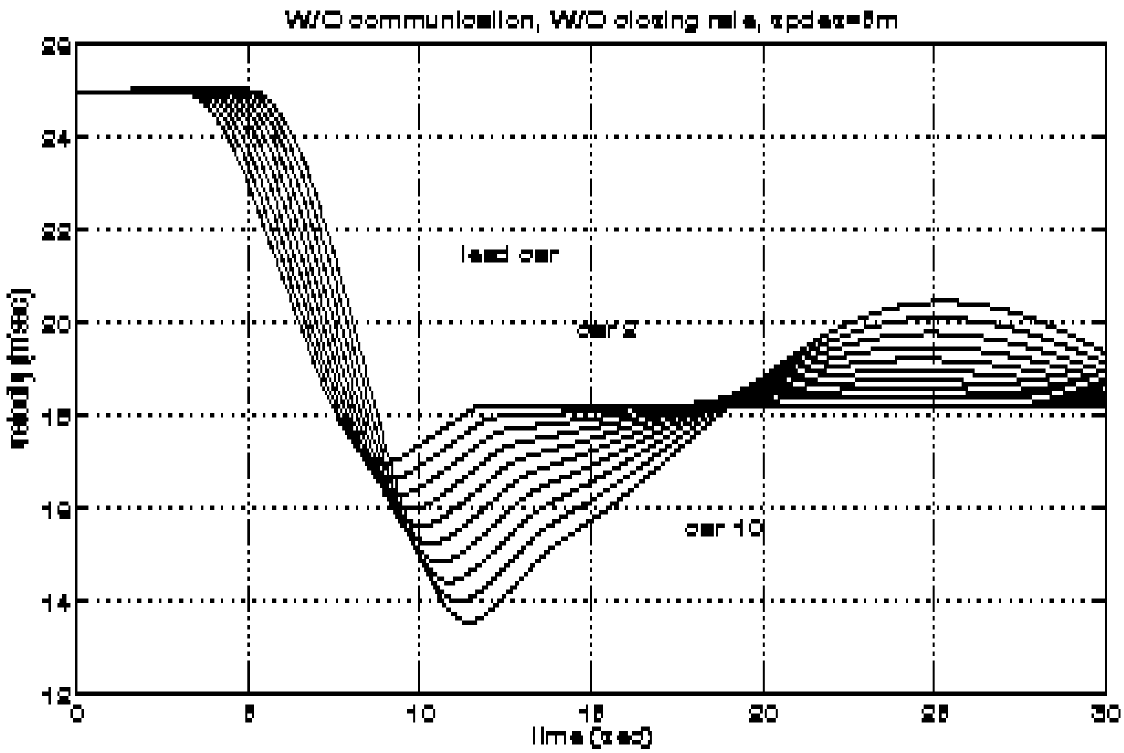

Figure 27. Velocity profile sp_{des} = 5m - no comm., no closing rate

This is clearly seen in the velocity and acceleration plots shown in Figures 27 and 28. The effect of no closing rate on spacing error is more acute and clearly rules out small desired spacing for cars of a platoon. The spacing error variations of the vehicles in the ten vehicle platoon are seen in Figure 29.

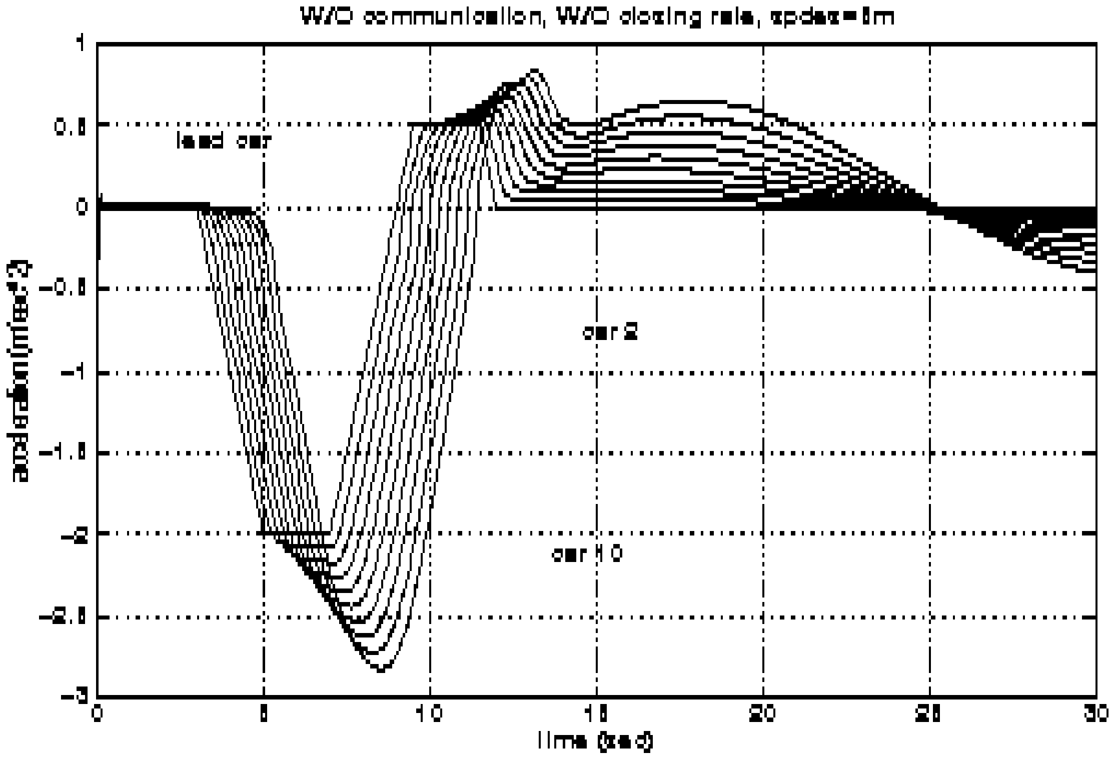

Figure 28. Acceleration profiles, sp_{des} = 5m - no comm. no closing rate

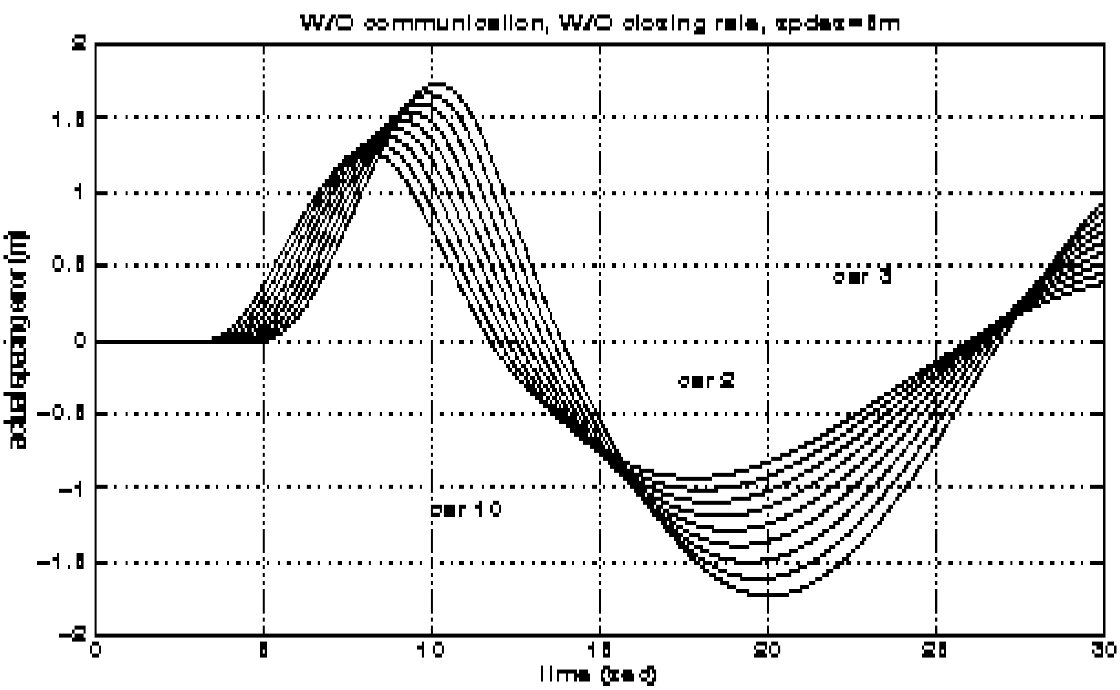

Figure 29. Spacing error profiles, sp_{des} = 5m - no comm., no closing rate

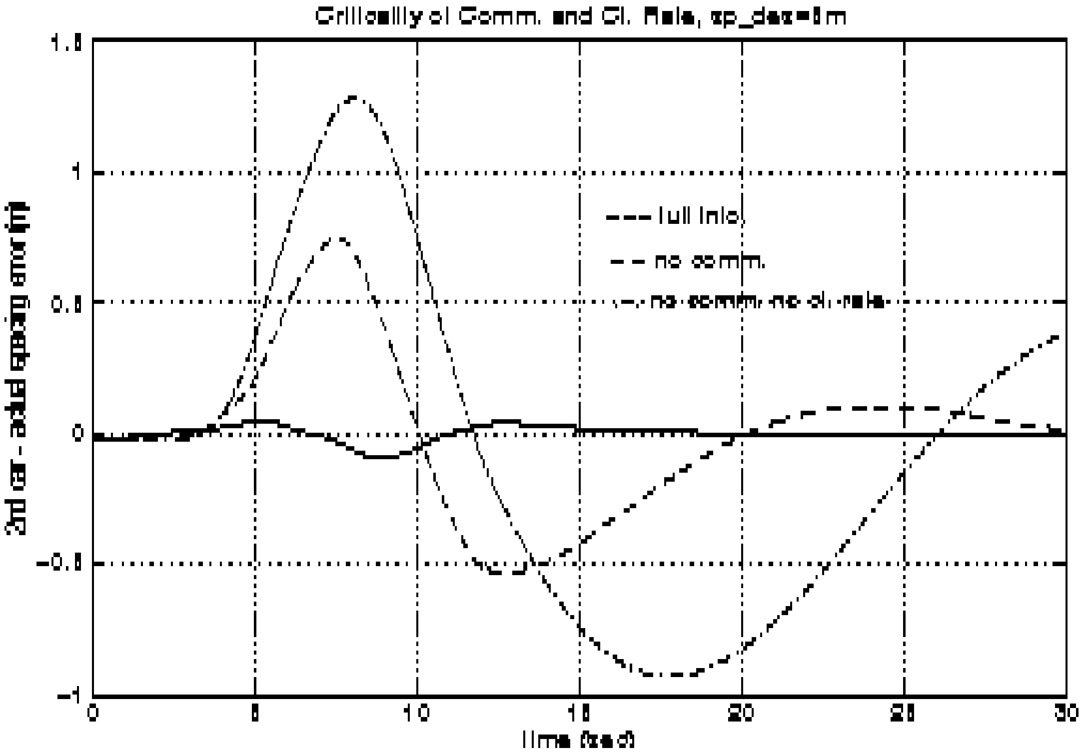

Figure 30. Spacing Error - 2nd vehicle, sp_{des} = 5m

The spacing errors are much larger for the same kind of lead vehicle acceleration profile. Also there is no attenuation of errors down the string of the vehicles. The comparison of the spacing errors of the 2nd, 3rd and 10th vehicles with reduced information control to the baseline simulation shows the extent of degradation of performance.

This is shown in Figures 31, 32, or 33. The plots show that small desired spacing following is not recommended for control without closing rate information. In the absence of communication, this is recommended only if accurate estimators can be built to estimate lead and preceding vehicle information.

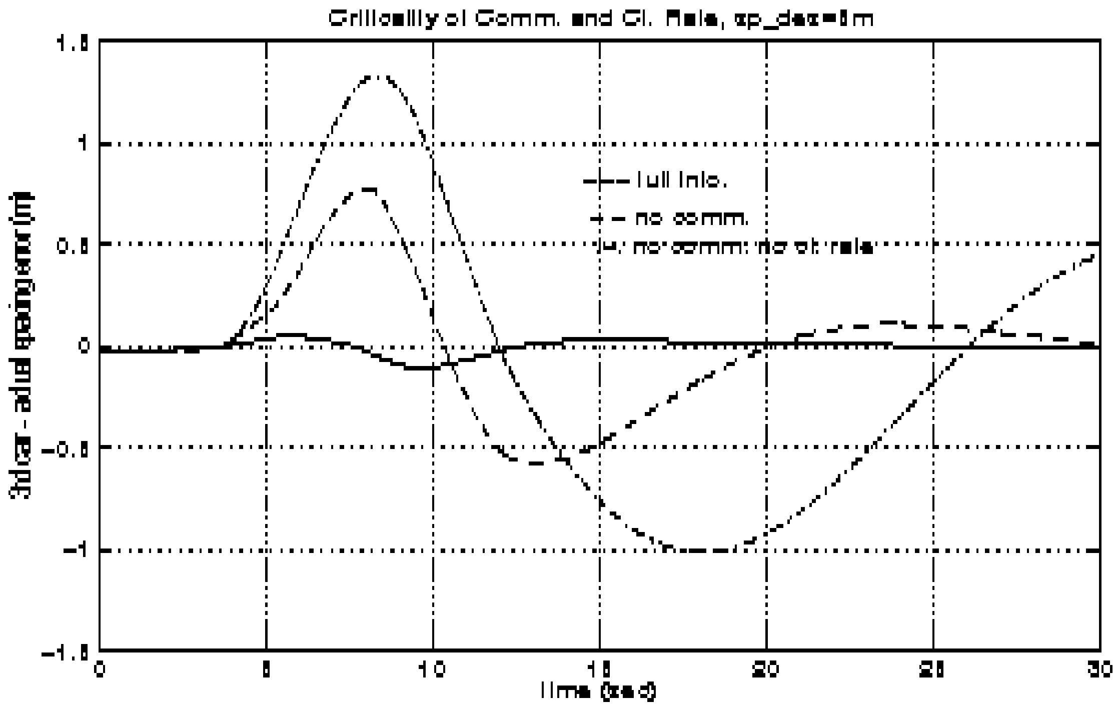

Figure 31. Spacing Error - 3rd vehicle sp_{des} =5m

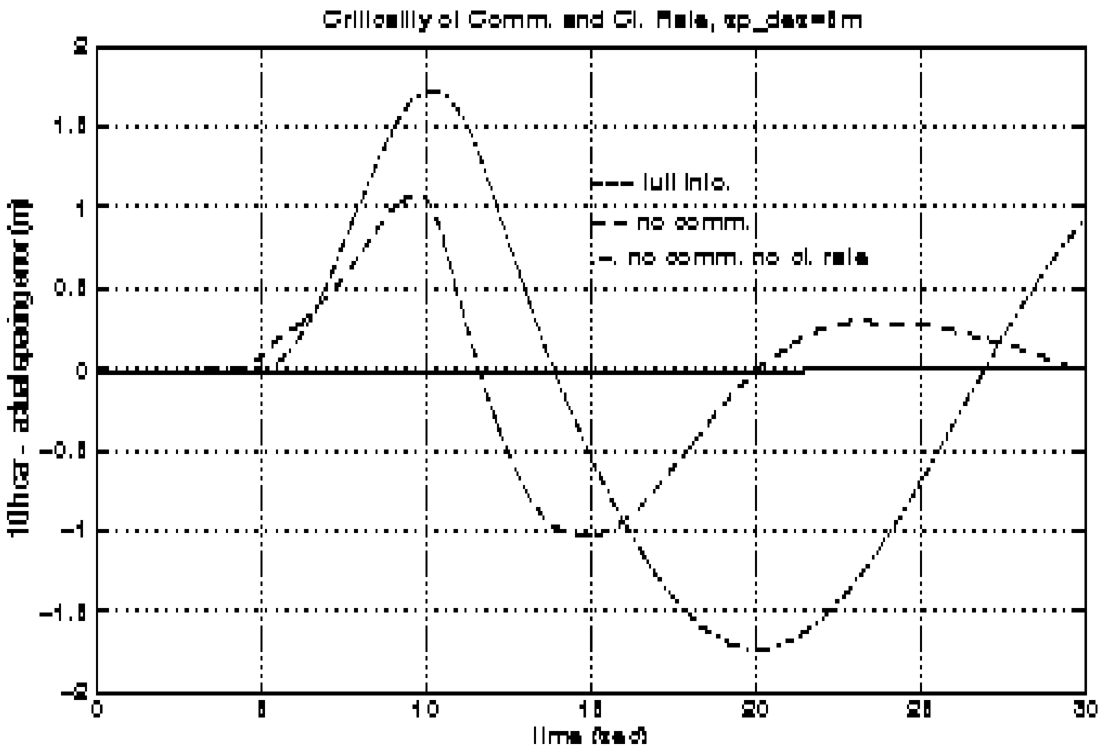

Figure 32. Spacing Error - 10th vehicle, sp_{des} =5m

Joining with Reduced Information Control

The control of vehicles during joining of platoons is a subset of vehicle longitudinal control. Since joining and splitting of platoons can be reduced to the problem of trajectory following, the join maneuver is essentially following an acceleration and decleration profile. The only difference is that vehicles now treat the merging vehicle as the lead vehicle.

