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<th><strong>Project Title:</strong></th>
<th>Enhanced Coordination and Link Layer Control Algorithms for Improving AHS Capacity</th>
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<td>(For FY 02-03 only proposals: project start date - 6/30/02); (For multi-year proposals: project start date - 6/30/02, and each subsequent fiscal year ending June 30)</td>
<td>Year 1: $ 112,269</td>
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<td>July 1, 2002</td>
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<td><strong>Topic Name (from RFP):</strong></td>
<td>Coordination and Link Layer Protocols for Automated Vehicles</td>
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B Summary

This proposal addresses Section 2.2.5 of PATH’s 2002 RFP, which requests the refinement and enhancement of previously designed coordination and link layer protocols, to make them more efficient. The two most important factors that need to be considered in the evaluation of AHS architectures are safety and capacity. The current PATH AHS architecture was designed to guarantee safety under normal and several degraded mode conditions, but is not necessarily optimal with respect to capacity considerations.

The goals of this proposal are:

1. To redesign and enhance certain existing coordination layer atomic maneuvers and their associated regulation layer controllers, so that the flow capacity of the PATH AHS is dramatically improved, without sacrificing safety.

2. To formulate new coordination-layer protocols, consisting of atomic maneuvers that permit multiple vehicles within a platoon to simultaneously change lane and permit platoons in adjacent lanes to simultaneously exchange multiple vehicles.

3. To refine the link-layer controller by incorporating the enhanced and newly designed coordination/regulation layers, and enhance the communication protocols to prioritize maneuvers, depending on the highway topology.

4. To evaluate the capacity of the enhanced architecture design and compare it to the previous design.

In contrast to previous coordination layer designs, the proposed coordination/regulation atomic maneuvers will use the intra-platoon LAN communications. Therefore, the vehicle will be able to execute most transient maneuvers in a much shorter time, while requiring significantly smaller inter-vehicle spacing to maintain safety.

The protocol specification of each redesigned maneuver and the overall coordination/regulation layers design will be formally specified, including communication protocols and requirements. Its logical correctness and safety will be verified using software verification tools and extensive simulation. The redesigned architecture will be simulated and tested using SmartAHS (micro-simulation) and SmartCAP (meso-simulation) software.

The proposed research will provide a much-needed overhaul to the coordination and link layer control protocols. Moreover, we believe that the proposed maneuver redesigns and new maneuvers represent the most cost-effective means of attaining such capacity improvements in both single-lane and multi-lane AHSs.

Progress will be reported quarterly as well as with year end and final reports. Simulation and verification software will be fully documented and made available to CALTRANS and other researchers in PATH working on similar research. The results of this research will be disseminated at PATH conferences and other technical conferences in the field. Future extensions and applications of this research will involve the implementation and testing of the enhanced algorithms in actual vehicles, as well as the eventual deployment of the redesigned architecture in a future CALTRANS/PATH demo.
C Background

C.1 Literature Review

The design of coordination and link layer protocols in AHS has been extensively investigated by PATH researchers, including the PI’s of this proposal. Here we provide a brief description of the current PATH AHS architecture. A more detailed discussion can be found in Horowitz and Varaiya (2000). Here we limit the description here to features of the current regulation, coordination, and link layers that are key for explaining how our proposed enhancements will be implemented.

Fig. 1 shows a block diagram of the five-layer PATH AHS normal mode of operation control architecture (Varaiya 1993). Starting from the top, the layers are called network, link, coordination, regulation, and physical. The top two layers of the architecture reside on the roadside, while the bottom three reside on-board in each vehicle. The overall architecture also includes several emergency modes that are automatically invoked in the event that a failure is detected. These degraded modes are briefly discussed later in this section.

Figure 1: The five-layer AHS control system architecture. The text describes each layer and its function.

On-board vehicle control system:

The physical layer comprises all the on-board vehicle controllers for the physical components of a vehicle. The physical layer also includes the inter-vehicle radio communication system with its medium access and network protocols, and the integration of the communication and control systems. The main function of the physical layer is to decouple the longitudinal (Swaroop et al. 1994) and lateral (Hingwe and Tomizuka 1997) vehicle guidance control, and to approximately linearize the physical layer dynamics (Hedrick et al. 1994; Pham et al. 1994).

The regulation layer is responsible for the longitudinal and lateral guidance of the vehicle, and the execution of the maneuvers commanded by the coordination layer. The regulation layer control tasks can be classified according to two major criteria:
• Those that require the use of an intra-platoon Local Area communication Network (LAN) (follower law) versus those that do not (all others).

• Those used during steady-state maneuvers (follower and leader laws) versus those used during transient maneuvers (all others).

The only regulation layer control task that presently requires the use of an intra-platoon LAN is the one used by the followers in a platoon and consists in maintaining a prescribed constant spacing from the preceding vehicle (follower law). While in follower mode, the control system receives, through the intra-platoon LAN, the velocity and acceleration of the platoon leader and the vehicle that precedes it in order to maintain a close intra-platoon vehicle spacing (< 2 meters), while achieving string stability (Swaroop 1994).

All other regulation layer control tasks (also referred to as maneuvers) do not presently utilize a LAN to obtain the velocity and acceleration of neighboring vehicles. These maneuvers (and their names) consist of: regulating the platoon (or free agent) velocity to a desired value, while maintaining a safe distance from the preceding platoon (leader law); joining with the preceding platoon (merge law); splitting a platoon (split law); and splitting from a platoon while maintaining safe distances from neighboring platoons in the adjacent lanes, in order to subsequently change lanes (split-to-changelane law); (Frankel et al. 1996; Li et al. 1996; Alvarez and Horowitz 1999a; Alvarez and Horowitz 1999b).

The two lateral control tasks of the regulation layer are to keep the vehicles in their assigned lane, or to change to an adjacent lane. The latter task is called the changelane maneuver (Peng 1992).

A third set of regulation layer tasks are the AHS entry and exit maneuvers (Godbole et al. 1995). For simplicity, we will not refer to these maneuvers in this proposal. However, the proposed enhancements apply to these maneuvers as well.

We refer to all longitudinal and lateral regulation layer control tasks and maneuvers as activities. Thus, the regulation layer is engaged in one activity at any time, and switches to another activity in response to commands from the coordination layer. There are steady-state activities (leader and follower laws), with their corresponding lateral lane-keeping control laws, while the rest are transient activities, which culminate in a steady state activity.

The coordination layer is responsible for selecting the activity that the vehicle should attempt or continue to execute in order to realize its currently assigned activity plan. This layer communicates and coordinates its actions with its peers—the coordination layers of neighboring vehicles—through a Wide Area communication Network (WAN) and supervises and commands the regulation layer to execute or abort maneuvers. It also communicates with the link layer roadside control system, from which it periodically receives an updated activity plan. Since these tasks involve discrete events, the behavior of the vehicle at the coordination layer is modeled as a discrete-event dynamical system (Varaiya 1993). By coordinating its actions with its peers, the coordination layer controller selects one activity from a finite set, which the coordination layer commands the regulation layer to execute.

The primary objective of the on-board vehicle control system is to safely control the vehicle while executing its activity plan as quickly and efficiently as possible. Thus, it was necessary to de-

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1We use the following convention: the lead car in a platoon is the leader and all other vehicles in the platoon are followers. A one-vehicle platoon is a free agent.
velop a design and verification methodology that guarantees the safety and efficiency of the overall on-board vehicle hybrid control system formed by the discrete-event coordination layer supervisor interacting with the regulation layer continuous-time dynamics. This goal was accomplished in three steps:

1) **Activity plan definition**: An activity plan was restricted to choices from a limited set of atomic maneuvers. Moreover, execution of the maneuvers was further restricted by insisting that a) only leaders (and free agents) can initiate maneuvers, while followers maintained platoon formation at all times; b) leaders can only execute one maneuver at a given time; c) maneuvers were coordinated with the relevant leaders of neighboring platoons; d) only after agreement was reached between these leaders was a maneuver initiated (Varaiya 1993). These restrictions dramatically simplified the tasks of the link and coordination layers.

2) **Coordination layer design**: The coordination of each maneuver was implemented by a protocol—a structured sequence of message exchanges—between the relevant peer leaders involved in the maneuver. The protocol specification and overall coordination layer design was formally specified and its logical correctness was verified using software verification tools, such as COSPAN (Har’El and Kurshan 1987). The overall state machine included over 500,000 states (Hsu et al. 1993; Varaiya 1993; Sachs 1995).