In this case the analysis studied the joining of a ten car platoon with another platoon. The preceding platoon is represented as a single car. At the beginning of the simulation the joining platoon is at a distance of 10m behind and the objective is to smoothly minimize the gap between the platoons to 1m. Thus the study assumes that the intervehicle spacing in platoons is 1m.

The first set of simulations are for control with full information availabile. Figure 33 shows the desired acceleration profile and the acceleration profiles for the vehicles in the 10 car platoon. Figure 34 is the velocity plot for the 10 vehicles.

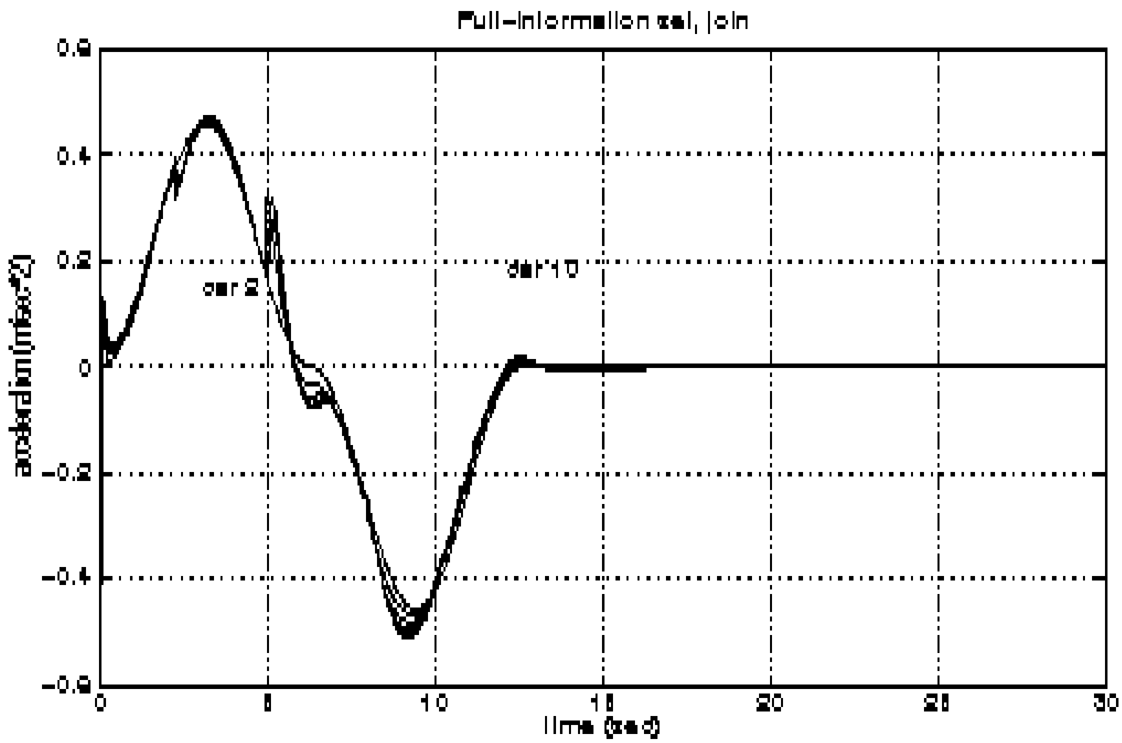

Figure 33. Vehicle accelerations - join maneuver

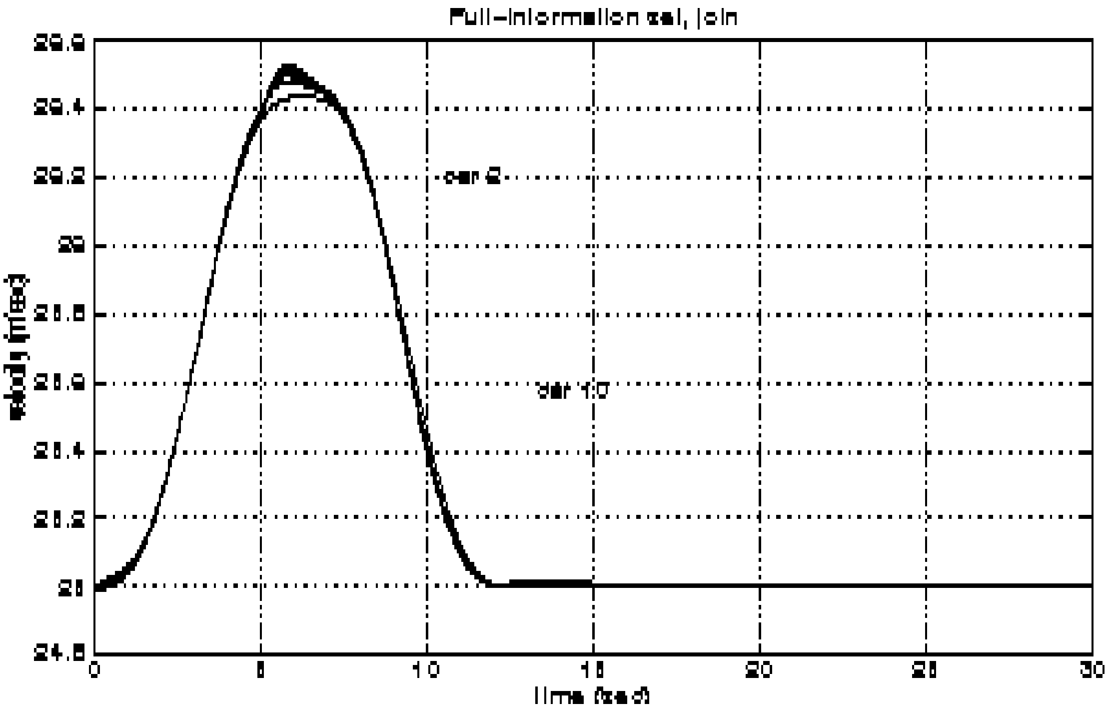

Figure 34. Vehicle Velocities - join maneuver

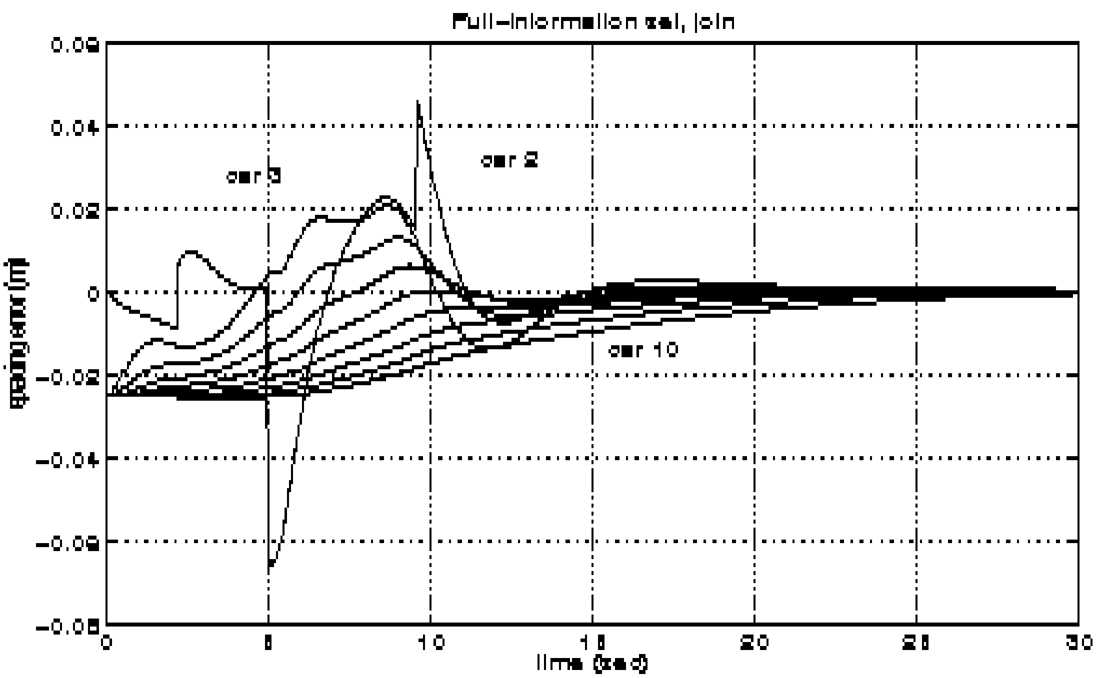

Figure 35. Vehicle spacing errors - join maneuver

The comparison of the join maneuvers with reduced information sets shows results similar to the ones obtained for vehicle following in the earlier sections. This is so since the join maneuver is similar to acceleration trajectory following.

The errors do not attenuate down the string of vehicles for control with no communication and closing rate. The error of the second vehicle is also crucial here since we must ensure that the overshoot in the error, if any, is minimum at the end of the maneuver. This will ensure that the vehicles will not crash. Figures 36 and 37 show the variation of the spacing errors of the 2nd and 10th cars of the platoon for the reduced information set control.

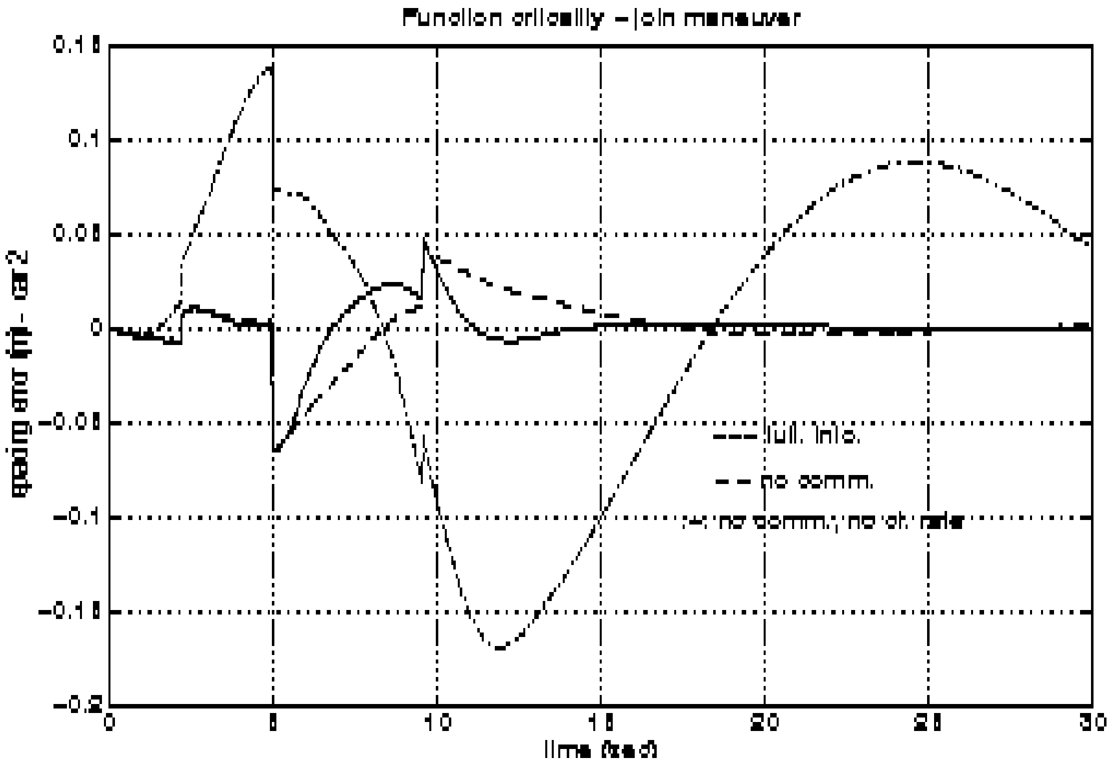

Figure 36. Spacing error (m)- 2nd vehicle, join maneuver

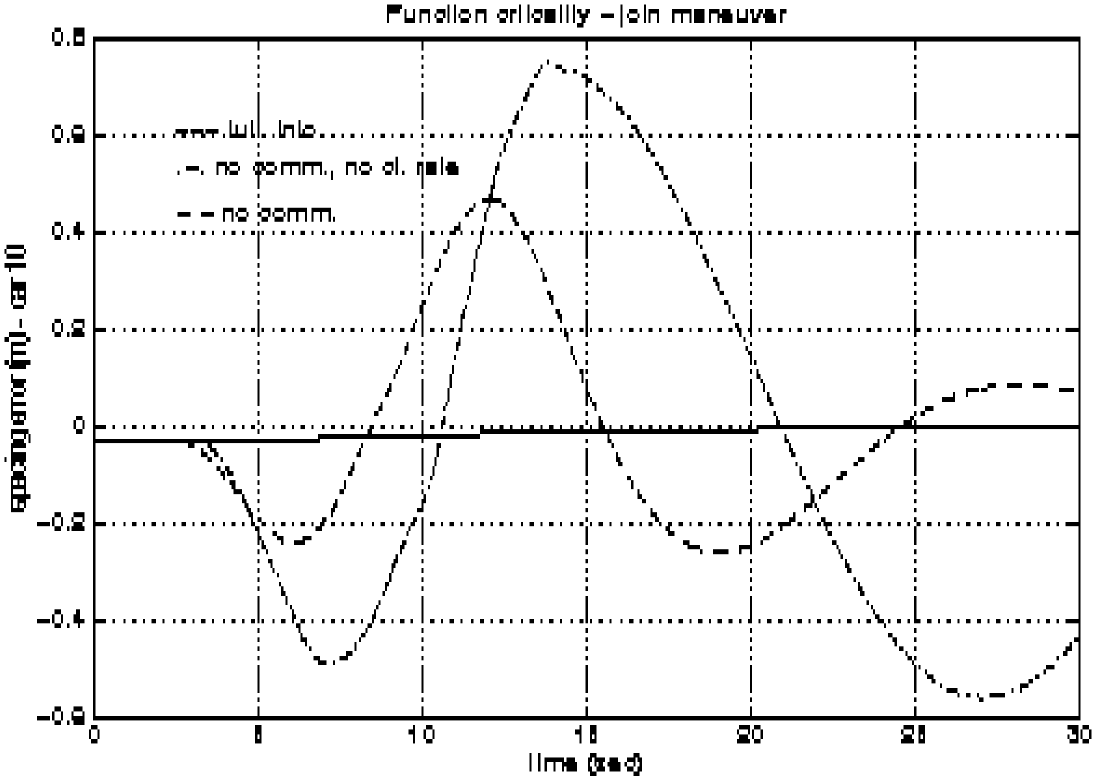

Figure 37. Spacing error (m)- 10th vehicle, join maneuver

7.3.3 Lateral Control Analysis

The lateral control criticality analysis uses a simulation of a car moving along an S curve of radius of curvature 300m. The road profile is shown in Figure 38. The profile has been obtained from the XY inertial coordinates of a controlled vehicle. The baseline model has no noise in any of the sensors. At the beginning of the simulation the vehicle is travelling at 25m/sec. The variables of interest are

Vehicle lateral deviation, y_y
Vehicle lateral acceleration, a_y
Vehicle lateral jerk, J_y

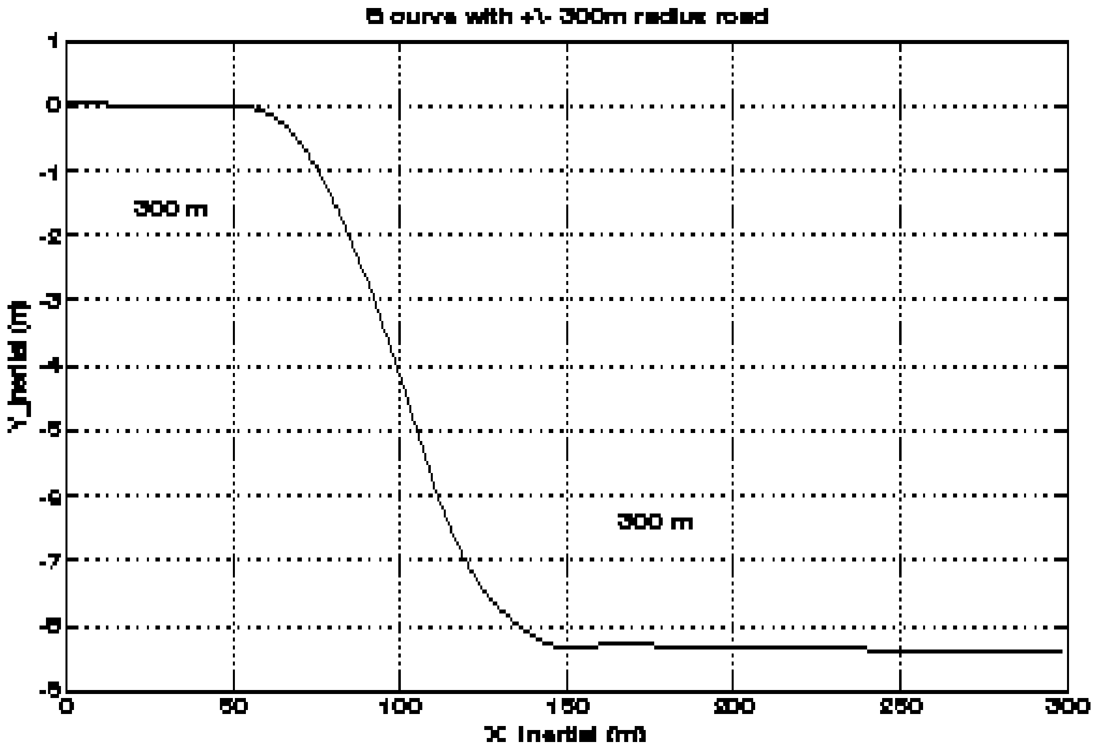

Figure 38. Road profile

Assumptions for Baseline model

The baseline simulation scenario is an ideal case scenario with the following assumptions:

- Controller sampling time is 6ms.
- A lateral deviation sensor provides lateral deviation, y_r
- An accelerometer provides lateral acceleration a_y
- A yaw rate sensor provides vehicle yaw information .
- Sensor sampling time is 6ms and sensor readings are noise free.
- Steering actuator has a 100ms time constant.

The lateral model is easier to analyze when compared to the longitudinal model because all performance is with respect to a fixed reference (center of lane) system. In the latter the reference is moving and is the preceding car. This analysis will examine the criticality of the lateral acceleration and yaw rate sensors. Another function that must be studied is the necessity of preview control. It is known that preview information enhances system performance - but the question addressed here is whether it is important enough to warrant requirement of preview road knowledge from a safety point of view.

Figures 39, 40, and 41 show the controlled vehicle lateral deviation, lateral acceleration and lateral jerk respectively. This is the case with no sensor noise. The “S” curve is sufficiently tight for the 25m/sec speed that is simulated here. This explains the fairly high accelerations as seen in Figure 39. The lateral deviation is small considering the tight turn and high velocity.

The variation of the jerk is frequently used to address ride comfort issues. In this case the jerk is shown to motivate the need for preview control.

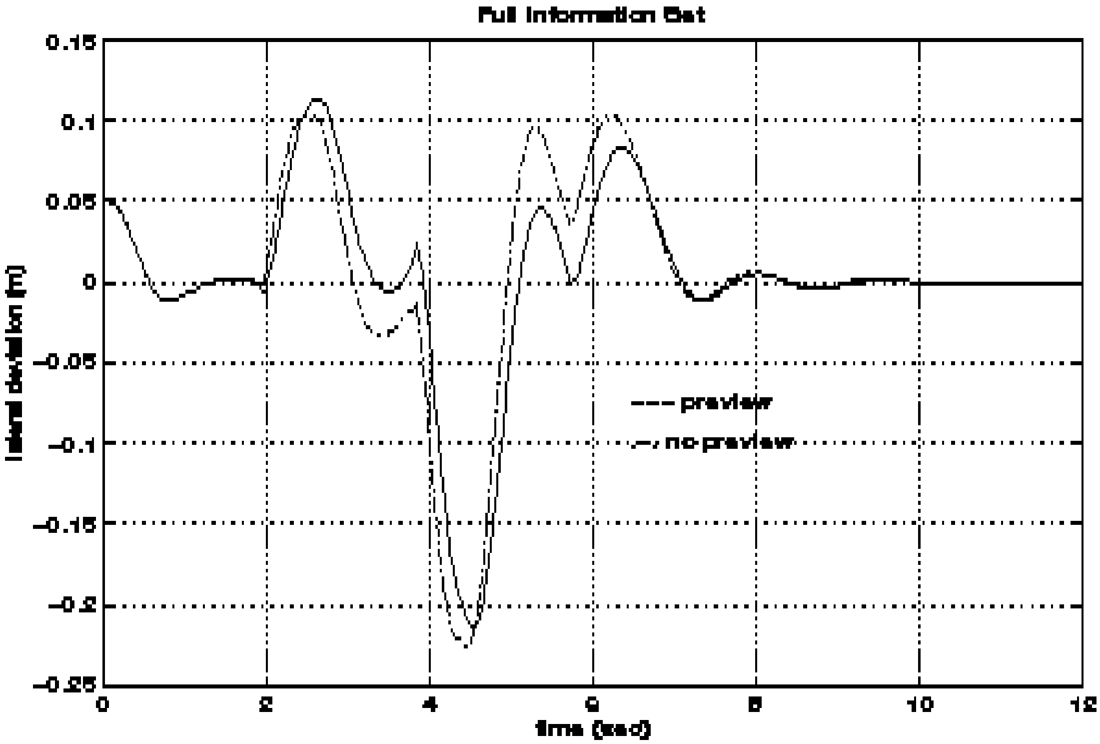

Figure 39. Lateral Deviation- no noise, full information.

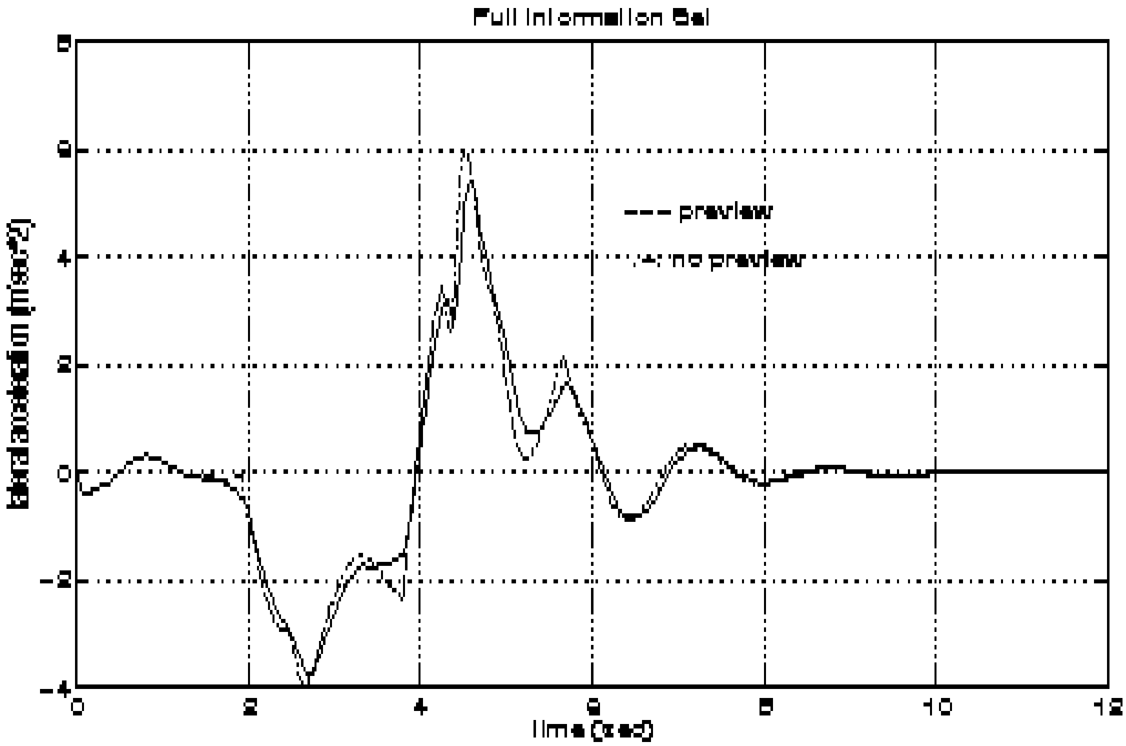

Figure 40. Lateral Acceleration - no noise, full information.

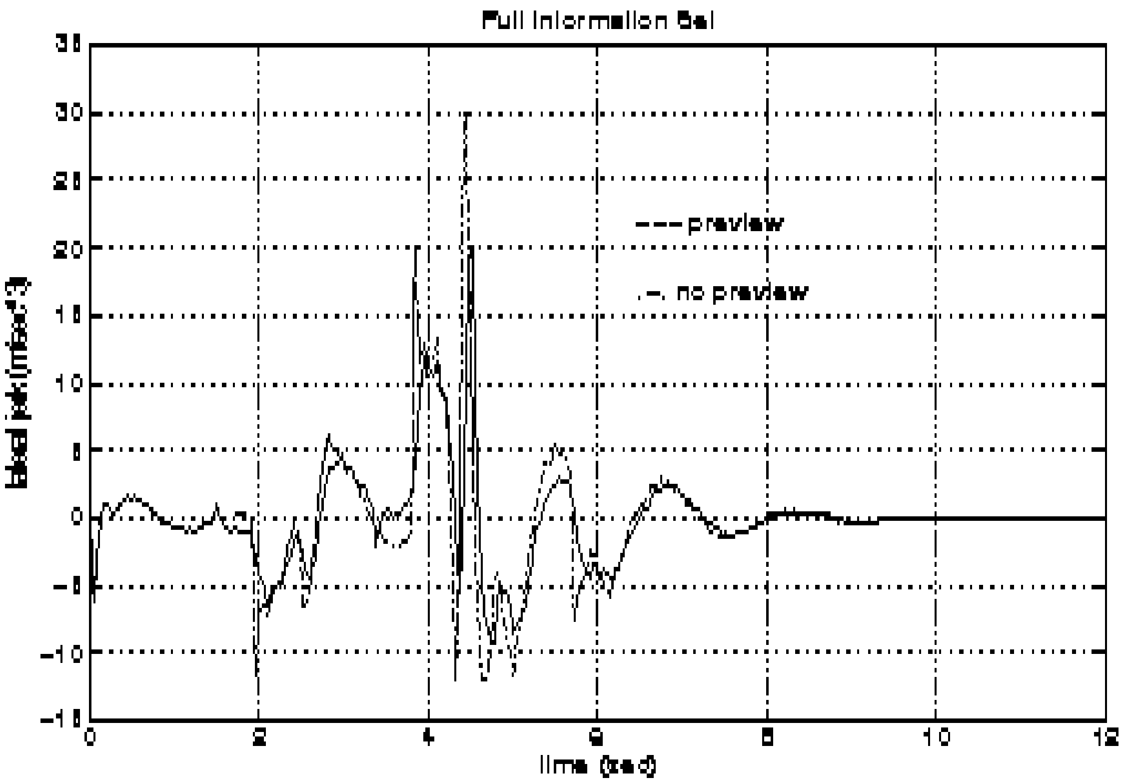

Figure 41. Lateral Jerk - no noise, full information

In each of the plots a comparison is made between performance with and without preview information. It is clear that preview information allows for a smoother ride. The lateral controller is quite robust to fairly large magnitude noise in the sensor channels. The next few simulations show performance in the presence of noise but with full information availability for control. There is 10 % noise in the lateral deviation, acceleration and yaw rate sensors.

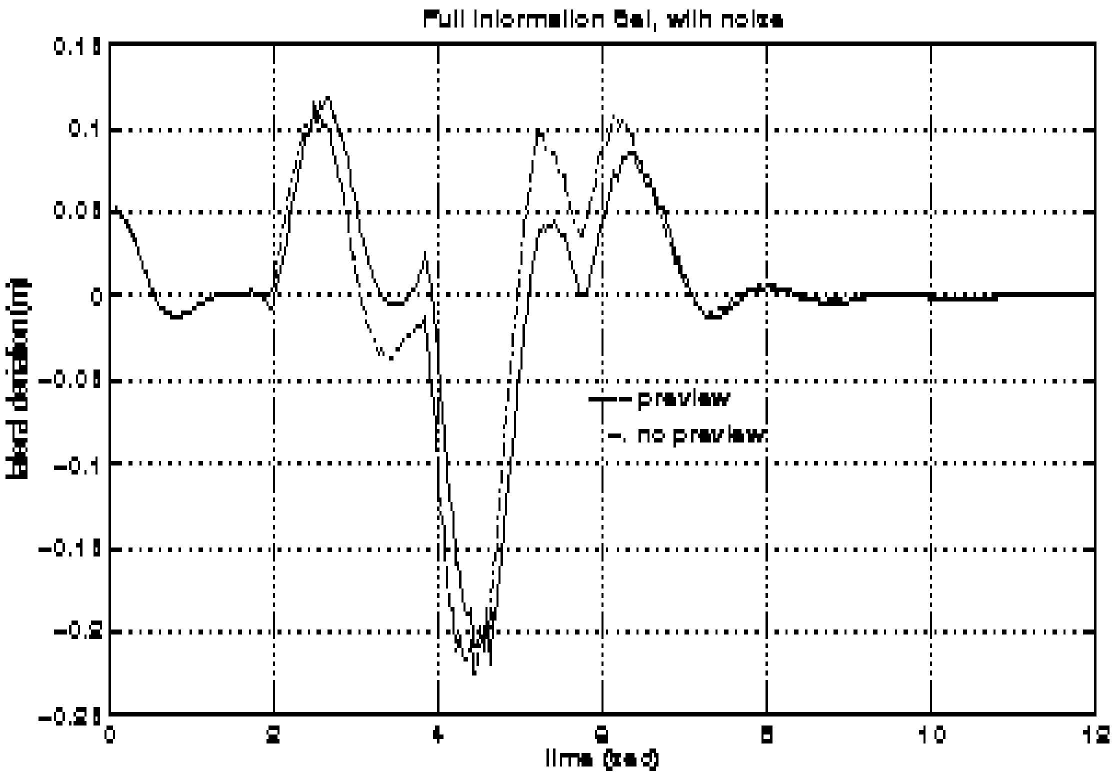

Figure 42. Lateral Deviation (m) - full information.

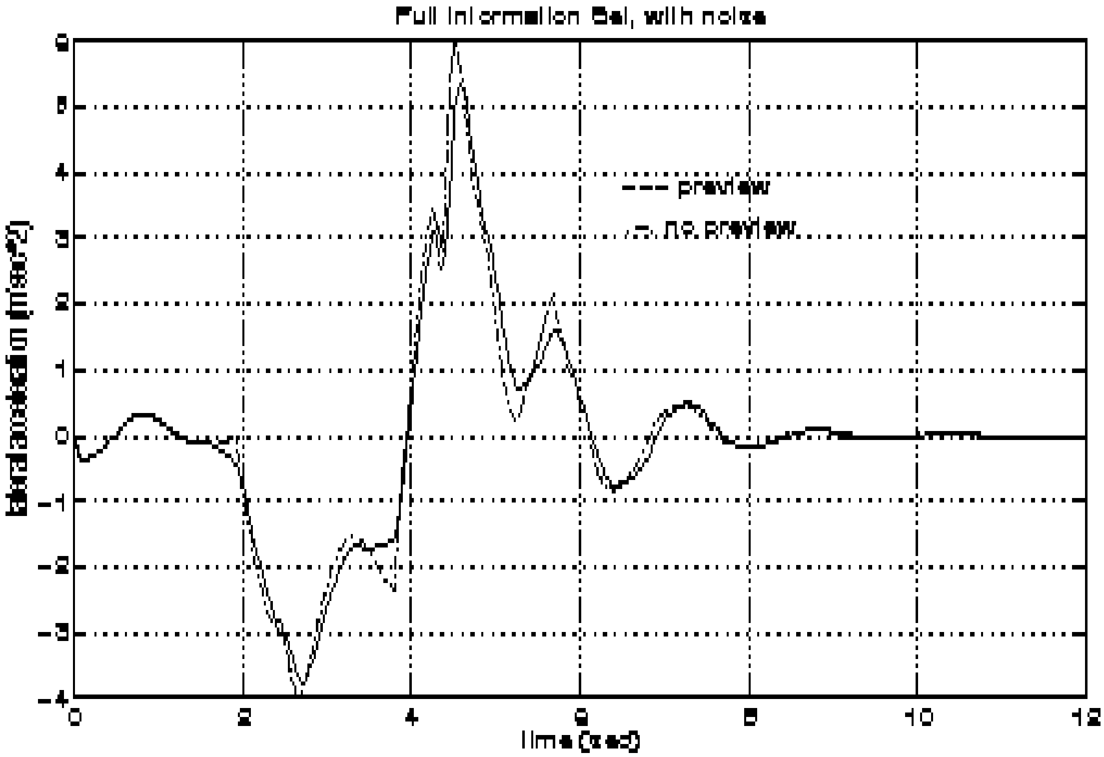

Figure 43. Lateral Acceleration - full information.