3) **Regulation layer design**: The regulation layer control system was designed so that the execution of every maneuver initiated by the coordination layer was guaranteed to safely follow the maneuver’s state machine protocol. That is, the hybrid system formed by coupling the coordination layer discrete-event system with the regulation layer continuous-time system produced the same sequence of events as those produced by the coordination layer discrete-event state machine alone (Frankel et al. 1996; Alvarez and Horowitz 1999b; Li et al. 1996; Lygeros 1996; Lygeros et al. 1998; Godbole et al. 1995).

**Road-side control system**:

The roadside control system’s primary objective is to optimize the capacity and traffic flow of the overall AHS.

There is one link layer controller for each 0.5 to 5 km-long segment of the highway, called a link. The models used in the link layer involve aggregated vehicle densities and traffic flows. At the link layer a large number of vehicles are controlled in a decentralized but coordinated manner, with activity vector fields. The activity plans for the vehicle coordination layer, such as leader law desired velocity, merge, change lane, etc., are modeled as time-varying spatial vector functions. Using density conservation flow models, the state of the link is described as vehicle aggregated density profiles, and the notion of the individual vehicle is lost.

The design of the current link layer control system was accomplished by dividing its functions into two tasks. The first task consists of the determination of a desired flow field, which must satisfy the topological and density capacity constraints of the current infrastructure state, as well as exit flow-rate constraints. It should also optimize highway capacity and vehicle travel time (Broucke and Varaiya 1996; Gomes et al. 2000)

The second link-layer controller task consists of the determination of the actual activity vector field that is broadcasted to the coordination layer on-board vehicle controllers using local road-side feedback information. The problem was solved by designing decentralized feedback laws that stabilize the actual flow field to the desired flow field (Li et al. 1997; Alvarez et al. 1997).
The task of the network layer is to control entering traffic and route traffic flow through the network of highway links that constitute the AHS in order to optimize the capacity and average vehicle travel time of the AHS and minimize transient congestion in any of its highway links. At this layer, the system is modeled as a capacitated graph. This layer is presently the least developed. An initial design can be found in Eskafi (1996).

Degraded and emergency modes:

The AHS control architecture described in the previous section was designed and verified under the assumption that the AHS is functioning in its normal mode of operation, under benign environmental conditions and faultless operation of all hardware. Extensions and enhancements of this architecture have been developed, which enable the AHS to function in a degraded mode of operation, while dealing with faults and adverse environmental conditions.

The design and formal verification of a fault management system (FMS) for longitudinal control for the current PATH AHS architecture was carried out under PATH MOUs 135, 288 and 373 (Lygeros et al. 2000; Godbole et al. 2000; Suryanarayanan et al. 2002). The FMS detects the presence of a fault utilizing information provided by a fault detection and identification system (Chung et al. 1997a; Chung et al. 1997b; Rajamani et al. 2001). Emergency vehicle coordination layer protocols and link-layer controllers, which permit ambulances or police cars to circulate in an AHS at higher speeds than the rest of the traffic, were developed under MOUs 287 and 311 (Toy et al. 2001).

Formal protocol verification and simulation:

Simulation tests for the normal mode coordination protocols were carried out under MOUs 135 and 238 using the SmartPATH micro-simulator (Eskafi 1996). Formal verification of the complete normal-mode and degraded mode maneuver protocols was accomplished under MOU 288 using COSPAN (Godbole et al. 2000), and complete simulation tests including the link, coordination and physical layers of the AHS architecture were performed under MOU 312 and 373 (Yi et al. 2001; Suryanarayanan et al. 2002), using the recently developed SmartAHS micro-simulation package (SmartAHS Development Team 1998). SmartAHS was written in SHIFT, an object-oriented language for hybrid automaton (Deshpande et al. 1997), which simplified the modeling of the link and coordination layer control systems. Recently, a general framework, which combines the SHIFT simulation environment with the KRONOS verification tool was developed under MOU 333 and was successfully applied to fault diagnosis for intra-platoon communications under MOU 332 (Eskafi 1999; Simsek et al. 1999).

In all of the above simulation and verification results, communication messages were simulated as synchronized events among the different finite state machines (Varaiya 1993; Godbole et al. 2000; Toy et al. 2001). This approach is not entirely realistic, since vehicle-vehicle and vehicle-roadside communications take time to execute and there are also additional delays and lost packets. A communication architecture was implemented in SmartAHS under MOU 258 (Murgier 1998; Misener 2000). However, this structure has not been completely verified. A simplified communication structure, consisting of a transmitter, a receiver and a monitor for the SmartAHS simulator, was developed and tested as part of the effort in MOU 312 (Yi et al. 2001). Recently, the interaction between the vehicle control and communication systems has been investigated un-
der MOUs 320 and 388 (Hedrick, Chen, and Mahal 2001; Hedrick, Uchanski, and Xu 2001).
In Hedrick, Chen, and Mahal (2001), the effect of communication delays and losses on the Platoons’s string stability was considered, and it was shown that it is possible to lose the string stability due to some communication delays. The redesign of the merge maneuver protocols, taking into account communication protocols, was considered in Hedrick, Chen, and Mahal (2001).

AHS capacity and safety

The two most important factors that need to be considered in the evaluation of AHS architectures are safety and capacity. It is well known that highway capacity can be considerably improved by reducing inter-platoon and intra-platoon vehicle spacing. However, this may result in an undesirable increase in the probability that vehicles collide. There are a few studies that have attempted to quantify the relationship between capacity and collision probabilities in AHS’s (Tsao and Hall 1997; Carbaugh et al. 1998). However, these studies focused on the trade-offs between collision probability and longitudinal capacity, and only considered lane-keeping maneuvers. However, as pointed out in Tsao et al. (1993), lane change activities play a crucial role in determining the true capacity of an AHS, and cannot be ignored in realistic AHS capacity estimation studies. In fact, for the current AHS architecture, the number of lane-changing maneuvers that are executed in a particular section of the highway may be the most important factor that affects flow capacity in that section. This has been observed in several simulation studies that were conducted, using SmartCAP, to determine capacity constraints in AHS’s and optimize throughput (Broucke and Varaiya 1996; Gomes et al. 2000).

C.2 Project Scope, Objectives, and Motivation

C.2.1 Problem statement

The two most important factors that need to be considered in the evaluation of AHS architectures are safety and capacity. As discussed in section C.1, the current PATH AHS coordination and regulation layer controllers were rigorously designed to guarantee safety under normal and several degraded mode conditions, but are not necessarily optimal with respect to capacity considerations. Many of the transient vehicle activities, such as the follower changelane maneuver, currently take a significant amount of time to execute (at least 35 sec. for the follower changelane maneuver) and require a significant amount of highway utilization (at least 1050 sec. × meters for the follower changelane maneuver) while they are being executed. Moreover, there is currently no attempt to coordinate simultaneous change lane maneuvers among adjacent lanes. As a consequence, the AHS capacity is currently unnecessarily restricted by the number of lane change maneuvers that are executed in a given highway sector.

This proposal addresses Section 2.2.5 PATH’s 2002 RFP, which requests the refinement and enhancement of previously designed coordination and link layer protocols, to make them more efficient.

The goals of this proposal are:

Details for estimated time and time-spacing for the follower changelane maneuver can be found in Table 1 in section D.1.1.
1. To redesign certain enhanced coordination layer atomic maneuvers, such as *changelane*, *split* and *merge*, and their associated regulation layer controllers, so that the flow capacity of the PATH AHS is *dramatically improved*, without sacrificing safety.

For example, we have estimated that our redesigned single-vehicle *changelane* maneuver would take 9 sec. (versus 35 sec. for the current design) to complete and would require either 300 or 90 sec. $\times$ meter of highway utilization (versus 1050 sec.$\times$ meter for the current design), depending on the final state of the vehicle after the maneuver is completed (e.g. 300 sec.$\times$ meter for a free agent and 90 sec.$\times$ meter for a follower). This represents a 3 to 10-fold improvement in highway utilization for most lane changes!

These redesigns will be accomplished following the rigorous verification and simulation steps that were employed in the current design, as described in section C.1 and Horowitz and Varaiya (2000):

a. Activity plans are restricted to choices from a limited set of atomic maneuvers and the maneuver communication protocols are restricted by requiring that platoons only execute one transient maneuver at a given time. Furthermore only after agreement is reached between two platoons, is a transient maneuver initiated.

b. The protocol specification of each redesigned maneuver and the overall coordination/regulation layers design will be formally specified; and its logical correctness and safety will be verified using software verification tools.

c. The redesigned maneuvers will be implemented and thoroughly tested using SmartAHS.

As will be detailed in section D, the verification of the above-mentioned enhanced re-designed atomic maneuvers will be accomplished without significantly altering coordination layer protocols nor modifying prior verification procedures. This will accelerate the design and testing process as well as their deployment in an actual vehicle demonstration.