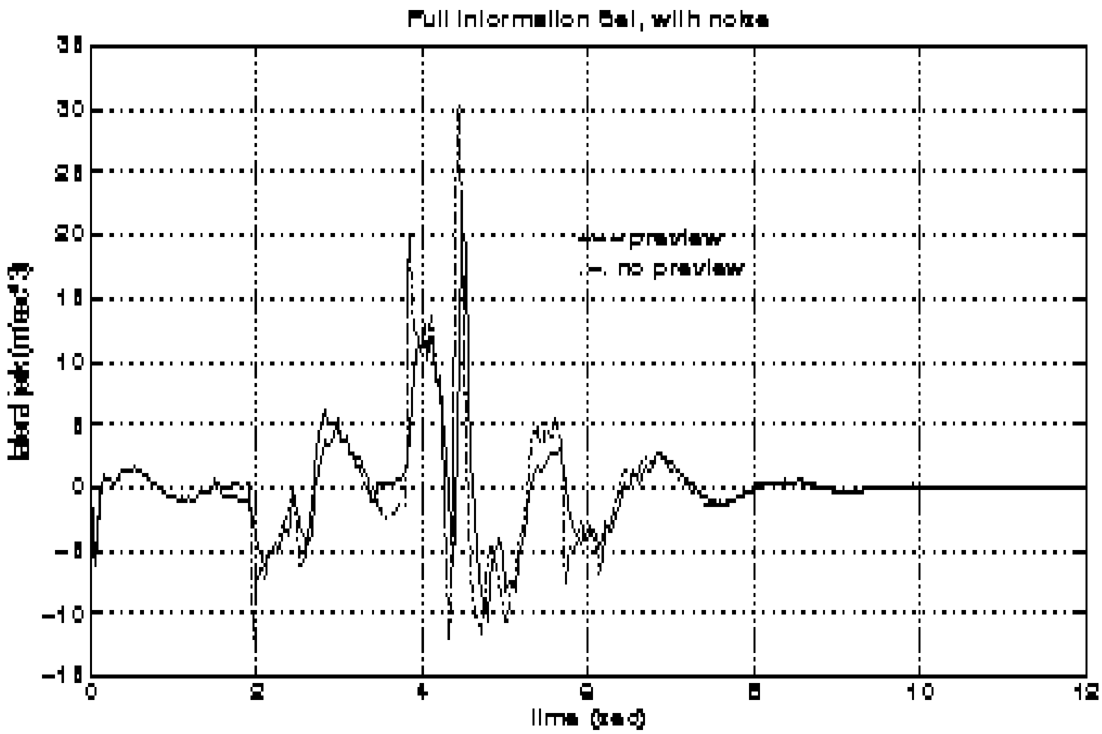

Figure 44. Lateral Jerk - full information

The lateral spacing errors are not very much larger than for the case with no noise. The vehicle acceleration and jerk are higher, as expected. The presence of noise further emphasizes the need for preview as is seen in the comparison of lateral spacing errors with and without preview control.

The lateral controller relies on lateral deviation, lateral acceleration and yaw rate measurements for control. The analysis studied the effects of control without lateral acceleration and yaw rate information. Vehicle lateral acceleration and yaw rate are difficult to estimate. So in the case of reduced information sets these parameters have been set to zero. The performance is not affected significantly and is clearly seen in Figure 45 which shows the lateral deviation without lateral acceleration and yaw rate sensor information. The difference is at best marginal where acceleration is concerned (Figure 46).

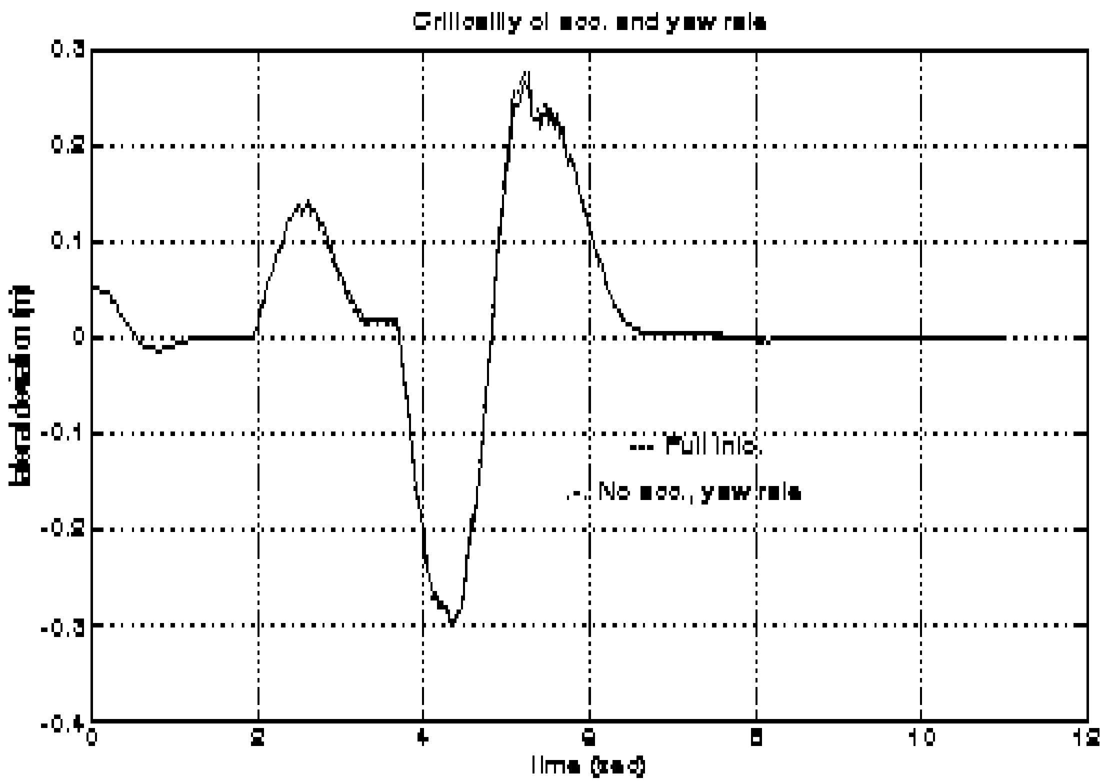

Figure 45. Lateral Deviation (m) - criticality of functions

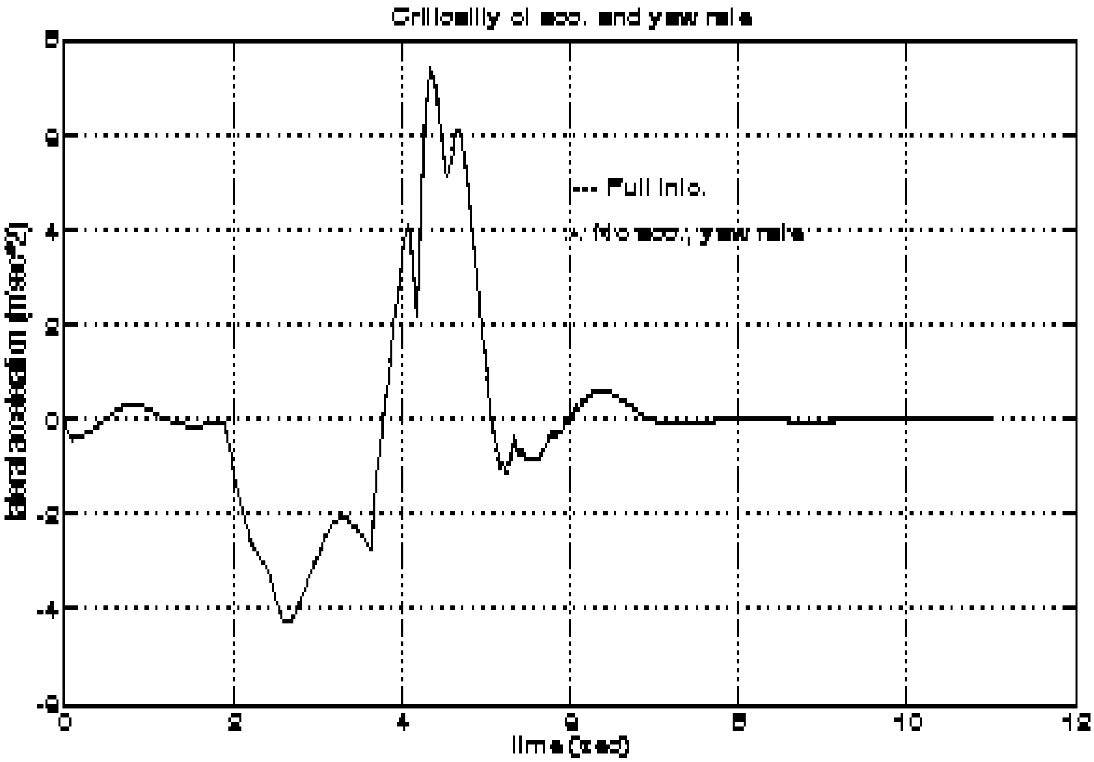

Figure 46. Lateral Acceleration - criticality of functions

The above simulation was for a 70 mph test with full sensor noise of 10%. This clearly indicates that the functions are not critical with the adopted control strategy.

The criticality of sensor functions are put to test at higher speeds. Figure 45 shows the variation of the spacing errors at 3 different speeds. The spacing errror is much larger for negotiating the “S” curve at higher speeds. As expected the vehicle accelerations and jerk are also much larger.

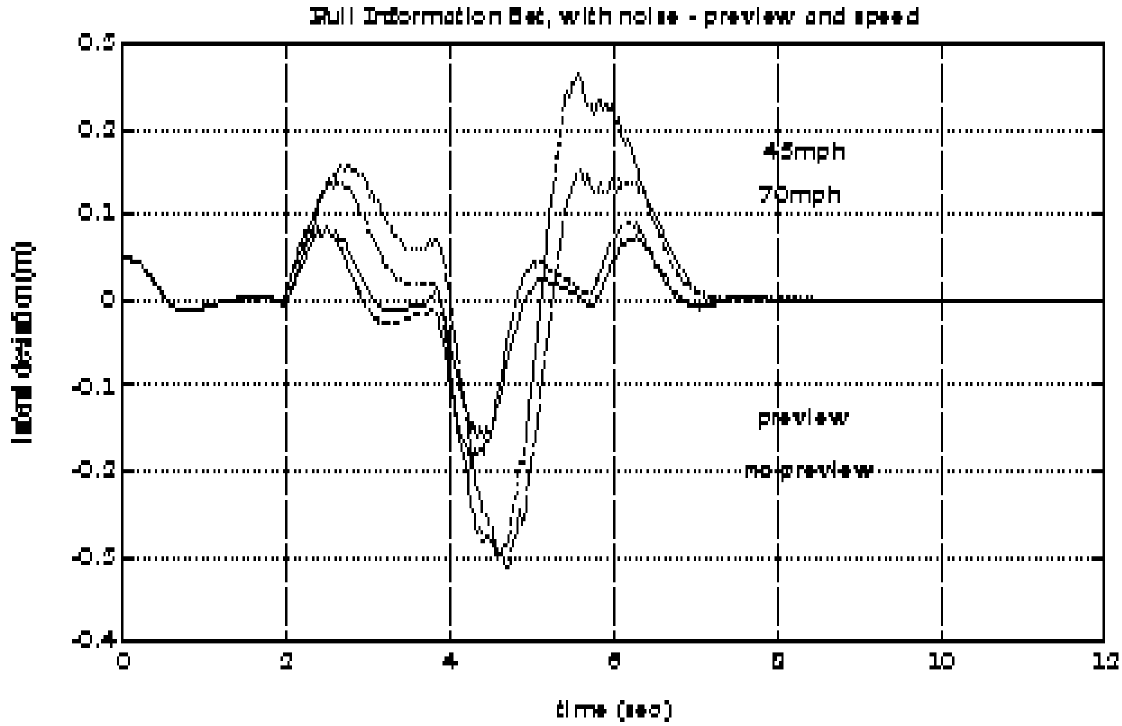

Figure 47. Lateral Deviation - at different speeds

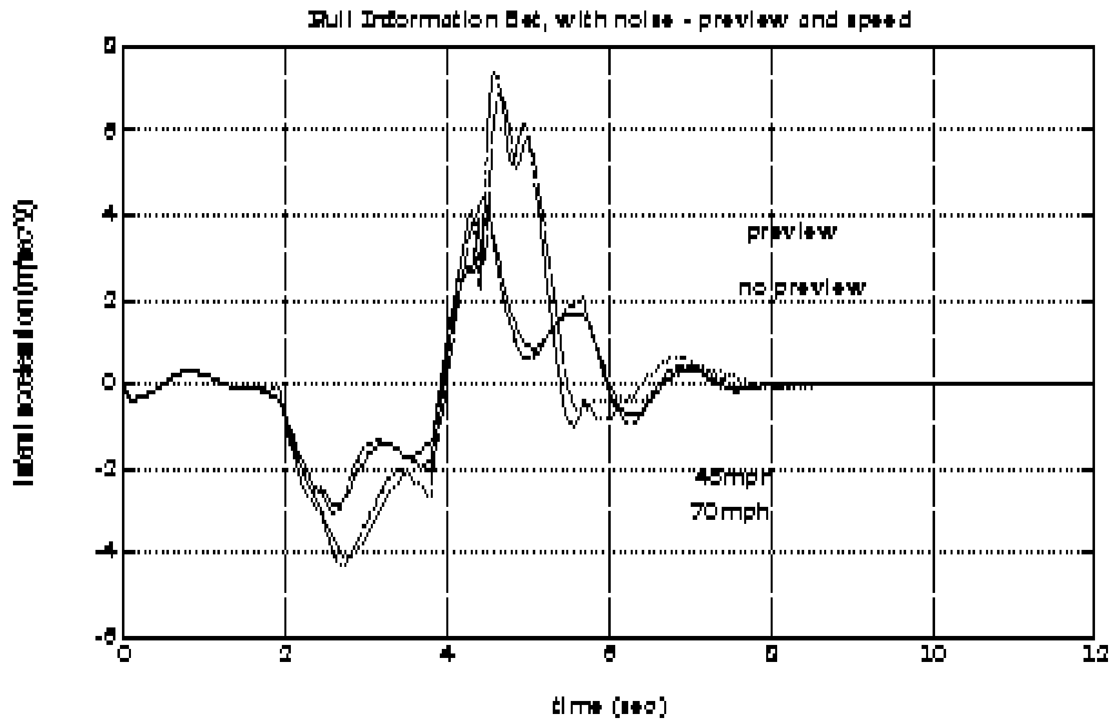

Figure 48. Lateral Acceleration - at different speeds

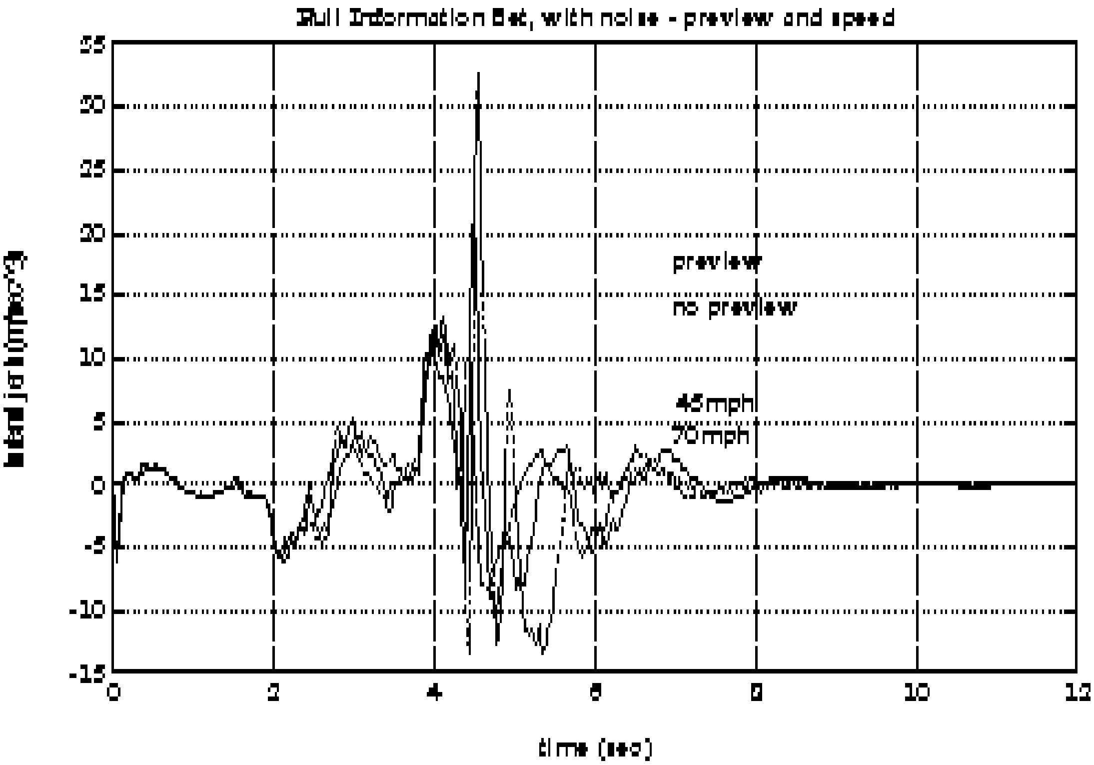

Figure 49. Lateral Jerk - at different speeds

7.3.4 Lateral and Longitudinal Criticality Conclusions

Longitudinal control conclusions

The longitudinal control criticality analysis was directed toward addressing the feasibility of reduced information set control. The study clearly indicates the necessity of lead vehicle information for control. Several points are to be noted.

- Performance of a string of vehicles in the presence of noise in various input channels is stable. The preceding plots shows sensor noise only in the spacing distance channel. Noise in the acceleration and closing rate sensors was also simulated and shown to be stable.

- The noise is a percentage of the target spacing. Hence spacing errors will be larger at larger target spacings. Vehicle following at larger spacing, albeit safer, will not necessarily result in the best form of control. Low gain controllers must be designed to ensure that small variations in spacing errors do not translate into high control effort and actuator saturation.

- The effect of actuator limitations was studied. It was found that throttle actuators at least as fast as 150 ms are fast enough for the frequency and type of maneuvers that can be be expected in AHS vehicle control. The brake actuator is slow and had a time constant of 75ms. Actuators slower than 150 ms can lead to poor tracking performance during high jerk deceleration maneuvers.

- The communication function is critical for control of strings of vehicles based on the spacing distance control. Autonomous or time headway control approaches are more robust to losses of communication. With spacing control, if there is no communication, it is not possible to guarantee attenuation of errors down a string of vehicles. The errors in tracking can be reduced through accurate estimators.

- The closing rate function is by far the most important function. Performance is greatly degraded in the absence of closing rate information. In addition, if the communications are not working, potentially hazardous situations can arise due to large lags in accleration tracking. The degradation of performance without closing rate and communication information is true regardless of the control approach used. The closing rate function is safety critical.

- The use of the closing rate and communications for IVHS besides ensuring safety of the longitudinal maneuvers can be used for vehicle control during non-ideal situations. The communication link and closing rate also add to redundancy in system sensor function thus giving us more than one way to calculate several sensor functions. This is particularly useful for fault detection and fault tolerant control of vehicles in AHS.

Lateral Control Criticality Conclusions

The lateral deviation sensor is the most important sensor for lateral control. Several simulations were performed to study the criticality of various functions.

- Preview control is a necessary component of vehicle control. Manual driving without preview information is equivalent to not looking ahead but instead looking down - say through the floor of the car and obtaining feedback by observing the deviation of the car from the center of the lane. The effect of control without preview is seen in the marginally higher lateral deviations but significantly higher lateral acceleration and jerks. It is not safety critical.

- The controller is robust through a wide range of vehicle velocities but lateral deviations increase with velocity. The effect of non-preview control will be felt more at higher velocities of travel.

- The lateral acceleration and yaw rate functions are not safety critical.

The results shown in the lateral part are constant input torque (to wheels) simulation tests. Further studies are necessary to evaluate the performance of the lateral controller with speed variations on curved sections of the highway.

7.4 Minimum Performance and Critical Faults

This section presents top level estimates for the minimum performance and critical faults for each of the elemental functions contained in the critical paths of the three operational functions previously discussed. When percent errors are presented they are based on experience and are intended to be used as guidelines rather than firm requirements.

P1.1 Sensing lateral position

a. Minimum performance requirement: Given the lane width l_w and vehicle width l_v the sensing range should be greater than $(l_w\text{-}l_v)/2$ and the error should be smaller than 10% of the measurement.

b. Critical fault: The vehicle rapidly deviates from the lane center but the sensor indicates small or no change in deviation.

P 1.3 Sensing longitudinal position

a. Minimum performance requirement: Longitudinal position must be available before a geometric point where lane merging, barrier gates, entrance, or exit occurs, and when vehicle coordination maneuvers are planned. Longitudinal position are likely needed on a continuous basis. Given the minimum allowable spacing between vehicles d_{min}, the desired spacing between vehicles d_{dsr}, the length of the gate l_g, and the minimal allowable longitudinal gap between the vehicle and the edge of the gate d_g, the error of the longitudinal position measurement should be smaller than $(d_{dsr} - d_{min})/2$ or $(l_g - l_v)/2 - d_g$ whichever is smaller.

b. Critical fault: The longitudinal position acquired by the vehicle is greater than the above indicated error limit.

P1.4 Lane recognition

a. Minimum performance requirement: Lane number must be correctly acquired by a vehicle immediately after entering the highway and before a highway diverging and exiting area.

b. Critical fault: The lane number acquired by the vehicle is not a true representation of the lane number that the vehicle is traveling on.

P1.5 Sensing velocity

a. Minimum performance requirement: The range of the velocity measurement should be 0 to 110% of the maximum vehicle speed. The error of the vehicle velocity measurement should be smaller than 5% of the measurement.

b. Critical fault: The vehicle velocity reading is significantly lower than the actual vehicle velocity.

P 1.11 Sensing distance to a frontal vehicle/object

a. Minimum performance requirement: The sensing range should be 0 to $1/2 * (V_{max}^2/a_{d\_max})$ where V_{max} is the maximum vehicle speed and a_{d_max} is the maximum vehicle deceleration. The error of the range measurement should be smaller than 10% of the measurement.

b. Critical fault: The sensor can not detect the frontal object or vehicle, or the distance measurements are larger than the actual distance between the controlled vehicle and the frontal vehicle.

P1.14 Sensing distance to a neighboring vehicle/object

a. Minimum performance requirement: The sensing range should be 0 to 2*l_w. The error should be less than 10% of the measurement.

b. Critical fault: The sensor can not detect the neighboring vehicle or the distance measurements are larger than the actual distance between the controlled vehicle and neighboring vehicle.

P2.1 Providing steering actuation

a. Minimum performance requirement: Under all possible conditions, the bandwidth of the steering actuation outputs should be no less than 1 hz. The range of the steering output should be greater than 5 degrees. The error should be smaller than 0.1 degree.

b. Critical fault: The steering actuation outputs are not responsive or over-reactive to the steering command which cause the vehicle to rapidly deviate from the predefined path.

P2.3 Providing brake actuation

a. Minimum performance requirement: The brake actuation unit responds to the bake control commands and causes the vehicle to decelerate at a deceleration up to 0.7g on a dry smooth pavement. The variation in performance of the brake actuation should not result in an error greater than 10% of the maximum deceleration.

b. Critical fault: The brake actuation unit fails to provide adequate output force demanded by the control commands to cause the vehicle to decelerate at the desired deceleration and to stay on the predefined path.

R1 Providing steering control command

a. Minimum performance requirement: The steering control commands are given at an interval t_{rs} which cause the steering actuation function (P2.1) to steer the vehicle to follow the predefined path with a deviation larger than y_{max} at a lateral acceleration no greater than a_{max}, where y_{max} is the maximum allowable deviation, defined as $(l_w-l_v)/2$ and a_{max} is the maximum allowable acceleration. t_{rs} should be smaller than 100 ms.

b. Critical fault: The steering controller provides unreasonable control commands causing the vehicle to rapidly deviate from the predefined vehicle path.

R3 Providing brake control command

a. Minimum performance requirement: The brake control commands are given at an interval t_b which cause the brake actuation device to decelerate the vehicle at a deceleration up to a_{d_max} defined as 0.7g on a dry smooth pavement.

b. Critical fault: The brake controller fails to command adequate level of brake force for decelerating the vehicle at a desire deceleration.

R6 Processing sensor information

a. Minimum performance requirement: The sensory information processing should provide undistorted interpretation of sensor inputs or observations using the sensor inputs according the predefined input-output mapping relationships.

b. Critical fault: The interpretation of the sensory information or the observation using the sensory information causes the vehicle to be unstable.

7.5 Elemental Function Criticality

This section presents a qualitative categorization of each elemental function in each of the control layers in terms of the impact a failure would have on the safety and efficiency of the overall AHS.

The description of the criticality of a failure of an elemental function uses the following four categories:

Safety critical (SC)
Conditional safety critical (SCC)
Efficiency critical (EC)
Non critical (NC)

An elemental function is Safety Critical if its failure will create an immediate hazard condition and this is true for all RSCs and possible implementation approaches. Conditional Safety Critical is used for an elemental function which is safety critical under some conditions and not under others.

An elemental function is Efficiency Critical if its failure will create an immediate and significant degradation to the functioning of the AHS.

A non-critical elemental function failure will never create a safety hazard or significantly disrupt AHS functioning.

By using these qualitative ratings, the level of criticality of each elemental function is specified according to the impact caused by the failure of such function on the safety or efficiency of the system operation. It is noted that the levels of criticality of some elemental functions are dependent on the system arrangements, operation strategies, or applied technologies. For example, maneuvering coordination is a safety critical function under group operations but can be designed as a non-safety critical function when vehicles are operated along headways. Accordingly, we use the following expression to represent conditionally safety critical or conditionally efficiency critical ratings:

SC (condition A): the function is safety critical under condition A

EC (condition B): the function is efficiency critical under condition B

The following tables present the initial effort at categorizing the criticality of each elemental function.

In general, the functions contained with the Network and Link layers are very important to an efficient AHS but do not have a major impact on the overall safety of the AHS. Maneuver coordination is a safety critical function when a vehicle is in a platoon with closely spaced adjacent vehicles. Most of the regulation functions are safety critical as are the functions of the associated regulation sensors.

Some information links can be safety critical or efficiency critical depending on the specific RSC. For example, the information link between the coordination layer and the regulation layer is safety critical for RSCs 1, 2, and 3 and efficiency critical for RSCs 4, 5, and 6. The information link between the regulation layer and the physical layer (actuators) is always safety critical.

Table 5. Safety and Efficiency Criticality of Elemental Functions (Upper Layers)

Network layer
N1 Monitoring traffic conditions and prediction congestion: EC
N2 Vehicle ID assignment: EC
N3 Route recommendation: EC

Link layer
L1 Lane assignment: EC
L2 Target speed: EC
L3 Maximum group size: EC
L4 Minimal separations: EC
L5 Prioritizing vehicle operations: EC
L6 Regional traffic conditions monitoring and incident management: EC

Coordination layer
C1 Off-vehicle inspection and monitoring: EC
C2 Issuing permission/rejection: SC
C3 Maneuvering coordination planning
- C3.1 Normal maneuver coordination planning: SC(group) EC (no group)
- C3.2 Maneuvering coordination planning for hazardous conditions SC(group) EC (no group)

C4 Supervising the sequence of the coordinated maneuvers: SC(group) EC (no group)
C5 Monitoring road surface conditions and weather: EC

Regulation layer
R1 Steering control command: SC
R2 Speed regulation command: SC
R3 Braking command: SC
R4 Vehicle condition monitoring and failure detection/diagnosis: SC
R5 Trip progress monitoring: NC

Table 6. Safety and Efficiency Criticality of Elemental Functions (Sensing and Actuation)

P1 Sensing:

State of the vehicle

P1.1 Lateral position: SC
P1.2 Distance and yaw angle to a forward roadway reference target: SC
P1.3 Longitudinal position: SC
P1.4 Land recognition:
P1.5 Velocity: SC
P1.6 Lateral acceleration: SCC/EC
P1.7 Longitudinal acceleration: SC
P1.8 Yaw rate: SCC/NC
P1.9 Roll rate: SCC/NC
P1.10 Pitch rate: SCC/NC
P1.11 Distance to a frontal vehicle/obstacle: SC
P1.12 Closing rate to a front vehicle/obstacle: SC(group) NC (non group)
P1.13 Identification of the frontal object: EC
P1.14 Distance to a neighboring vehicle/object: SC
P1.15 Closing rate to a neighboring vehicle/object: SC
P1.16 Distance to a rear vehicle/obstacle: SC
P1.17 Closing rate to a rear vehicle/obstacle: EC

Condition of the vehicle

P1.18 Dynamic response of the propulsion system EC
P1.19 Dynamic response of the braking system: SC
P1.20 Dynamic response of the steering system: SC
P1.21 Condition of the propulsion system: EC
P1.22 Condition of braking system: EC
P1.23 Condition of steering system: EC
P1.24 condition of electrical system: EC
P1.25 Tire pressure: SCC/NC
P1.26 Energy level: SC

Information about the infrastructure

P1.27 Horizontal curves: SC
P1.28 Vertical curvatures: SCC/EC
P1.29 Size and location of entrance/exit gates: SC
P1.30 Road surface condition: SC

Weather Conditions

P1.31 Visibility: SCC/NC
P1.32 Wind: SCC/EC

Traffic signal/sign information

P1.33 Traffic signal: SC
P1.34 Traffic sign: SC

P2 Actuation:

P2.1 Steering actuation: SC
P2.2 Propulsion actuation: SC
P2.3 Brake actuation: SC

Table 7. Safety and Efficiency Criticality of Elemental Functions (Human machine interface)

Information display/warning

P3.1 Permission/rejection: SC
P3.2 Vehicle speed: SC
P3.3 Spacing or headway: SC
P3.4 Location: EC
P3.5 Lane recognition: NC
P3.6 Energy level and low fuel warning: SC
P3.7 Diagnosis information and warning signals: SC
P3.8 Command signal for human takeover: SC
P3.9 control process report: NC
P3.10 Route recommendation information or traffic information: EC
P3.11 Trip progress report: EC
P3.12 Yellow page information: EC

Human input/inquiry

P3.13 Request for entering or exiting automated highway: SC
P3.14 Inputs for route recommendation: EC
P3.15 Lane selection: NC
P3.16 Trip progress information inquiry: NC
P3.17 Vehicle condition information inquiry: EC
P3.18 Performance adjustment: NC
P3.19 Responses to interrogation about readiness to resume manual control: SC

Manual control mechanisms

P3.20 Switching mechanism for alternating between automatic control and manual control: SC
P3.21 Emergency switching mechanism for human backup operation: SC
P3.22 Manual steering: SC
P3.23 Manual propulsion control: SC
P3.24 Manual brake control: SC

Table 8. Safety and Efficiency Criticality of Elemental Functions (Information Links, Secondary functions, Essential human functions)

P4 Information links:

P4.1 Information link between the network layer and the link layer: EC
P4.2 Information exchange between the link layer and the coordination layer: EC
P4.3 Information link between the coordination layer and the regulation layer:
1,2,3--SC; 4,5,6--EC
P4.4 Information link between the regulation layer and the physical layer: SC

P5 Secondary functions: NC

Essential human functions
H1 Manually maneuver vehicle: SC
H2 Request information EC
H3 Receive information: SC
H4 Provide information:
Requests to enter the AHS: SCC
Destination: EC
Requests to immediately exit AHS: EC
Authorization for change from manual to automated mode: EC
Responses to interrogation about readiness to resume manual control: SC

8.0 Self Diagnosis - Self Monitoring Technology

The technology to continuously monitor and evaluate the performance of a sensor or actuator has been evolving for many years and can be a key element in the overall safety of AHS. The capability to predict a failure in advance of the actual event or to know when a sensor is not working correctly and transmitting false or erroneous data will allow timely and effective safety measures to be taken before a hazard condition arises.