In contrast to the previous coordination layer designs, the communication requirements of the maneuvers, as well as the communication protocols will be explicitly taken into consideration in our redesigns.

2. To formulate new coordination-layer protocols, consisting of atomic maneuvers that permit *multiple* vehicles in a platoon to simultaneously change lanes and permit parallel platoons in adjacent lanes to simultaneously exchange *multiple* vehicles through change lane commands.

In contrast to the maneuvers in 1), the coordination-level protocols in these maneuvers may involve simultaneous coordination and communication exchange among more than two vehicles. However, we believe that we will be able to cast the formal verification of these maneuvers in a similar manner as the procedure outlined above.

3. To revamp the link-layer controller by:

a. incorporating the enhanced coordination/regulation layers designs in 1) and the new designs in 2) into the link layer modeling abstraction and subsequently designing a link layer controller, which incorporates the enhanced and new activity flow fields, utilizing prior design procedures (Horowitz and Varaiya 2000);

b. incorporating an enhanced communication protocol between the link and the coordination layers, which prioritizes maneuvers depending on the highway topology, such as the scheme proposed in Bana (2000), and coordinates vehicle activities to enhance throughput.
4. To evaluate the capacity of the enhanced architecture design and compare it to the previous
design, using both analytical and simulation studies and probabilistic frameworks such as those
presented in Carbaugh et al. (1998).

C.2.2 Proposed Solution

In the current AHS architecture design all transient atomic maneuvers (e.g. merge, split and
change lane) are considered inter-platoon maneuvers, which do not make use of the intra-platoon
LAN, to obtain the leader’s and front vehicle’s velocity and acceleration. As a consequence, a large
inter-vehicle spacing is required when a vehicle is engaged in those maneuvers, and the maneuvers
take a large amount of time to execute. In contrast, the follower law utilizes the intra-platoon LAN
to maintain string stability, and, as a consequence, requires a much smaller inter-vehicle spacing.

We propose to design enhanced transient atomic maneuvers that will make use of the intra-
platoon LAN, so that the vehicle executing the maneuver will remain a logical unit of the platoon,
allowing its control system to receive acceleration and velocity information from neighboring vehi-
cles, as well as transmitting its own. As a consequence, the string stability (or in some maneuvers
the mesh stability (Seiler et al. 1999; Pant et al. 2001)) of the platoon will be preserved, and
the vehicle will be able to execute the transient maneuver in a much shorter time, while requiring
significantly smaller inter-vehicle spacings to maintain safety. The proposed enhancements are
described in much more detail in section D.1.1.

As described in more detail in section D.4, recent and expected advances in wireless commu-
ications will extend the spatial range and bandwidth of intra-platoon LANs so that the proposed
enhancements will be possible, perhaps without even requiring dual-channel intra-platoon LANs.
Moreover, as discussed in section D.1.2 we do not expect that the costs of the additional radars
that will be necessary to implement these enhancements will make their deployment prohibitively
expensive.

C.3 Relationship to Other PATH Projects

The proposed research will utilize and complement a major portion of the research completed or
currently underway at PATH, involving the design, verification, and simulation of AVCSS control
and communication architectures. Below we cite some of these projects as examples:

- MOUs 235/304: Evaluation and Analysis of Automated Highway System Concepts and
  Architectures
  This MOU developed predictions of inter-vehicle spacings that could be used in order to
  improve both throughput and safety of highway traveling in AHS. In order to better under-
  stand the different approaches to vehicle automation, this project considered issues such as
  lane change maneuvers, roadside traffic flow control, and synchronization of maneuvers by
different vehicles. The proposed research will complement the results from this MOU for
  efficiency improvement of automated vehicles and platoons.

- MOUs 238/310: Design of Safe Switched and Feedback Based Maneuvers for Vehicle
  Control Systems
  There are important results developed in MOU 238/310 that are related to the problem of
safety regulation layer control system design. Safe leader control laws were developed for longitudinal maneuvers, and different transient maneuver control laws were designed for safe vehicle operations. A systematic and practical methodology for evaluating hierarchical control architectures to ensure safe system operation was also investigated. The proposed research will apply some approaches and results from this project, and extend them in the enhanced and new coordination and regulation control systems.

- **MOU 243: Verification of AHS Vehicles Maneuver Design**
  This project developed hybrid system models that are well-suited for computational treatment, in order to provide a means to prove that the AHS vehicle maneuvers are effective and safe. The proposed verification scheme in this project will complement the results from this MOU.

- **MOUs 288/312: Design of Fault Tolerant Control Systems for AHS: Fault Detection, Fault Handling and Verification**
  MOU 288 expands on earlier research to define a unified framework for a fault-tolerant automated vehicle control system. This project aimed at detecting failures and proving that safety can be maintained even in the presence of failures. In addition, MOU 288 formally verified the degraded mode maneuver protocols using COSPAN, whereas MOU 312 investigated those simulation tests using SmartAHS.
  We propose to use the simulation package developed in MOUs 288/312 and extend it to simulate the enhanced coordination and link layer protocols.

- **MOU 318: Address Resolution, Configuration Management, and Routing in Wireless Communication for AVCS**
  The objective of this project was to invent protocols (distributed algorithms) for vehicle address resolution, configuration management, and routing. These protocols were formally specified, verified for correctness, and analyzed for performance. This project also examined how these protocols could be implemented in the wireless systems currently used or under development in PATH, such as the Wavelan radios, MPI system and the Infrared network. The results of this MOU are helpful for the proposed communication structure.

- **MOU 320: Optimized Vehicle Control/Communication Interaction in an Automated Highway System**
  The objective of this project was to define and optimize the interactions between the communication system and the vehicle control system, from both a hardware and software standpoint. This project used existing vehicle control algorithms developed by PATH researchers at U.C. Berkeley and off-the-shelf communication technology to design a coordination protocol. By these the control and communication systems can affect the various maneuvers required by an automated highway system. We plan to investigate the communication/control interactions for our proposed new and enhanced vehicle/platoon maneuvers.

  This project investigated and implemented a general framework for the simulation, verification, and prototyping of control algorithms for intelligent vehicles and highways. This
general framework developed, combined SHIFT simulation with the KRONOS verification. The proposed research will extend the use of the SHIFT/KRONOS tool for the verification of complex hybrid systems.

- **MOU 334: Designing a Framework Vehicle-to-Vehicle and Vehicle-to-Roadside Communication**
  The goal of this project was to create a framework for vehicle-to-vehicle and vehicle-to-highway communications. A suitable hierarchical communication structure was designed in this project. This structure can support the mobile environment with the distinct characteristic that the topology of the communication network changes and has to be adapted as the mobiles (vehicles and platoons) move. The system was simulated using SHIFT and SmartAHS. The results of this project are helpful for simulations of proposed communication systems.

- **MOU 388/4210: Enhanced AHS safety through the integration of vehicle control and communication**
  This project will develop three related concepts which exploit the cooperative nature of AHS (with vehicles communicating and coordinating with each other and the roadway) to yield safety and capacity gains. The first task uses communication systems to implement dynamic position tracking of vehicles on an AHS and fully coordinated platoon maneuvers. The second task will develop and experimentally test an algorithm that exploits the position tracking and communication abilities to estimate the friction characteristics of the road and construct a map of the roadway’s friction characteristics as a function of location. The third task merges the results in the previous two tasks with existing and emerging PATH work on emergency maneuvers to produce a detailed simulation of emergency stopping of a platoon on slippery roads. We plan to investigate the communication/control interactions for our proposed new and enhanced vehicle/platoon maneuvers.

- **MOU 389: A Robust Communication Link and Architecture Design for the AHS**
  This project investigates the different communication requirements and quality of service (such as messages of varying lengths and priorities) for data access in AHS communications. This project will design robust communication link and data access protocols by considering the problem that the overall communication architecture for an AHS is complicated by (i) the propagation environment of the signals, (ii) the existence of multiple interface signals, and (iii) the mobility and dynamic character of platoons. The focus will be on the design of a hierarchical communication system architecture that supports all different layers (application, transport, network, data, link, physical) and fulfills the communication requirements. The communication structures in this MOU are helpful for the proposed vehicle-to-vehicle and vehicle-to-roadside communications.

C.4 Project Outcomes and Further Research

The proposed research will provide a much-needed overhaul to the coordination and link layer control protocols, which will result in verifiable dramatic AHS capacity improvements, without sacrificing safety. As will be outlined in section D, many of the proposed enhancements may be carried out with relatively minor additional communication and infrastructure requirements.
Moreover, we believe that the proposed maneuver redesigns and new maneuvers represent the most cost-effective means of attaining such capacity improvements in both single-lane and multi-lane AHSs.