For example, if it was possible to predict an actuator failure even 30 to 60 seconds before the actual failure, it would be possible to take evasive action and stop the vehicle in a safe place, hopefully out of the main stream of traffic.

Two basic types of error can be detected by self-monitoring and self diagnosis technology:

1. Hard failures of a Control Element (CE)
Sensor or actuator does not respond to event signature and estimated delay has elapsed.

2. Transient Failures of Controls Elements
Incorrect state change can be detected when it is out of sequence or does not satisfy the estimated temporal relationships.

Several basic approaches are possible to monitor the health of an actuator or sensor:

1. Behavior models
2. Temporal models
3. Combination of Behavior and Temporal models

A behavior model of a Control Element is defined by a signature of discrete events. These events are typically required to perform the function of the control element. An example signature of discrete events is

- Actuator 1 changes state from 0 to 1 within a prescribed time.
- In response to this change of state Sensor 3 changes state from 1 to 0 within a prescribed time.
- In response to this event sensor 5 changes sate from 0 to 1 within a prescribed time.

The temporal models involve timing relationships that are learned in real-time. This involves dynamically updating the estimates for delays in the Control Elements for each run. Many statistical approaches are possible to characterize the temporal characteristics of a Control Element. When a control element's temporal behavior deviates too far from the estimated or predicted statistical performance a warning can be issued.

Other methods for self-diagnosis includes approaches which incorporate both the behavior and temporal model approaches.

Because most of the sensors associated with AHS involve a time series of data, an approach which utilizes a continuous temporal statistical characterization of the sensor output can be very effective. This approach would continuously determine a "distance distribution" to an ideal sensor. Based on this distance measure, performance out of the normal could be rapidly identified.

Detailed analyses of specific sensors in specific situations will be needed to determine the exact sequence of events which might occur prior to a failure. With detailed sensor and actuator data such as this, it would be possible to design and therefore quantify the impact of a self monitoring system on AHS. This next step requires a specific system design and is not within the scope of the current AHS Precursor Systems analysis.

The following table indicates the specific approach which may be used to monitor and diagnose each of the sensing and actuation elements in the physical layer. The following abbreviations are used in the tables:

B: behavioral model
T: temporal model
B,T: combination of behavior and temporal models
S: statistical characterization

Table 9. Monitoring and Diagnosis for Elemental Functions (Sensing and Actuation)

P1 Sensing:

State of the vehicle

P1.1 Lateral position: S
P1.2 Distance and yaw angle to a forward roadway reference target: S
P1.3 Longitudinal position: S
P1.4 Lane recognition: S
P1.5 Velocity: S
P1.6 Lateral acceleration: S
P1.7 Longitudinal acceleration: S
P1.8 Yaw rate: S
P1.9 Roll rate: S
P1.10 Pitch rate: S
P1.11 Distance to a frontal vehicle/obstacle: S
P1.12 Closing rate to a front vehicle/obstacle: S
P1.13 Identification of the frontal object: B
P1.14 Distance to a neighboring vehicle/object: S
P1.15 Closing rate to a neighboring vehicle/object: S
P1.16 Distance to a rear vehicle/obstacle: S
P1.17 Closing rate to a rear vehicle/obstacle: S

Condition of the vehicle

P1.18 Dynamic response of the propulsion system: B,T
P1.19 Dynamic response of the braking system: B,T
P1.20 Dynamic response of the steering system: B,T
P1.21 Condition of the propulsion system: B,T
P1.22 Condition of braking system: B,T
P1.23 Condition of steering system: B,T
P1.24 condition of electrical system: B,T
P1.25 Tire pressure: S
P1.26 Energy level: S

Information about the infrastructure

P1.27 Horizontal curves: S
P1.28 Vertical curvatures: S
P1.29 Size and location of entrance/exit gates: S
P1.30 Road surface condition: S

Weather Conditions

P1.31 Visibility: S
P1.32 Wind: S

Traffic signal/sign information

P1.33 Traffic signal: B
P1.34 Traffic sign: B

P2 Actuation:

P2.1 Steering actuation: B,T
P2.2 Propulsion actuation: B,T
P2.3 Brake actuation: B,T

9.0 Primary Study Conclusions

The following observations and conclusions have been derived from this study:

1. Because of the significant communications requirements between the Coordination and Regulation layer for the Maneuver Planning function, it appears that the maneuver planning function of the Coordination layer should be done on the vehicle. This allows the coordination-regulation communications to be intra-vehicle instead of infrastructure-vehicle communications.

Several recent analyses support vehicle based maneuver planning including spontaneous platooning and mixed mode AHS evolutionary concepts.

Additional analysis must be done to examine other issues related to performing the coordination function on the vehicle. Stability must be examined within the context of specific algorithm approaches across expected operating regimes.

2. It is important for vehicles in a platoon to maintain communications with the lead vehicle. It is possible to build accurate acceleration estimators to decrease the chances of collision but the problem of non-decreasing spacing errors down the string of vehicles can cause potential problems for sufficiently long platoons of vehicles.

3. The noise experienced in a platoon is a percentage of the target spacing. Hence spacing errors will be larger at larger target spacings. Vehicles following at larger spacing, albeit safer, will not necessarily result in the best form of control. Low gain controllers must be designed to ensure that small variations in spacing errors do not translate into high control effort and actuator saturation.

4. The effect of actuator limitations was studied but it was found that throttle actuators at least as fast as 150 ms are fast enough for the frequency and type of maneuvers that can be expected in automatic vehicle control on highways. Brake actuators slower than 150 ms can lead to poor tracking performance during high jerk deceleration maneuvers.

5. The communication function is critical for control of strings of vehicles based on the spacing distance control. Autonomous or time headway control approaches are more robust to losses of communication. With spacing control, if there is no communication, attenuation of errors down a string of vehicles cannot be guaranteed. The errors in tracking can be reduced, somewhat, through accurate estimators.

6. The closing rate function is by far the most important function for longitudinal control. Performance is greatly degraded in the absence of closing rate information. In addition, if communications are not working properly, potentially hazardous situations can arise due to large lags in acceleration tracking. The degradation in performance without closing rate and communication information is true regardless of the control approach used. The closing rate function is safety critical.

7. Self-diagnosis and self-monitoring technology can have significant benefit to improving the safety of AHS. Additional study is needed to determine the best technology approach and whether it is best to have a centralized self monitoring elemental function or to have a distributed monitoring capability with each element performing its own diagnostics, or a combination of both.

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Appendix A: Elemental Functions

C.1 Network layer

The network layer is responsible for route and flow control within a network. Based on the nature of an inquiry, the network layer can provide either information reflecting the traffic conditions on a specific route or route recommendations designed to achieve a desired traffic flow. The vehicle operator finalizes the route selection and informs the network of his/her selected route.

N1. Monitoring traffic conditions and predicting congestion: The network layer manages network traffic data and predicts when and where congestion will occur based on real-time traffic information.

N2. Vehicle ID assignment: Upon approving the request for entering, the network assigns an identification code to a vehicle. During the entire trip this ID code will be used for obtaining special instructions from the coordination or higher layers, and for coordinating maneuvers with other vehicles.

N3. Route recommendation: The route recommendation is developed based on users' requests and traffic conditions. Upon receiving the location and the destination of a vehicle, the network layer may recommend the shortest/fastest route. Route recommendation may be provided at the beginning of a trip or anytime during the trip. Route selection or route change may be requested by the vehicle operator or mandated by the network due to changes in traffic flow.

C.2 Link layer

Each route in the automated highway network can be subdivided into sections, defined as links. The link layer is responsible for path and congestion control within an individual link on the assigned route. The link layer may select a lane for each vehicle, sets target speeds for vehicles or platoons for each section of the route, and manipulates platoon size (when relevant) depending on the flow. It may also prioritize the vehicle's operation during cooperative maneuvers and manage incident responses.

L1. Lane assignment: The link layer may provide lane assignments in accordance with the selected route and traffic conditions. Lane assignments may be given before lane-changing is needed, and at locations such as entrance, exit, or diverging points where decisions are needed for choosing a path.

L2. Target speed: The target speed is provided in accordance with the local traffic conditions.

L3. Maximum group size: When groups are used, the maximum size of group is provided based on the current traffic conditions.

L4. Minimal separations: The required minimal headway is provided in accordance with the weather and roadway conditions. In a system with groups the spacing between groups are provided.

L5. Prioritizing vehicle operations: Vehicles with special missions, such as ambulances or fire engines or high occupancy vehicles, are given priority over other vehicles.

L6. Regional traffic conditions monitoring and incident management: Traffic conditions are monitored. In the incident conditions, the link layer selects paths for vehicles, adjusts target speed, or instructs vehicles to changes lane for diversion around incidents.

C.3 Coordination layer

The coordination layer is responsible for microscopic management of a subsection within a link. The coordination layer inspects and monitors vehicles and traffic flows, issues permission/rejection, and coordinates complicated maneuvers under both normal and incident conditions. The coordination layer also provides information regarding the road surface conditions and weather, and sets minimal separations. In a system with platoons, the coordination layer is also responsible for joining and splitting platoons.

C1. Off-vehicle inspection and monitoring: The vehicle inspection could be performed before the vehicle enters the AHS, or while the vehicle is on the AHS. The inspection and monitoring functions, which may work together with on-vehicle detection/diagnosis devices, provide vehicle health or condition reports.

C2. Issuing permission/rejection: Based on the inspection/monitoring outcome, the coordination layer issues permission for entering or remaining on the AHS. Should a fault(s) be detected, a rejection command will be issued.

C3. Maneuvering coordination planning: Maneuvering coordination planning determines the sequence of a number of vehicles performing a coordinated maneuver. Maneuvering coordination planning is performed for both normal and abnormal conditions.

C3.1 Normal maneuver coordination planning: Normal maneuvers that require coordination between vehicles, such as lane-changing, merging, entering or exiting an AHS, or joining or splitting a group, are handled by the coordination layer. A series of control commands which may include time and/or location for performing a specific maneuver will be developed for the affected vehicles in order to coordinate the sequences of coordination maneuvers. The coordination layer also sets up coordination protocols among the involved vehicles and determines commanded speed, location, and conditions for maneuvering action.

C3.2 Maneuvering coordination planning for hazardous conditions: Under hazardous conditions, the coordination layer provides information regarding specific hazards to vehicles which are potentially affected, and provides commands or instructions for avoiding collisions.

C4. Supervising the sequence of the coordinated maneuvers: The coordination maneuvers will be monitored by the coordination layer.

C5. Monitoring road surface conditions and weather: The coordination layer senses and provides information regarding weather and road surface conditions.

C.4 Regulation layer

The regulation layer carries out the directions of the coordination layer. It tracks target speeds, maintains separations between vehicles and between platoons, and provides commands to perform steering and speed control for maintaining the lateral position of the vehicle and the longitudinal separation between vehicles. It also provides commands to implement lane-changing, merging, and splitting/joining a platoon. The regulation layer is also responsible for monitoring vehicle conditions and for on-board failure detection/diagnosis.

R1 Steering control command: Commands for providing the required lateral motion are constantly updated based on information regarding the vehicle's lateral position, yaw motions, lateral acceleration, and upcoming road geometry.

R2 Speed regulation command: The speed control command is issued based on the instruction provided by the coordination layer and sensor and vehicle performance feedback from the physical layer.

R3 Braking command: The braking command is issued when reduction of the vehicle speed is required. The braking command can be issued in combination with the speed control command.

R4 Vehicle condition monitoring and failure detection/diagnosis: Vehicle conditions will be monitored using the sensory information provided by the physical layer. Failure detection and diagnosis will be performed when a system fault is discovered.

R5 Trip progress monitoring: The trip progress will be monitored by reporting to the operator the information regarding vehicle location and traffic conditions and estimated arrival time.

C.5 Physical Layer

The physical layer includes the actuation and sensing devices that actually carry out the control commands of the regulation layer and feed information back to it. The physical layer is also responsible for human-machine interaction.

P1 Sensing: Four groups of sensory information are needed. The sensory information can be obtained through direct sensing or combined sensing and signal processing. The following information may be entirely or partially needed for any specific AHS design.

(a) State of the vehicle

P1.1 Lateral position: The distance from a point along the longitudinal centerline of the vehicle to a reference line or marker is measured. The reference can be a roadway reference which delineates the center or the edge of a traffic lane or a roadside reference which retains a constant spacing from a lane centerline.

P1.2 Distance and yaw angle to a forward roadway reference target: When a forward-looking sensing device is used, the distance and the yaw angle to a roadway reference target(s) is measured.

P1.3 Longitudinal position: The longitudinal position of the vehicle relative to a milepost is acquired.

P1.4 Lane recognition: The number of the lane on which the vehicle is traveling is acquired.

P1.5 Velocity: The distance traveled in a specified time interval is measured.

P1.6 Lateral acceleration: The variation in velocity in the lateral direction during a specified time interval is measured at the mass center.

P1.7 Longitudinal acceleration: The variation in velocity in the longitudinal direction during a specified time interval is measured at the mass center.

P1.8 Yaw rate: The angular change in a specified time interval along the axis perpendicular to the road surface through the mass center is measured.

P1.9 Roll rate: The angular change in a specified time interval along the longitudinal axis through the mass center is measured.

P1.10 Pitch rate: The angular change in a specified time interval along the lateral axis through the mass center is measured.

P1.11 Distance to a frontal vehicle/obstacle: The distance to a frontal vehicle/obstacle is measured as the separation between the controlled vehicle and the frontal vehicle/obstacle.

P1.12 Closing rate to a front vehicle/obstacle: The closing rate to a frontal vehicle/obstacle is measured as the variation in distance between the controlled vehicle and the frontal vehicle/obstacle in a specified time interval.

P1.13 Identification of the frontal object: The obstacle detection function involves identification of the nature of an obstacle on the vehicle path, including vehicle, pedestrian, or any other obstacle that obstructs the vehicle path.

P1.14 Distance to a neighboring vehicle/object: The distance to a neighboring vehicle/obstacle is measured as the separation between the controlled vehicle and the neighboring vehicle/obstacle.

P1.15 Closing rate to a neighboring vehicle/object: The closing rate to a neighboring vehicle/obstacle is measured as the variation in distance between the controlled vehicle and the neighboring vehicle/obstacle in a specified time interval.

P1.16 Distance to a rear vehicle/obstacle: The distance to a rear vehicle/obstacle is measured as the separation between the controlled vehicle and the rear vehicle/obstacle.

P1.17 Closing rate to a rear vehicle/obstacle: The closing rate to a rear vehicle/obstacle is measured as the variation in distance between the controlled vehicle and the rear vehicle/obstacle in a specified time interval.

(b) Condition of the vehicle

P1.18 Dynamic response of propulsion system: The dynamic response of the propulsion system is characterized by the time interval required for accelerating the vehicle to a target speed from a specified initial speed.

P1.19 Dynamic response of braking system: The dynamic response of the braking system is characterized by the time interval required for decelerating a vehicle from a certain speed to a stop.

P1.20 Dynamic response of steering system: The dynamic response of the steering system is characterized by the frequency response of the steering system and the deadband.

P1.21 Condition of propulsion system: Several parameters such as temperature, pressure (for an internal combustion system), or current (for an electrical system) are selected to represent the health of the propulsion system .

P1.22 Condition of braking system: Several parameters such as temperature of brake discs or shoes and pressure of brake hydraulic system are selected to characterize the health of the braking system.

P1.23 Condition of steering system: Several parameters such as hydraulic pressure (for a hydraulic steering actuator) or current (for an electrical steering actuator) and temperature will be used to characterize the health of the steering system.

P1.24 Condition of electrical system: Several parameters such as voltage, current, and temperature will be used to characterize the electrical system.

P1.25 Tire pressure: Tire pressure can be physical measurements or estimation based on dynamic performance.

P1.26 Energy level: Energy level can be fuel level (for an internal combustion propulsion system) or voltage (for an electrical propulsion system) or both (for an hybrid vehicle).

(c) Information about the infrastructure

P1.27 Horizontal curves: A horizontal curve is characterized by several parameters, i.e., radius and length of the curvature, and distance to the curvature.

P1.28 Vertical curvatures: A vertical curvature is characterized by gradient and the length of the curvature and distance to the curvature.

P1.29 Size and location of entrance/exit gates: When entrance/exit gates are present, the distance to a gate, the direction of the gate, and the size of the gate will be given.

P1.30 Road surface condition: The condition of the road, particularly the parameters which will affect the vehicle cornering force, will be monitored.

(d) Weather conditions

P1.31 Visibility: The visibility will be monitored and graded.

P1.32 Wind: The direction and magnitude of the wind will be measured.

(e) Traffic signal/sign information

P1.33 Traffic signal: Traffic signals for speed control will be transmitted to or recognized by the vehicle.

P1.34 Traffic sign: Traffic signs will be transmitted or recognized by the vehicle.

P2 Actuation: Actuation is provided in two dimensions, steering and speed control. The speed control includes control of both the propulsion and the braking systems.

P2.1 Steering actuation: The steering actuation causes the wheels to turn forcing the vehicle to change its moving direction.

P2.2 Propulsion actuation: The propulsion actuation causes a vehicle accelerate or decelerate (using engine brake).

P2.3 Brake actuation: The brake actuation causes a vehicle to decelerate.

P3 Human-machine interface: The human-machine interface enables the human operator to monitor the performance of the vehicle, to adjust performance parameters within a reasonable working range, to be aware of hazardous conditions, and to take over control tasks if necessary. It may be implemented using audio, visual, or tactile displays, voice or key input devices, and steering and speed control mechanisms.

(a) Information display/warning

P3.1 Permission/rejection: Self explanatory.

P3.2 Vehicle speed: Display information acquired by P1.5.

P3.3 Spacing or headway: The distance in time or space between the controlled vehicle and the vehicle in front.

P3.4 Location: The location of the vehicle can be given by the name of a street or a town or distance to a reference location.

P3.5 Lane recognition: Display information acquired by P1.4.

P3.6 Energy level and low fuel warning: Display information acquired by P1.26. A warning signal is given when fuel level is low.

P3.7 Diagnosis information and warning signals: Selected diagnostic signals are displayed. Warning signal is given when failure is detected.

P3.8 Command signal for human takeover: Should the safety-critical component fail, a command signal is given to instruct the driver to take over the control.

P3.9 Control process report: Each control process can be displayed at driver's request.

P3.10 Route recommendation information or traffic information: Route recommendation or traffic information is available anytime at use's request. P3.11 Trip progress report: The remaining distance to the destination and the required time for completing the trip is reported.

P3.12 Yellow page information: Business and commercial information can be searched and displayed.

(b) Human input/inquiry

P3.13 Request for entering or exiting automated highway: The driver requests entering or exiting the automated highway through an interface mechanism.

P3.14 Inputs for route recommendation: The driver provides the planned destination, preferred route sections, or passing point to the network for route recommendation.

P3.14 Route selection: Upon receiving the route recommendation information, the driver can select a route recommended by the network or input his/her own choice.

P3.15 Lane selection: The driver may select a preferred lane.

P3.16 Trip progress information inquiry: The driver can request information regarding the trip progress.

P3.17 Vehicle condition information inquiry: An interface mechanism allows the driver to inquire about vehicle conditions.

P3.18 Performance adjustment: Interface mechanisms allow the driver to adjust the vehicle's performance such as ride comfort or headway within the specified tolerances.

P3.19 Responses to interrogation about readiness to resume manual control: An input mechanism allows the driver to inform the system of his/her readiness to resume manual control.

(c) Manual control mechanisms

P3.20 Switching mechanism for alternating between automatic control and manual control: Switches allow a driver to enable automatic control functions or disable specified automatic control functions following a standard procedure.

P3.21 Emergency switching mechanism for human backup operation: A kill switch disables critical control functions for immediate human backup.

P3.22 Manual steering: A mechanism allows a driver to fully control the steering actions of the vehicle.

P3.23 Manual propulsion control: A mechanism allows a driver to fully control the speed of the vehicle.

P3.24 Manual brake control: A mechanism allows a driver to fully control the deceleration of the vehicle.

P4 Information links: The information links facilitate the information exchange between two adjacent control layers. Each end of the information link is responsible for transmitting and receiving information and transmitting information to the intended recipient.

P4.1 Information link between the network layer and the link layer: The network layer receives information regarding traffic conditions and route selection requests from the link layer. The network layer also provides information regarding route recommendation, traffic condition prediction information, and vehicle ID assignment to the link layer or to the intended recipient via the link layer.

P4.2 Information exchange between the link layer and the coordination layer: The link layer receives information regarding traffic conditions of the subsections within the link, designated destination of a vehicle, and information addressing the network layer from the coordination layer. The link layer also provides information regarding vehicle operation parameters such as target speed and minimal separation to the coordination layer or to the intended recipient via the coordination layer.

P4.3 Information link between the coordination layer and the regulation layer: The coordination layer receives information regarding the requests for a coordinated maneuver, status information about affected vehicles from the regulation layer, and information addressing the link layer or the network layer, such as driver's inquiry, from the regulation layer. The coordination layer also provides information regarding operation commands which defines the sequences of coordination maneuvers, information such as road surface conditions and weather to the regulation layer, and information addressing the regulation layer from the link layer or the network layer.

P4.4 Information link between the regulation layer and the physical layer: The regulation layer receives information regarding sensory measurements and user's requests from the physical layer. The regulation layer also provides control commands to the physical layer.

P5 Secondary functions: The secondary functions that exist on the existing vehicles such as windshield wipers and lights will be incorporated in the AHS.

C.6 Essential Human Functions

The set of functions that the driver is responsible for is highly dependent upon the specific AHS scenario under consideration and the level of automation used. However, in all AHS scenarios envisioned, even the most highly automated, the driver has a certain minimal set of functions to perform. As the level of automation is reduced, the driver assumes responsibility for additional functions. For example, in some AHS concepts, lane selection is not performed by the roadside or vehicle control systems, but by the driver. In still less automated concepts, travel within the lane is automated, but maneuvering between lanes is not. All sensing, decisions, planning, and control actions related to lane-changing would be relegated to the driver in such scenarios. The minimal set of human driver functions in an AHS is described below:

H1 Manually maneuver vehicle: The driver will be required to perform manual speed and steering control during the following operations:

- merging into the mixed stream of traffic in the transition lane during entry

- driving in a mixed stream of traffic prior to control transfer to the automated system during entry

- driving in the mixed stream of traffic following a return to manual control on exit

- merging into the stream of manual traffic to complete an exit.

In addition, manually controlled maneuvers might be required during failure mode operations.

H2 Request information: The driver may request various kinds of information from the system, including:

vehicle status
trip progress
traffic conditions

H3 Receive information: The driver will receive information from the vehicle, the roadside, and the traffic management center.

H4 Provide information: The driver will be required to provide information to the system. This includes the following:

- Requests to enter the AHS: The vehicle operator requests permission to enter the AHS

- Destination: The driver will be required to designate a destination for his/her trip. This function also will allow the driver to change that destination during the trip.

- Requests to immediately exit AHS: The driver may request to leave the system at the closest possible exit or to leave the transition lane prior to entering the automated lane.

- Authorization for change from manual to automated mode: The driver must provide a final authorization in order for the manual to automated control transition to proceed.

- Responses to interrogation about readiness to resume manual control: The driver will have to make some input when cued by the system to indicate his/her readiness to resume manual control.

Appendix B: Longitudinal Vehicle Control Model

Engine Dynamics

The characterization of the engine dynamics closely follows the development of an engine model by Cho and Hedrick. A similar model was used by McMahon and Hedrick for longitudinal vehicle control studies in IVHS.

The engine dynamics are captured through two engine states - mass of air in the intake manifold, m_a, engine speed, $_e$. Figure 50 shows a schematic of the engine. The dynamics are represented as below.

$$\dot{m}_a = \dot{m}_{ai} - \dot{m}_{a0}$$

$$\dot{}_e = ((t_{net} - t_{pump}) / j_e$$

$\dot{m}_{ai}, \dot{m}_{a0}$ are the mass rates of air flow into and out of the intake manifold respectively

$$\dot{m}_{ai} = \beta_1 PRI(p_m/p_a \, TC_{(\alpha)}$$

p_a, p_m are atmospheric and manifold pressures respectively, α is the throttle angle and PRI and TC are nonlinear functions. t_{net}, t_{pump} are the net engine and pump torques respectively.

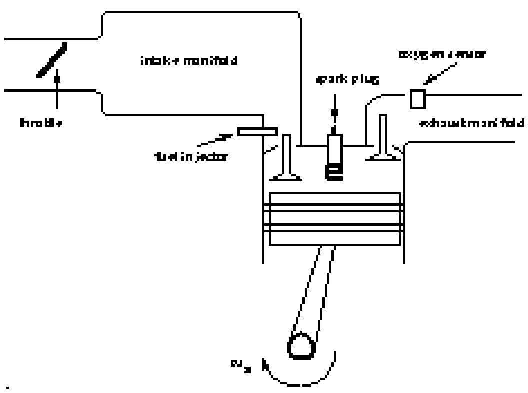

Figure 50. Engine schematic

j_e is the effective engine inertia and $_i$ is an engine constant.

Steady state engine maps were provided for the Lincoln town-car. These maps were used to develop table look-up functions for $t_{net}, \dot{m}_{a0}$. The tables are indexed by two variables - $_e$ and the pressure in the manifold, p_m, both of which can be measured.

Drivetrain Dynamics

The model includes a torque converter. The pump torque (engine side) and turbine torque (transmission side) are calculated from torque converter maps indexed by the angular speed ratio across the torque converter. The pump torque, t_{pump}, is then given by

$t_{pump} = f_{tq}(sp_{ratio})$
$sp_{ratio} = {}_e * r^* / {}_w$
r^* is the effective reduction across the transmission and ω_w is the average driven wheel angular speed. The turbine torque, t_{turb}, is calculated in a similar fashion.

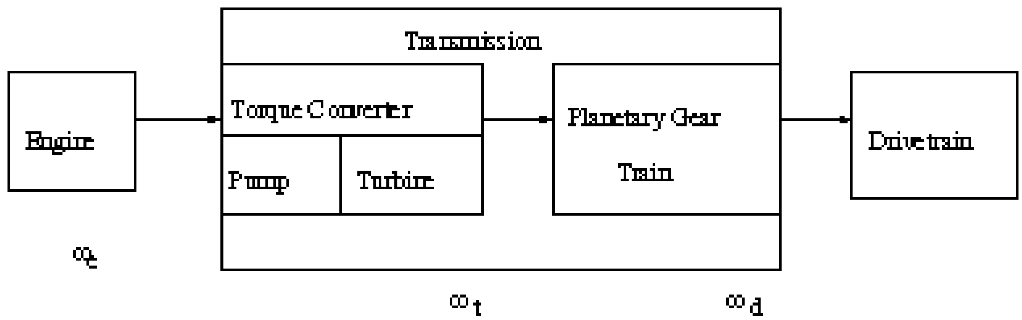

Figure 51. Transmission schematic

The gear shift dynamics have not been modeled. Figure 51 is a schematic of the vehicle transmission. We have neglected shaft torque dynamics by assuming a rigid coupling between the turbine of the torque converter and the vehicle rear wheels. This allows the calculation of input torque to the driven wheels by simply referring the turbine torque to the wheel side. Assuming this is split up equally between the two rear wheels, the driven wheel equations are given by

$$\dot{j}\ \dot{}_{w,i} = \frac{t_{turb} * r^*}{2} - \frac{t_{br}}{2} - r_w f_{xi}$$

f_{xi} is the tractive force and
${}_{w,i}$ is the angular velocity of the i^{th} wheel,
r_w is the effective wheel radius and
t_{br} is the net braking torque on the driven wheels.

The tractive forces in the rear wheels are assumed to be directly proportional to the wheel slip,
$f_{xi} = k_r r_{slip,i}$

where, k_r is the proportionality constant and the wheel slip for the i^{th} wheel is given by

$$r_{slip,i} = \frac{r_w \ {}_{w,i} - V}{r_w \ {}_{w,i}}$$

Assuming that the slip is the same in each of the driven wheels, (i.e. $f_{x3}=f_{x4}=f_x$), we have, ${}_w$ (= ${}_3$ = ${}_4$). Assuming minimal contribution of tractive forces from the non driven (front) wheels, the net tractive force $f_{trac} \approx 2f_x$. Then the longitudinal vehicle velocity equation is given by
$V = f_{trac} - f_{drag} - f_{roll}$

f_{drag}, f_{roll} are the net drag and rolling resistance forces on the vehicle and tires respectively.

The braking torque, t_{br}, is represented in the form of a first order brake model given by

$$\dot{t}_{br} = (t_{br,c} - t_{brd}) / \quad _b .$$

$t_{br,c}$ is the commanded brake torque and τ_b is the time constant of the brake.

The inputs to the model are the throttle angle,   and the commanded braking torque, $t_{br,c}$.

Simplifications for Control

1. No-slip assumption - there is no slip between the wheels and the road. This allows us to relate the vehicle speed to the engine speed.

$$V = r^* r_w \quad _e$$

2. Since platooning operations are high speed - high gear operation of the vehicle, we assume that there is negligible slip across the torque converter.

Note: With assumptions 1 and 2 we can reflect the wheel load, t_{load}, to the engine side and rewrite the engine speed state equation as below.

$$\dot{\quad}_e = (t_{net} - t_{load}) / j_e$$

where $t_{load} = r^*(r_w f_{trac} + t_{br})$.

Recalling the vehicle velocity state equation, we eliminate the tractive force, f_{trac}, between the V and ω_e state equations to obtain an equation of the form below.

$$j^* \dot{\quad}_e = t_{net} - r_w r^* (f_{drag} + f_{roll}) - r^* t_{br}$$

where $j^* = j_e$ + mass * $r^{*2} r^2_w$

3. For vehicle position control applications the intake manifold dynamics are sufficiently faster, than engine dynamics. Hence we can write

$$\dot{m}_{a1} \approx \dot{m}_{a0}$$

$$\dot{m}_{a0} \approx \quad _1 PRI(p_m / p_a) TC(\quad)$$

In view of the above equations we can simplify the net torque calculation to obtain t_{net} as a function of ω_a and α.

The simplifying assumptions allow us to reduce the model to a simpler form for controller design. The model is represented by the following state equations.

$$\dot{x} = r^* \quad _e$$

$$j^* \dot{\quad}_e = t_{net} - r_w r^* (f_{drag} + f_{roll}) - r^* t_{br}$$

$$\dot{t}_{br} = (t_{br,c} - t_{br}) / \quad _b$$

Controller Design

Longitudinal vehicle control is achieved by one of 2 approaches - time headway or spacing distance control. The former involves control of the time of separation between succeeding vehicles while the latter is simply distance control. In this study we have adopted spacing control.

The controller design in the next few paragraphs deals with control of vehicles for platoon operations. The controller can be extended to take into account transition modes by replacing the constant desired spacing, $sp_{des,i}$ by a time varying desired spacing profile. The velocity regulation controller is slightly different but can be derived in a similar fashion.

A sliding mode approach has been followed. We define the spacing error

$$e = x_i - x_{i-1} - sp_{des,i}$$

$sp_{des,i}$ is the desired spacing specified for platoon operation. We also define a scalar function, s_1,

$$s_1 = \dot{e} + c_1 e + c_2 \int e dt$$

Differentiating the above function and expanding $\ddot{e}$ we have

$$\dot{s}_1 = \frac{r^* r_w}{j^*}(t_{net,des} - r^* r_w(f_{drag} + f_{roll}) - r^* t_{br}) - \ddot{x}_{i-1} + c_1 \dot{e} + c_2 e$$

In the above equation we can select $t_{net,des}$ to achieve $\dot{s}_1 = -k_1 s_1$ for some positive k_1. This ensures convergence of the errors to zero.

With knowledge of $t_{net,des}$ and engine speed ω_e we can calculate the desired throttle angle, $_{des}$. In case α_{des} is less than a threshold we calculate the desired brake torque from the above equations. In order to determine the desired brake input $t_{br,c}$ we have to define another scalar function, s_2.

Differentiating this and in a procedure similar to the case for net desired torque we can calculate the desired brake torque such that $\dot{s}_2 = -k_2 s_2$.