We expect that future extensions and applications of the results of this research will involve the implementation of the proposed coordination layer protocols and regulation layer algorithms in actual vehicles, as well as the eventual deployment of the redesigned architecture, including the revamped link layer road-side control system, in CALTRANS/PATH sponsored demonstrations.

The redesigned architecture will be simulated and tested using SmartAHS (micro-simulation) and SmartCAP (meso-simulation) software. Progress will be reported quarterly as well as with year end and final reports. Simulation and verification software will be fully documented and made available to CALTRANS and other researchers in PATH working on similar research. The results of this research will be disseminated at PATH conferences and other technical conferences in the field.

D Methodology

D.1 Refinement of Coordination Layer Protocols

D.1.1 Enhancement of maneuver protocols

Among all coordination maneuvers, including those of the normal and degraded modes, leader and follower are the two steady-state maneuvers: each vehicle maintains its operating state in one of these two maneuvers for most of its time on the highway. Correspondingly, we can consider all other maneuvers, such as changelane, to be transient maneuvers. Each transient maneuver in a platoon is overseen by the leading vehicle using communications; for example, the merge maneuver is achieved through coordination between two platoon leaders. In AHS operations, one assumption has been made for automated vehicles: a platoon can be engaged in at most one transient maneuver at a time. For example, once the leader in the platoon initiates a merge request to the platoon ahead, the leader will reject any other transient maneuver requests from the followers (e.g. for a split maneuver), and from platoons in adjacent lanes (e.g. for a changelane maneuver). This assumption simplifies the design and verification of the coordination maneuver protocols.

We propose to develop enhanced coordination layer protocols using the vehicle controls and communication/control interactions in a systematic manner. We plan to refine the coordination maneuver protocols in a manner that allows more efficient maneuvers to be executed without violating the assumption that at most one transient maneuver can be performed at a time by one platoon. By modifying the communication protocols among the followers and leaders, we can extend the original AHS coordinated maneuver protocols so that steady-state vehicles have more flexibility and efficiency to initiate a transient maneuver without sacrificing safety.

Besides the enhanced coordination and link layer protocols, we also propose to enhance the inter- and intra-platoon spacing policies in order to improve maneuver efficiency at the regulation layer. For the current AHS design, a regulation level control law has been designed to regulate the inter- and/or intra-platoon space for each steady-state or transient maneuver. After we refine the coordination and link layer protocols for maneuvers, we will refine the corresponding regulation level control laws such that tighter safety spacing policies can be achieved through the control/communication interactions. Later in this section, we will discuss how control/communication
interactions can be used to achieve such improvement in the regulation layer.

In this section, we explain the design improvements using the example of the *changelane* maneuver. Since the *changelane* maneuver requires the most complex coordination protocols, we can apply the same ideas to other maneuvers, such as *merge* and *split*.

Fig. 2 illustrates a *changelane* maneuver procedure in the AHS. If vehicle A in a platoon needs to move to the right lane, it first initiates a *changelane* request to the platoon leader B; if the platoon leader B acknowledges this request, it will initiate a *leader split* maneuver. After vehicle A completes the *leader split* maneuver, it will request that follower C perform a *follower split* maneuver. Once vehicle C finishes the *follower split* maneuver, vehicle A becomes a free agent and can initiate a *changelane* maneuver to the right lane: first vehicle A communicates through wide area network (WAN) with vehicle E, which is behind vehicle A in the adjacent lane, to open up a safety space $L_{safe}$ between vehicles A and E. At the same time, vehicle A keeps tracking vehicle D, which is in front of vehicle A in the adjacent lane, to maintain a safety distance $L_{safe}$ between vehicles A and D. Once the safety distances between A and D and E have been established, vehicle A can start moving to the right lane. If it is successful, vehicle A will become a free agent in the right lane.

The state transition diagram for vehicle A in a regular *changelane* maneuver is shown in Fig. 3.

In order to maintain string stability in a platoon, a local area network (LAN) is formed inside the platoon for intra-platoon communications. Through this LAN, the platoon leader and followers exchange critical control information, such as velocity and acceleration. In Fig. 2, we illustrate an example of how the LAN works in platoon B in the current AHS design: during 20 msec, leader B broadcasts its velocity and acceleration information to each follower, and within the same time slot, each vehicle transmits its velocity and acceleration information to the vehicle behind it. For example, in Fig. 2 vehicle A transmits information to vehicle C. In the rest of the figures in this section, we will use a dotted circle to include all the vehicles that share one LAN. Besides LAN communications, WAN is also used in vehicle-to-vehicle communications for coordinated maneuvers. We will discuss these communication issues in detail in section D.4.

From our experiments in SmartAHS simulation and analysis of regulation control laws, we can estimate that the *split* maneuver normally takes approximately 15 seconds to finish when vehicles travel at 25 m/s (Alvarez 1996) and the *changelane* maneuver takes 5 seconds when a vacancy is available in the adjacent lane (Peng 1992). Therefore, we can estimate that a *changelane* maneuver for vehicle A (as shown in Fig. 2) takes $15 \times 2 + 5 = 35$ seconds. The time we estimate here does not include time delays from coordination communications and the time required in certain cases where there are nearby vehicles in the adjacent lanes. Moreover, a large amount of time-consuming *changelane* maneuver requests may result in the formation of a bottleneck in either or both lanes of the AHS, or may result in low exit success rates (Tsao *et al.* 1993).

In the proposed enhanced design, we can improve the *changelane* maneuver so that it is not...
necessary to perform two split maneuvers to make vehicle A a free agent before allowing it to change to the right lane. Instead, we propose a follower-to-freeagent changelane maneuver as illustrated in Fig. 4.

The enhanced coordination protocols for the follower-to-freeagent changelane maneuver consist of one coordinated maneuver (changelane) and a short-split regulation action inside the platoon. First, vehicle A requests its leader B for a lane change. Once leader B acknowledges the request, vehicle A will start separating from the previous and following vehicles, while still being a member of platoon B, i.e. the intra-platoon communication is still active between vehicle A and
the other vehicles in platoon B. The intra-platoon spacing at the beginning is $L_1$ (1-2 meters for AHS design) and after the short split the intra-platoon spacing becomes $L_2$, which is determined by the lower limit of spacing for loss of string stability and by the minimum safe spacing for the changelane maneuver\(^6\). The short split maneuver is immediately followed by a coordinated changelane maneuver. Platoon leader B coordinates this maneuver with the upstream platoon E in the adjacent lane through the WAN in order to establish a safety space $L_{safe}$ between vehicles A and E. Meanwhile, platoon leader B also maintains the same safety distance between vehicle A and the downstream platoon D in the adjacent lane. Once enough space has been opened in the

\(^6\)Using the fact that we still have access to the leader’s velocity and acceleration information through intra-platoon communications, we can conclude that $L_2 \ll 30 - 60$ meters, which is the normal inter-platoon spacing. Moreover, the proposed design does not need split maneuver protocols, which makes it more efficient. The calculation and design of the short split spacing policy will be investigated in this proposal and requirements of the intra-platoon communications will be discussed in detail in section D.4.
adjacent lane, vehicle A moves to the right lane, *while still being part of platoon B on the left lane*, and maintaining string stability with this platoon, until it moves completely to the right lane. Once the *coordinated changelane* is completed, vehicle A becomes a free agent and severs its LAN communication with platoon B. Simultaneously, the two vehicles that were following and preceding vehicle A in platoon B rearrange their LAN communication protocols to maintain string stability, and initiate a *short-merge* to close the gap left by the absence of vehicle A. The state transition diagram for the *follower-to-freeagent changelane* maneuver of vehicle A is shown in Fig. 5.

![State transition diagram](image)

**Figure 5:** A state transition diagram of *follower-to-freeagent changelane* maneuver for follower A

The *follower-to-freeagent changelane* maneuver described above for vehicle A should be used when vehicle A needs to change lanes, in order to exit the highway.

We now propose the *follower-to-follower changelane* maneuver, which can be used for the case when vehicle A needs to change lanes to accommodate a traffic flow pattern, but does not need to become a free agent after changing lanes. This maneuver is shown in Fig. 6. In the *follower-to-follower changelane* maneuver, vehicle A first short-splits from its preceding and following vehicles in the platoon, and then requests leader B for a *follower-to-follower changelane* maneuver. Leader B then coordinates with the leader C of the platoon in the adjacent lane. Once platoon leader C acknowledges the request, it asks its follower vehicles D and E to open up enough space within them, in order to let vehicle A move to the right lane and become part of platoon C. During the entire maneuver process, platoons B and C have to be “locked” to each other, through LAN communications and utilizing radar sensors, so that its members can maintain the necessary relative positioning to allow vehicle A to change lanes and transition from one *follower* state to another *follower* state. The radar sensor requirements that will enable platoons B and C to be “locked” to each other will be discussed in detail in section D.1.2. Vehicle A will need to establish an extra LAN communication channel with vehicles D and E, in the adjacent lane so that it can simultaneously maintain string stability as a member of both platoons, while changing lanes. Alternatively, it may be possible for the LAN of both platoons to merge into a single LAN, while the two platoons are “locked” in this maneuver, in essence becoming a single two-dimensional mesh. The concept of mesh stability (Seiler *et al.* 1999) will be used to investigate and formulate the regulation control systems that will allow this maneuver to be accomplished safely and efficiently. Once the spacing between vehicles D and E and the relative velocities among vehicles A, D, and E are safe for a *changelane* maneuver, vehicle A starts the maneuver. After vehicle A completes the lane change, and it decouples from platoon B. Simultaneously, platoons B and C “unlock,” becoming independent platoons, and their LAN reconfigure to accommodate their new topologies. As in the *follower-to-freeagent changelane* maneuver, vehicles F and G initiate a *short-merge* to close the gap left by the absence of vehicle A in platoon B.
The state transition diagram for vehicle A involved in the follower-to-follower changelane maneuver is shown in Fig. 7.

We plan to design a regulation layer control law for the follower-to-follower changelane maneuver. The mesh stability results developed for unmanned aerial vehicles by Pant et al. (2001), can be adapted to the automated vehicles in this study. For example, in Fig. 6, if vehicle A can have access to the velocity and acceleration information of vehicles D, E, F, G and leaders B and C, then by the results of Pant et al. (2001), vehicle A can achieve mesh stability through acceleration control. The required velocity and acceleration information to maintain mesh stability for vehicle A can be obtained through the LAN communications. Details describing the requirements on the communication systems are discussed in section D.4.

Figure 6: A schematic for a follower-to-follower changelane maneuver

In a follower-to-follower changelane maneuver, the time spent in coordinating two platoons, merging them into a mesh, and then splitting the mesh back into two platoons may be significant, as compared to the time spent by the vehicles in physically changing lanes. With this observation, it is natural to consider the further enhancement of the follower-to-follower changelane maneuver, so that not only one, but several vehicles within the formed mesh are able to change lanes before the
mesh splits, as illustrated in Figure 8, where vehicles A and F change lanes. However, in order to comply with the constraint that only one transient maneuver is allowed at a time, we would have to arrange the lane changes so that they are executed in a sequential manner. Clearly, this is inefficient and it is necessary to redesign the coordination protocols so that several followers are allowed to change lanes simultaneously. This case is more difficult to analyze than the previous cases and may require significant changes in methodology and assumptions used to setup the verification solution. We propose to consider this maneuver during the second year of the proposed work, after the design and verification of the previous maneuvers is accomplished. We will then evaluate the benefits and feasibility of this maneuver, before starting with its design and formal verification.

![Figure 8: A schematic for a possible multiple-follower-to-follower changelane maneuver](image)

The enhanced follower-to-freeagent changelane and follower-to-follower changelane maneuvers that were previously described satisfy all of the requirements and assumptions that are necessary to perform a formal verification of the coordination layer protocols, using the well established mechanism described in section C.1 and in Horowitz and Varaiya (2000).

Table 1 shows a rough estimation of the time and highway utilization improvements that can be gained with these maneuvers.\(^7\) Comparing the state transition diagrams shown in Figs. 3, 5, and 7

\(^7\)For the time and highway utilization calculations of various changelane maneuvers we only considered time and space required to perform vehicle physical actions and we exclude the time required by the communication and coordination protocols. We assume that it takes 15 seconds for a regular split maneuver and 5 seconds for a free agent to move from one lane to another. For simplicity, we use an intra-platoon spacing of 1 meter before vehicles short-split, and of 2 meters after the short-split. The time-space occupied by a maneuver is calculated by the product of the inter-vehicle distance and the time spent to complete the maneuver. For example, at the beginning of the split maneuver, the inter-vehicle space is 1 meter and at the end of the maneuver, it is 30 meters. If we assume that the split maneuver takes 15 seconds and that the inter-vehicle spacing increases linearly, the time-spacing is then \((1 + 30) \times 15/2 \approx 225\) sec.\times meters. Similar estimations of time and time-spacing are calculated for other maneuvers in Table 1. Better estimates can be obtained by integrating along the actual spacing trajectory.
and the results Table 1, it is evident that the follower-to-follower changelane maneuver is the most efficient, while the current changelane is the most inefficient maneuver. However, the enhanced maneuvers will require modifications in the vehicle-to-vehicle communications protocols. We will discuss more details of the proposed communication structures and requirements in section D.4.

**Table 1:** Comparison of estimated time and highway utilization needed for different changelane maneuvers

<table>
<thead>
<tr>
<th>Different maneuvers</th>
<th>Time (sec.)</th>
<th>Time-spacing (sec. × meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>current follower changelane</td>
<td>35</td>
<td>1050</td>
</tr>
<tr>
<td>proposed follower-to-freeagent changelane</td>
<td>9</td>
<td>326</td>
</tr>
<tr>
<td>proposed follower-to-follower changelane</td>
<td>9</td>
<td>91</td>
</tr>
</tbody>
</table>

We also propose a new maneuver in order to enhance the current coordination protocol design and improve efficiency: the platoon changelane. Fig. 9 describes a schematic of the proposed platoon changelane maneuver.

![Figure 9: A schematic of a platoon changelane maneuver](image)

In a platoon changelane maneuver, the whole platoon behaves like one “large vehicle” carrying out a changelane maneuver. Compared with a regular free agent changelane maneuver, two critical issues should be addressed: (1) communication requirements, and (2) safety criteria. For the communications, we assume that the intra-platoon communication inside platoon A (LAN) will work during the whole maneuver. However, this is not enough for maneuver safety because the whole platoon undergoes not only longitudinal but also lateral motions. We will consider both longitudinal and lateral string stability, i.e. mesh stability (Pant et al. 2001), in the coordination and regulation layer design. Roughly speaking, in the LAN communication level, we have to broadcast
the leading vehicle’s lateral velocity and acceleration information to each of its followers in order to maintain both lateral and longitudinal string stability. An investigation of the interactions between the lateral vehicle controls and the additional LAN communication will be conducted as part of the proposed research. Similar to the regular vehicle changelane maneuver, platoon changelane requires WAN communication to coordinate with platoon B, as well as regulation level tracking with platoon C to maintain safe spacing in the adjacent lane. At the regulation level, we propose to design a new continuous-time control law for the platoon changelane maneuver. As far as safety criteria are concerned, we need to determine safety requirements for the combined longitudinal and lateral vehicle/platoon dynamics; for example, the intra-platoon spacing $L_2$ should be increased to accommodate for lateral motion in order to maintain mesh stability.

The state transition diagram for the platoon changelane maneuver is shown in Fig. 10.

![Figure 10: A state transition diagram of platoon changelane maneuver](image)

**D.1.2 Sensor requirements**

Our proposed enhancements to the changelane maneuver include the follower changelane maneuver, in which a follower in a platoon is able to change lanes to join another platoon in an adjacent lane and becomes a follower directly, and the platoon changelane maneuver, in which all the vehicles in a platoon change lanes within a short period of time. In both cases, vehicles belonging to one platoon could be located in two adjacent lanes, and thus mesh stability, instead of string stability, needs to be maintained in order to guarantee AHS safety and attain good efficiency.

Pant et al. (2001) analyzed mesh stability of unmanned aerial vehicle clusters and designed a controller based on the feedback of relative position error between neighboring vehicles and their velocities and accelerations. We believe that their results for aerial vehicles in 3-dimensional space are still valid for our AHS vehicles on the 2-dimensional highway surface. Therefore, both lateral and longitudinal velocities and accelerations need to be communicated between neighboring vehicles in a platoon. The required bandwidth is supported by the communication structures, as discussed in section D.4.

However, current unboard sensor systems of automated vehicles have to be enhanced in order to provide the required 2-dimensional relative distances. Under the current architecture, the automated vehicles use, for example, laser radar sensors to detect vehicles and obstacles in front, and to measure the relative distance to them. These radar sensors are installed on the front and rear bumpers and their emitted light beams have small spread angles (about 8°–12°). Under this sensor configuration, vehicles will not be able to detect objects in adjacent lanes. Considering the fact that
radar sensors have been well developed and are relatively inexpensive, we propose to increase the number of radar sensors on each vehicle. We will investigate the minimum required number of radar sensors and design an optimal configuration on the vehicle.