Appendix C: Lateral Control Vehicle Models

The lateral vehicle model describes vehicle sprung mass dynamics in the six directions of motion, i.e., longitudinal(x), lateral(y), vertical(z), roll(ϕ), pitch(θ), and yaw(υ). The model does not include the engine dynamics but assumes that required torque at the wheels can be provided by the engine powerplant. This model was developed for a Toyota Celica by Peng.

Vehicle Spring Mass Dynamics

Figure 52 shows the angles and dimensions associated with the vehicle in motion.

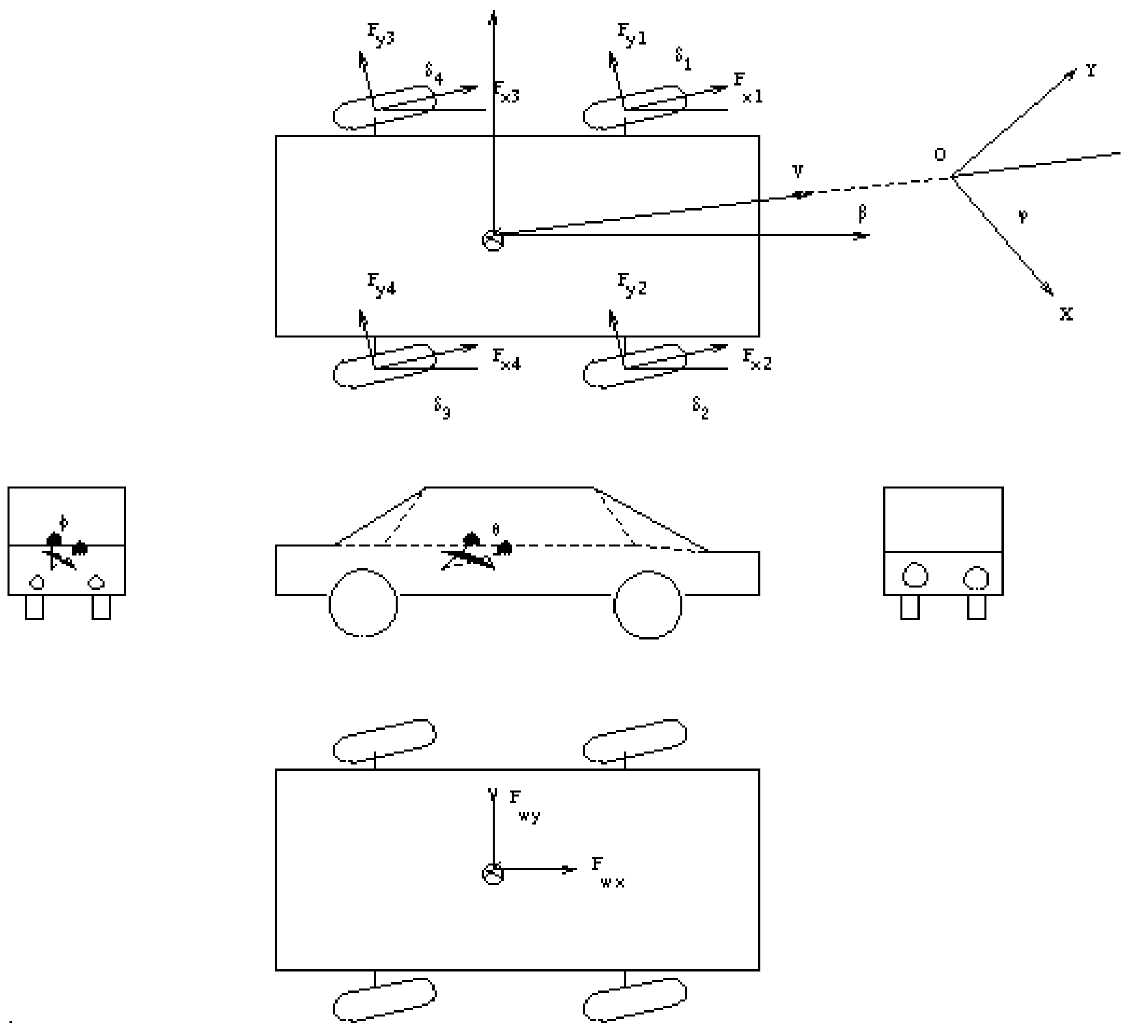

Figure 52. Vehicle Dimensions

Nomenclature

M_x, M_y, M_z	: moments about x ,y,z direction
XYZ	: inertial frame of reference.
xyz	: body fixed axis.

V_x (V_y,V_z)	: velocity in x (y,z) direction
F_{Ai}(F_{Bi})	: longitudinal (lateral) force on i^{th} tire.
F_{Pi}	: normal force on i^{th} tire.
F_{roll}	: rolling resistance of tires.
C_{dx}, C_{dy}	: drag coefficient in x,y direction.
f_{wx}, f_{wy}	: drag force in x,y direction.
m	: mass.
h_2 (h_4,h_5)	: distances of c.g. from roll center (pitch center and ground).
I_x (I_y,I_z)	: inertias about x y,z) axis
β	: side slip angle
χ	: velocity angle $\chi = \psi+\beta$

The vehicle slip angle χ is measured with respect to the sprung mass fixed co-ordinates while the vehicle yaw and velocity angles are measured with respect to the inertial coordinates. The relative yaw of the vehicle with respect to the road is given by $\psi_c = \psi\ \psi_{d.}$ ψ is the actual vehicle yaw while ψ_d is the desired yaw as determined from the road curvature information.

The next few sections deal with the calculation of the tractive and suspension forces and moments required for deriving the equations of motion of the sprung mass dynamics.

Tire Forces

The tire forces are calculated from a tire model developed by Peng. The tire model was developed using the Bakker-Pacjecka-Lidner model. This is a model that has been obtained through experimental study followed by nonlinear curve fit to obtain the longitudinal and lateral tire forces f_{xi} and f_{yi}). Test data was obtained from a YOKOHAMA P205/60R1487H steel belted radial tire. The tire forces for the i^{th} wheel are given by the functional expressions:

$$f_{xi} = f_{x()i}(\ _i, f_{zi})$$
$$f_{yi} = f_{y()i}(\ _i, f_{zi})$$

where $_I$, $_I$ are the slip ratio and slip angle respectively of the i_{th} tire, and f_{zi} is the normal force on the i_{th} tire.

The slip ratio is defined as

$$_i = \frac{r_w\ _{wi} - V_x}{r_w\ _{wi}} \qquad \text{traction}$$

$$_i = \frac{r_w\ _{wi} - V_x}{V_x} \qquad \text{braking}$$

$_{wi}$ is the angular velocity of the i^{th} wheel, and r_w is the effective wheel radius.

The slip angle is the angle between the tire orientation plane and its velocity and is given by

$$_I = \ _i - \ _i$$

where ξ_i is the angle between the forward speed of the i^{th} tire and the vehicle body, and δ_i is the wheel angle of the i^{th} tire. We call this the steering angle.

$$\tan(\zeta_1) = \frac{V_y + l_1\dot{\psi}}{V_x - \frac{s_{b1}\dot{\psi}}{2}} \qquad \tan(\ _2) = \frac{V_y + l_1 \dot{}}{V_x + \frac{s_{b1}}{2}\dot{}}$$

$$\tan(\ _3) = \frac{V_y - l_1\dot{}}{V_x - \frac{s_{b2}}{2}\dot{}} \qquad \tan(\ _{42}) = \frac{V_y - l_1\dot{}}{V_x + \frac{s_{b2}}{2}\dot{}}$$

s_{b1}, s_{b2} are the front and rear treadwidths respectively.

The above equations allow us to calculate tire forces under pure traction or cornering maneuvers. Bakker proposed a method to correct these forces under the case of combined traction and cornering. For this we define normalized slip factors * and *

$$^* = \frac{}{_{max}}$$

$$^* = \frac{}{_{max}}$$

where, $_{max}$ and $_{max}$ are the values at which f_{xi} and f_{yi} achieve their peak values respectively. These are the f_{xi} and f_{yi} values from the traction only and cornering only tests. Now the correction factor is described as

$$^* = [(\ ^*)^2 + (\ ^*)^2]^{.5}$$

Then the longitudinal and lateral tire forces are corrected by the following two equations.

$$f_{xi} = \frac{^*}{^*} f_{x()i}(\ ^*, f_{zi})$$

$$f_{yi} = \frac{^*}{^*} f_{y()i}(\ ^*, f_{zi})$$

From these equations we can obtain the net longitudinal and lateral tire forces contributed by the i^{th} wheel from the relations below.

$F_{Ai} = f_{xi}\cos(\ _i) - f_{yi}\sin(\ _i)$

$F_{Bi} = f_{xi}\sin(\ _i) - f_{yi}\cos(\ _i)$

Suspension Forces

We have assumed a suspension system similar to what Peng used for his lateral control study. The suspension consists of a spring and damper at each wheel. The deflections of the suspension joints can be calculated from geometry. The spring is assumed to be of the hardening type and is modeled as

$$F_{si} = C_{1i}(e_i + C_{2i}e_i^5)$$

where C_{1i}, C_{2i} are spring constants and e_i is the deflection of the suspension at the i^{th} wheel.

The damper is a simple velocity type damper with the damper force F_{di} at the i[th] wheel being directly proportional to the suspension deflection rate, $\dot{e}_i$.

The net vertical forces, F_{ps} are then given by the following equations

$$F_{pi} = \frac{mgl_2}{2(l_1 + l_2)} + F_{si} + F_{di} \qquad i=1,2$$

$$F_{pi} = \frac{mgl_1}{2(l_1 + l_2)} + F_{si} + F_{di} \qquad I=3,4$$

Moments Acting on the Vehicles

The moments acting on the vehicle through the tires are computed from the following equations.

$$M_x = (\frac{S_{b1}}{2} + h_2 \quad)F_{P1} + (\frac{S_{b2}}{2} + h_2 \quad)F_{P3} - (\frac{S_{b1}}{2} - h_2 \quad)F_{P2} - (\frac{S_{b2}}{2} - h_2 \quad)F_{P4} + (z - h_5 \quad)\sum_{i=1}^{4} F_{Bi}$$

$$M_y = (l_2 + h_4 \quad)(F_{P3} + F_{P4}) - (l_1 + h_4 \quad)(F_{P1} + F_{P2}) - (z - h_5)\sum_{i=1}^{4} F_{Ai}$$

$$M_z = (l_1 - h_4 \quad)(F_{B1} + F_{B2}) - (l_2 + h_4 \quad)(F_{B3} + F_{B4}) - (\frac{S_{b1}}{2} + h_2 \quad)F_{A1} + (\frac{S_{b1}}{2} - h_2 \quad)F_{A2} -$$

$$(\frac{S_{b2}}{2} + h_2 \quad)F_{A3} + (\frac{S_{b2}}{2} - h_2 \quad)F_{A4}$$

These are the expressions of the moments in the unsprung mass axes and since the sprung mass rotates relative to the unsprung mass we need to multiply the above moments with a transformation matrix which finally gives us the moments about the sprung mass.

We can now sum up all the forces and moments in the x, y, z directions and using the Euler equations obtain the following equations of motion. The road super-elevation and gradient angles have been neglected in the following vehicle equations.

$$m(\dot{V}_x - V_y \quad + h_4 \quad + h_2 \quad + h_2 \quad) = \sum_{i=1}^{4} F_{Ai} - C_{dx}V_x^2 - F_{roll}$$

$$m(\dot{V}_y + V_x \quad - h_2 \quad + h_4 \quad + h_4 \quad) = \sum_{i=1}^{4} F_{Bi} - C_{dyx}V_y^2$$

$$m(\dot{V}_z + V_x \quad - h_5 \quad) = \sum_{i=1}^{4} F_{Pii} - mg$$

$$I_x(\quad - \quad - \quad) - (I_y - I_z) \quad = M_x - \quad M_z$$

$$I_y(\quad + \quad + \quad) - (I_z - I_x) \quad = M_y + \quad M_x$$

$$I_z(\quad + \quad - \quad) - (I_x - I_y) \quad = M_z + \quad M_x - \quad M_y$$

The only inputs to the system are the steering angles, δ_i (of the i[th] wheel). The steering angles δ_i appears implicitly in the tire forces.

In addition to these states we also keep track of the deviation of the vehicle c.g. from the center of the lane, y_r. y_r is obtained from the following equation.

$$\dot{y}_r = V_y + \dot{V}_x$$

$$y_s = y_r + d_s$$

where, y_s is the deviation of the magnetometer, the lateral position sensor (located at a distance d_s m ahead of the vehicle c.g.), from the center of the lane.

Simplifications to Model For Control Purposes

1. Assuming small vertical, roll and pitch motions we neglect these.
2. Small yaw angle assumption.
3. Vehicle longitudinal speed is constant.
4. We consider a front wheel steered vehicle. Hence,

   $_1 = {}_2 = {}_f$

   $_3 = {}_4 = {}_r = 0.0$

By retaining only the lateral and the yaw motions we obtain the simplified set of equations below.

$$\frac{d}{dt}\begin{bmatrix} y_r \\ \dot{y}_r \\ {}_c \\ \dot{}_c \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{A_1}{V} & -A_1 & \frac{A_2}{V} \\ 0 & 0 & 0 & 1 \\ 0 & \frac{A_3}{V} & -A_3 & \frac{A_4}{V} \end{bmatrix}\begin{bmatrix} y_r \\ \dot{y}_r \\ {}_c \\ \dot{}_c \end{bmatrix} + \begin{bmatrix} 0 \\ B_1 \\ 0 \\ B_2 \end{bmatrix} + \begin{bmatrix} 0 \\ A_2 - V^2 \\ 0 \\ A_4 \end{bmatrix}\frac{1}{p}$$

$$A_1 = 2\frac{C_{sf} + C_{sr}}{m} \qquad A_2 = 2\frac{l_1 C_{sf} - l_2 C_{sr}}{m}$$

$$A_{31} = 2\frac{l_1 C_{sf} - l_2 C_{sr}}{I_z} \qquad A_4 = 2\frac{l_1^2 C_{sf} - l_2^2 C_{sr}}{I_z}$$

The above equations are linear and greatly facilitate development of control laws for the vehicle. The assumption that vehicle velocity is constant will not be true for maneuvers such as lane change but even in such cases finely tuned gain scheduled controllers can be developed if the linear assumption is retained.

Controller Design

The equations in the simplified system equations are in linear state space form. Hence linear system control theory can be applied to control the vehicle lateral motion. The controller adopted for this study was developed by Peng. The controller is a frequency shaped linear quadratic (FSLQ) controller.

The performance index for the FSLQ controller is based on the tracking error, passenger ride quality and robustness to high frequency unmodeled dynamics. Hence the performance index is formulated as below.

$$J=\frac{1}{2}\int_{-\infty}^{\infty}[a^{*}(j\ \ )\frac{q_a^2}{1+\ \ _a^2\ \ ^2}a(j\ \ )+y_s^{*}(j\ \ )\frac{q_y^2}{1+\ \ _y^2\ \ ^2}y_s(j\ \ )+(\dot{\ }_c(j\ \ ))^{*}\frac{q^2}{1+\ \ ^2\ \ ^2}\dot{\ }_c(j\ \ )$$

$$+y_s^{*}(j\ \ )\frac{q_i^2}{(j\ \ )^2}y_s(j\ \ )+\ ^{*}(j\ \ )R\ \ (j\ \ )]d$$

*

denotes the complex conjugate.

The coefficient λ_a determines the bandwidth of the weighting on lateral acceleration while λ_y and λ_ψ are determined by considering both the high frequency robustness and tracking performance. The parameters q_a, q_y, q_ψ are then tuned to compromise between ride quality and tracking error. R is fixed to be one. Now the FSLQ problem can be transformed to a standard LQ optimal control problem by introducing augmented state variables

$$z_1^{*}z_1=a^{*}(j\ \ )\frac{q_a^2}{1+\ \ _a^2\ \ ^2}a(j\ \ )$$

$$z_2^{*}z_2=y_s^{*}(j\ \ )\frac{q_{ay}^2}{1+\ \ _y^2\ \ ^2}y_s(j\ \ )$$

$$z_3^{*}z_3=(\dot{\ }_c(j\ \ ))^{*}\frac{q^2}{1+\ \ ^2\ \ ^2}\dot{\ }_c(j\ \ )$$

$$z_4^{*}z_4=y_s^{*}(j\ \ )\frac{q_i^2}{(j\ \ )^2}y_s(j\ \ )$$

Now the gain vector of the feedback controller can be determined by solving the Algebraic Riccati Equation.