D.2 Refinement of Link Layer Protocols

As indicated in section C.1 and Horowitz and Varaiya (2000), the models used in the link layer involve aggregated vehicle densities and traffic flows, but not individual vehicles. Vehicles are controlled in a decentralized but coordinated manner, with activity vector fields, which are abstractions of the current coordination layer activities of all vehicles in a given section of the highway.

The first link layer task consists in the determination of a desired time-varying density profile, and its corresponding activity vector field, which together form the desired flow field of the link. This desired flow field must satisfy inlet and outlet flow demands, as well as the density and occupancy constraints of the infrastructure. Moreover, it should ideally optimize highway capacity, as well as user travel time. Thus, global state information (the density profile) for the entire link is required, and its solution involves solving a constrained optimization problem (Broucke and Varaiya 1996; Gomes et al. 2000). However, in order to properly formulate and solve this problem, the space-time highway utilization of each microscopic coordination layer maneuver must be properly abstracted at the link layer level. For example, the current change-lane maneuver involves the transition of the vehicle from follower to free agent and requires that space, sufficiently large for free agent to circulate, be simultaneously available in both lanes of the highway, while the maneuver is being executed. In contrast, the enhanced change-lane maneuver that has been proposed will require significantly smaller space-time highway utilization. Similarly, it is necessary to abstract all redesigned and newly formulated coordination layer maneuvers in the form of corresponding activity vector fields, in order to properly implement the existing link-layer stabilizing controller in (Li et al. 1997; Alvarez et al. 1997). Both of these tasks will be carried out in this project.

D.3 Interface Between Coordination and Link Layers

The current AHS design of the interface between the link and coordination layers uses a random choice approach for each individual vehicle to select the activity plan from the link layer. In each segment of the highway, the link layer controller broadcasts the commanded traffic density, velocity, and maneuver activity information to each vehicle on that segment of the highway. The commanded traffic density and velocity information is computed using decentralized feedback laws (Li et al. 1997; Alvarez et al. 1997). Each vehicle in the segment of highway receives the command broadcasted by the link layer controller and a randomly voting mechanism is used to determine whether the vehicle should take a certain activity commanded by the link layer controller. For example, a coin-tossing choosing scheme has been implemented in an integrated meso/micro SmartAHS/SmartCAP simulator under MOU 383/TO 4208 (Munoz et al. 2001). From our simulation experience, we found that such interface was not efficient for the AHS operation since the coordination layer did not consider the vehicle operating conditions, such as leader or follower state and vehicle origin/destination route, etc.

8Based on private communications with Dr. Han-Shue Tan at the PATH.
We propose to enhance the interface between the link and coordination layers using the concept of prioritizing objectives developed by Bana (2000). We plan to use a ranking system for the actions commanded by the link layer that will prioritize the commands. This format specifies a “cost” associated with the state (e.g. leader or follower) of each vehicle. The coordination layer will then minimize the cost through actions.

Associated with each individual coordination layer, a cost function will be first formulated to determine the maneuver that will be executed after receiving the command from the link layer controller. Different factors, such as vehicle operation state (leader or follower) and origin/destination pair, should be considered in calculating the cost for various actions. For example, it is much more expensive for a follower to execute a changelane maneuver than a free agent; it is also much more expensive for a vehicle in the left lane to change to the right lane if its destination is far away than a free agent who needs to exit soon. Based on the cost calculations and assignment, an “optimal” choice of activities for each vehicle is determined by the coordination layer to minimize the cost under the current state. Clearly, the actual cost is not as important as is the ordering of the cost values. Once the “optimal” action has been chosen by the coordination layer, it will be executed through the corresponding maneuver protocols.

We plan to design this prioritizing-objectives interface in the second year of the proposed work after we accomplish the enhancement of the coordination and link maneuver protocols. Formal verification and integrated simulation with coordination and link layers will also be accomplished in the second year.

D.4 Communications

Communication is critical to effective coordination and safety guarantee of the automated vehicles. In support of the AHS platoon structure and the coordination layer maneuvers, vehicle-to-vehicle communications are divided into two classes: intra-platoon and inter-platoon communications. For each platoon on the highway, a channel is allocated and a local area network (LAN) is formed. Through this LAN, the platoon leader and followers exchange control messages, which are periodically generated by their controllers. Timely delivery of these messages is essential to maintain the string stability of the platoon. On the other hand, the inter-platoon communications are carried out by the platoon leaders in order to coordinate their relative positions and maneuvers. For example, before a free agent changes lanes, it must make sure that there is enough vacant space in the lane where it wants to change into and that no other free agents want to occupy the same space. Therefore, this changelane maneuver requires inter-platoon communications between the free agent and the surrounding platoon leaders or free agents to obtain clearance.

In our proposed enhancement to the changelane maneuver, vehicles changing lanes are not necessary free agents. The lane changer might remain to be a platoon member during the most part of the lane change procedure. Therefore, the lane changer needs not only inter-platoon communications to coordinate with the surrounding vehicles, but also intra-platoon communications to maintain the platoon string or mesh stability. In some cases, for example, when a platoon member changes lane and becomes a member of another platoon in an adjacent lane, the lane changer will be a member of two platoons simultaneously and will need to carry out intra-platoon communications in two channels.

We propose that the communications required for these enhanced maneuvers be consistent with the evolving national ASTM DSRC architecture (Cash 2001) and all communications be designed
over OFDM (Orthogonal Frequency Division Multiplexing) transceivers using the IEEE 802.11a protocols (WLAN Standards Working Group 2002), while the intra-platoon communications use the existing PATH wireless token ring protocol (Attias et al. 2001) running over OFDM transceivers.

We assume that platoons are running a token ring network (Attias et al. 2001). The ASTM architecture (Cash 2001) allocates one channel for vehicle-vehicle communications (channel 172). We treat this as a shared multiple access channel used for non-real-time communications. There are several other shared private and public safety channels (channels 172, 174, 175, 176, 180, 181, 182, and 184) that we assume can be allocated for intra-platoon communications in the vicinity of the automated highway system.

In the following paragraphs, we will discuss, case by case, the impact of the enhanced lane change maneuvers on the communication systems and our proposed approach in detail. For each of the following cases, the left side of the arrow is the status of the vehicle before lane change, while the right side is the status after lane change.

**Free agent → free agent.** In this case, the vehicle is a free agent both before and after the lane change. This is exactly the case of the current changelane maneuver. We propose that communications be carried out over a shared multiple access channel using the 802.11a wireless ad-hoc protocols by all parties. Reliable reception is to be achieved by re-transmission. The maneuver should be designed to be robust to variable communication delays.

**Free agent → platoon member.** In this case, a free agent wants to change lane and join a platoon in an adjacent lane. During the maneuver, the free agent establishes contact with the platoon using the ad-hoc multiple access channel and then joins the platoon token ring at an appropriate point on the platoon token ring channel. Our research will derive the appropriate stage at which the free agent starts joining the ring, analyzes robustness with respect to variations in the joining time, channel switching, and failure of joining, and enables the subsequent exchange of all lane change communications on the token ring, even while the longitudinal control communications continue to flow.

**Platoon member → free agent.** In this case, a platoon member changes to an adjacent lane, without first splitting from the platoon. This lane changer must continue communicating with other platoon members to maintain platoon string stability, while at the same time talk with surrounding platoons and free agents to obtain clearance for lane changing. In our discussion of the enhanced maneuvers in Section D.1.1, we proposed to use the platoon leader as a relay between the vehicle changing lanes and surrounding platoons. A platoon member first obtains approval for the lane change request from its platoon leader. The platoon leader then, on behalf of the lane changer, talks with other platoon leaders or free agents in an inter-platoon channel. Therefore, on the intra-platoon communication network, not only vehicle-following control messages, such as velocity and acceleration, are exchanged, but also other information necessary for lane change coordination needs to be forwarded. The required increase of intra-platoon channel bandwidth to accommodate the increased information flow is provided by the OFDM transceivers, which appear to support 54 Mbps at a short range (Chen and Gilbert 2001). We will design the appropriate stage at which the procedure of leaving the token ring and establishing communications on the shared multiple access channel is triggered.
Platoon member → platoon member. This proposed maneuver is more complicated than the previous three cases. While remaining to be a member of the first platoon, the lane changer gets approval for the lane change request from the platoon leader and coordinates with the second platoon in an adjacent lane using its own platoon leader as a relay. The lane changer virtually joins the second platoon by communicating with its members on the token ring channel of this platoon, i.e., there is a time interval during which the vehicle changing lanes is part of both token rings. Since the two rings are expected to be on different channels, they will not interfere. However, since state-of-the-art 802.11a transceivers tune to only one channel at a time, the receiver will have to switch from one channel to the other to receive the communications on both channels. Our approach will be to merge the two token rings on one channel for the duration of the maneuver. This can be done if there is sufficient bandwidth, which is certainly provided by the OFDM transceivers since they may support 54 Mbps at a short range. We propose to design a ring merge protocol on top of the existing token ring protocol.

Platoon lane change. In this case, the whole platoon, led by the platoon leader, changes lanes within a short period of time. During the lane change maneuver, the platoon has a degree of freedom two, i.e., the platoon can deform not only in the longitudinal direction, but also in the lateral direction. Thus additional information, such as lateral velocity and acceleration, needs to be exchanged between platoon members to maintain mesh stability. Once again, the increased bandwidth requirement is supported by the OFDM transceivers.

We will also consider the blocking probability of channel allocation. If the request for a communication channel is denied, the desired maneuver will not be able to be executed. For example, in the last stage of platoon-member-to-platoon-member lane change procedure, the merged token ring will be split back into two separated ones so that a new channel will have to be allocated. If this request is denied, the lane change maneuver will not be able to be completed. On the other hand, with the increase of vehicle density on the highway, which is an important benefit of our proposed enhancement, the demand for communication channels in a unit area will also increase. This raises difficulties to maintain a low blocking probability of channel allocation. We will analyze this issue and design our channel allocation algorithms and communication protocols so that a sufficiently low blocking probability can be achieved.

D.5 Verification of the Enhanced Protocols

To verify the enhanced coordination and link layer protocols, we propose to use two complementary approaches. In the first approach, we will use the same strategy that has been exploited successfully for the previous AHS protocol design, verifying the discrete-event protocols and designing safe regulation control laws separately; in the second approach, we will exploit the recently developed hybrid automata verification tools. This is appropriate since the protocols and control laws can be modeled as one hybrid system. These two approaches are complementary since the former approach can precisely capture the complex dynamics of the vehicle and control systems in the physical and regulation layers, while the latter approach can check the safety of the complete system states, but currently can only be applied to some special continuous-time dynamics.
D.5.1 First verification approach

In our verification framework, we plan to first design safe regulation layer control laws for the enhanced maneuvers discussed in section D.1.1 to guarantee that the vehicle systems are always in safe regions. These regulation control laws will be based on the previous work for the existing AHS maneuvers developed under MOUs 238/310 (Alvarez 1996; Li et al. 1997). Moreover, we will also consider the results from recent developed researches. For example, we will use the concept and results of mesh stability (Pant et al. 2001) to design a safe regulation control law for the follower-to-freeagent changelane and follower-to-follower changelane maneuvers. Based on the regulation control laws for the follower-to-follower changelane maneuver, in the second year we plan to investigate the feasibility of regulation laws for the more efficient multiple-follower-to-follower changelane maneuver.

Once the safe regulation level control laws have been developed, we will verify the proposed coordination and link layer protocols in sections D.1 and D.2. These protocols will first be modeled as finite state machines. Discrete-event verification tools, such as COSPAN, will be used to formally verify these protocols to guarantee the absence of deadlock, completeness (i.e., liveliness), and fairness. Finally, combining the verified protocols and the desired safe regulation control laws, we will guarantee the safety of the maneuver protocols.

D.5.2 Second verification approach

We also plan to use the general framework of the SHIFT/KRONOS tool developed under MOU 333 (Eskafi 1999) to verify the enhanced protocols. The framework developed under MOU 333 uses a coherent set of tools that model a hybrid system for simulation, verification, and prototyping of control algorithms. SHIFT/KRONOS takes a control system design, simulates it, and verifies it. The specification of the control algorithms is performed in the SHIFT/SmartAHS environment. A formal hybrid verification platform is used to carry out the correctness proofs of the control algorithms. Compared with the previous approach, this verification approach has several advantages:

1. Under the general framework of the SHIFT/KRONOS tool, the same specification is used for both verification and simulation. This reduces the possibility that errors will be generated during the manual translation from the design/verification to the simulation environments.

2. Verification can help us check the safety criteria of the protocol and control algorithm design. Under some restrictions and abstractions imposed by the design specification (Eskafi 1999), KRONOS can be used to verify the hybrid systems that combine the complex continuous-time dynamics of the regulation and physical layers with the discrete-event protocols in the regulation, coordination, and link layers. Even though the restrictions and abstractions have to be enforced, the SHIFT/KRONOS tool can give us the formal verifications for the safety of the complex hybrid systems.

In this approach, all the enhanced protocols will be verified with simplified vehicle dynamics and regulation control laws that satisfy the SHIFT/KRONOS requirements. The verified maneuvers can then be used for simulations using the SHIFT/KRONOS tool.

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9The details of the restriction in the SHIFT/KRONOS program can be found in (Eskafi 1999). The abstraction we currently need to place on the SHIFT/KRONOS program is to approximate the complex governing nonlinear dynamics by differential equations.
D.6 Simulation of the Enhanced Protocols

To validate the proposed maneuver protocols and the regulation level control laws, we plan to use the SHIFT language to implement and simulate the enhanced coordination and link layer protocols described in sections D.1.1 and D.2, along with the regulation and physical layers. We will use a set of full vehicle dynamics and highway systems, which have already been developed and implemented under MOUs 288/312 (Yi et al. 2001) and MOU 383, to test the new regulation control laws and the enhanced protocols.

To simulate the proposed link layer protocols, we will use the integrated meso/micro-scopic simulator developed under Task Order 4207. This meso/micro-scopic AHS simulator integrates the micro-simulator SmartAHS, with the meso-simulation SmartCAP, in order to simulate the AHS network and link layer behaviors along with the coordination, regulation, and physical layers. Through this simulation package, we can test and validate the enhanced link layer protocols and the enhanced interface between the link and coordination layers.

Different scenarios will be simulated to test and verify the enhanced protocols in the SmartAHS/SmartCAP package under various highway and environmental configurations. Moreover, the same design will be passed through the formal verification tool discussed in the previous section, SHIFT/KRONOS. The process of simulation and part of verification is described in the diagram of Fig. 11.

![Diagram of Simulation and Verification Process](image)

**Figure 11:** Simulation and verification of SHIFT/KRONOS programs

D.7 Evaluations of the Design Enhancement

In order to compare our design of enhanced coordination and link layer protocols with previous approaches, we propose to investigate the capacity and safety of the AHS performance under the enhancements of the coordination and link layers using two approaches: analytical and simulation studies.

In the analytical study, we will investigate the quantitative improvements of the highway capacity and vehicle collision safety under the new coordination and link layer protocols, at both the
micro- and macroscopic levels. At the microscopic level, we can calculate the improvements in completion time for safe maneuvers. For example, under the proposed platoon changelane maneuver, we can calculate the average elapsed total time for this maneuver given a distribution of platoon sizes. Safe intra- and interplatoon spacing policies will be incorporated for this study under the new coordination and link layer protocols. At the macroscopic level, both longitudinal and lateral highway capacities will be examined for the improvements over the original AHS coordination and link layer protocols. We assume that sufficient individual vehicle/platoon information will be available for computing macroscopic quantities.

For the simulation study, we will systematically design a set of experimental scenarios, run these experiments in the SmartAHS simulation package, and test the performance of the enhanced design. Different factors will be considered in the design of the simulation experiments, such as highway capacity, platoon size, safe intra- and interplatoon spacing policies, highway traffic velocity, entry/exit routine table, etc. Comparisons with original coordination and link layer protocol designs will be carried out to study improvements in capacity and safety.

E Research Plan and Deliverables

The proposed project has a planned 2 year duration. A concise statement of the tasks to be performed is given below.

Year 1: Coordination layer protocols enhancement

- **Task 1.1**: Survey literature and study the original AHS coordination and link layer protocols.
- **Task 1.2**: Design the enhanced coordination layer maneuver protocols using the methods described in section D.1.1.
- **Task 1.3**: Design and test the regulation layer continuous-time feedback control laws for enhanced maneuvers in sections D.1.1 and D.5.1.
- **Task 1.4**: Design the intra- and inter-platoon communication protocols for new enhanced maneuvers described in section D.4.
- **Task 1.5**: Formally verify the maneuver and communication protocol designs in the regulation and coordination levels using methods in section D.5.1.
- **Task 1.6**: Formally verify the maneuver and communication protocol designs in the regulation and coordination levels using methods in section D.5.2.
- **Task 1.7**: Integrate, simulate, and test the enhanced design of the coordination layer maneuver protocols with the regulation layer controllers using SmartAHS discussed in section D.6.

Year 2: Link layer protocols enhancement and performance study

- **Task 2.1**: Design the enhanced link layer protocols as described in section D.2.
• **Task 2.2:** Design the interface between the enhanced coordination and link layer protocols as described in section D.3.

• **Task 2.3:** Design the protocols of the vehicle-to-roadside communications for the enhanced link layer protocols described in section D.4.

• **Task 2.4:** Formally verify the protocol enhancements in the link layer and the interfaces with the coordination layer described in section D.2.

• **Task 2.5:** Formally verify the design of the vehicle-to-roadside communications for the enhanced link layer protocols described in section D.4.

• **Task 2.6:** Simulate and test the whole enhanced system design using integrated SmartCAP/SmartAHS meso/micro-simulator as described in section D.6.

• **Task 2.7:** Study the system capacity/safety improvements of the enhanced coordination and link layer protocols using the methods described in section D.7.

### Milestones

<table>
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<tr>
<th>List of tasks</th>
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<th>End date</th>
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<tbody>
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<td>1. Task 1.1 (Professors R. Horowitz and R. Sengupta, Dr. C-W. Tan)</td>
<td>7/1/02</td>
<td>8/31/02</td>
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<td>2. Task 1.2 (Professor R. Horowitz)</td>
<td>9/1/02</td>
<td>11/30/02</td>
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<td>3. Tasks 1.3 and 1.5 (Professor R. Horowitz)</td>
<td>12/1/02</td>
<td>2/28/03</td>
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<td>4. Task 1.4 (Professor R. Sengupta)</td>
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<td>5. Task 1.6 (Professor R. Sengupta)</td>
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<td>2/28/03</td>
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<tr>
<td>6. Task 1.7 (Professors R. Horowitz and R. Sengupta)</td>
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<td>7. Task 2.1 (Professor R. Horowitz)</td>
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<td>9. Task 2.3 (Professor R. Sengupta, Dr. C-W. Tan)</td>
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<td>11. Task 2.4 (Professor R. Horowitz)</td>
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Deliverables

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<td>1. Finite state machines (FSMs) of the enhanced coordination protocols</td>
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<tr>
<td>2. MATLAB validations of the new regulation control algorithms</td>
<td>2/28/03</td>
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<tr>
<td>3. FSMs of the vehicle-to-vehicle communication protocols</td>
<td>11/30/02</td>
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<tr>
<td>4. KRONOS verifications of maneuver and communication protocols</td>
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</tr>
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<td>5. SmartAHS simulation software of the enhanced maneuvers</td>
<td>6/30/03</td>
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<td>6. An interim report with documentation</td>
<td>6/30/03</td>
</tr>
<tr>
<td>7. A workshop presentation</td>
<td>6/30/03</td>
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<tr>
<td>8. FSMs of the enhanced link layer protocols</td>
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<tr>
<td>9. KRONOS verifications of the vehicle-to-road communication protocols</td>
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<td>10. Integrated SmartCAP/SmartAHS simulation software of the enhanced link and</td>
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<td>coordination layer protocols</td>
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F Qualifications of Principal Investigator, Key Researchers and Collaborators

Roberto Horowitz, Ph.D., received the B.S. degree with highest honors in mechanical engineering from the University of California at Berkeley in 1978 and the Ph.D. degree in 1983. In 1982 he joined the Department of Mechanical Engineering at the University of California at Berkeley. He is currently a Professor in the same department where he teaches and conducts research in the areas of adaptive, learning, nonlinear and optimal control, and dynamic systems, with applications to many mechatronics devices including micro-electromechanical systems, disk file systems, photocopying and printing machines and robots, as well as in the areas of the control of complex and hierarchical systems and intelligent vehicle and highway systems.

Dr. Horowitz is an associated faculty member of the Berkeley Sensor & Actuator Center (BSAC), a member of the Computer Mechanics Laboratory (CML), a principal investigator of the Partners for Advance Transportation and Highways (PATH) research program of University of California and CALTRANS, and a faculty member of the National Storage Industry Consortium (NSIC).

Dr. Horowitz has been or is currently principal investigator of the following PATH research projects:


• MOU 383: Development of integrated meso/microscale traffic simulation software for testing fault detection and handling in AHS.

Dr. Horowitz has been and is currently involved in the formulation, design, testing and verification of many maneuvers and control laws for PATH’s AHS normal and degraded mode control architectures. As part of this work, Dr. Horowitz analyzed the link and network layers of the PATH architecture and synthesized decentralized and distributed control laws for these systems which were proven to be stabilizing. These control algorithms have been also tested extensively using AHS simulation tools. Dr. Horowitz has also been involved with the design, analysis and safety verification of the hybrid system formed by the coordination/regulation layers of the current PATH AHS control architecture.

Raja Sengupta, Ph.D., is currently an Assistant Professor engaged in research on Information Technology for Large-Scale Systems in the Department of Civil and Environmental Engineering at the University of California at Berkeley. He is PI of a project on Distributed Autonomous Agent Networks within an ONR UAV research program. He is also Co-PI on an NSF project researching sensor webs for fire and earthquake management. He is also currently a research scientist with the California PATH program at the University of California at Berkeley, where he leads the networking research. His current research projects are in sensor networks, unmanned air vehicle systems and wireless networks for intelligent transportation systems. These projects are developing distributed probabilistic mapping protocols, a theory of networked estimation and control, distributed fault detection in networked systems, service networks, and wireless ad-hoc networks. He has successfully executed projects funded by CALTRANS, USDOT, and the Office of Naval Research. He has received gifts from wireless networking and the automotive companies given to further his research program. He received his PhD in Systems Engineering from the University of Michigan in 1995 where he worked on optimal control, and traffic signal optimization. Prior to his current assignment his research focused on advanced vehicle safety systems. He led the system safety research for the National Highway System Consortium till 1997 and worked briefly for Mitretek Systems providing program advice to the ITS Joint Programs Office of the USDOT. He is the author of several academic publications, reviewer for several academic journals.

Chin-Woo Tan, Ph.D., is a native of Hong Kong. He received the degrees of B.Sc. and Ph.D. in electrical engineering, and M.A. in mathematics, all from the University of California at Berkeley. From January 1991 to August 1994, he was a post-doctoral researcher and lecturer at U.C. Berkeley and U.C. Davis. From August 1994 to September 1996, he worked at Polotec, Inc. in Santa Clara, CA. Since September 1996, he has been an assistant research engineer and project manager with the California Partners for Advanced Transit and Highways (PATH) at the University of California, Berkeley. His areas of research interest are nonlinear dynamics, signal processing, and intelligent transportation.
G Vita

Roberto Horowitz

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Vice Chair of Graduate Study
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University of California, Berkeley CA 94720-1740
Tel: (510)642-4675. Fax: (510) 642-6163.
E-mail: horowitz@me.berkeley.edu

Field of Specialization

Adaptive, learning, nonlinear and optimal control, with applications to many mechatronics devices including Micro-ElectroMechanical Systems (MEMS), disk file systems, photocopying and printing machines and robots. Control of complex and hierarchical systems. Intelligent vehicle and highway systems (IVHS).

Education

B.S. Mechanical Engineering, University of California at Berkeley, 1977.
Ph.D. Mechanical Engineering, University of California at Berkeley, 1983.

Experience

Acting Assistant Professor, University of California, 9/82 - 6/83.
Assistant Professor, 6/83 - 7/89
Associate Professor, 7/89 - 7/94
Professor, 7/94 - present.
Vice Chair of Graduate Study, Department of Mechanical Engineering, 7/01 - present.

Societies

Member, American Society of Mechanical Engineers (ASME).
Member of IEEE.

Awards

NSF Presidential Young Investigator Award
IBM Young Faculty Development Award.
Japanese Foreign Research Fellowship.

Recent IVHS Publications


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Assistant Professor of Civil and Environmental Engineering
University of California, Berkeley CA 94720-1740
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Field of Specialization
Information technology for large-scale systems. Control of complex and hierarchical systems. Intelligent vehicle and highway systems (IVHS).

Education

Experience
Assistant Professor, University of California, 7/01 - present.
Assistant Research Engineer, California PATH, 12/98 - 7/01.
Assistant Research Engineer, California PATH, 4/95 - 5/98.

Societies
Member of IEEE and ITS America.

Recent Publications


Chin-Woo Tan

Personal
Office address: California PATH, Headquarters
University of California, Berkeley
Richmond Field Station, Bldg. 452
1357 South 46th Street, Richmond, CA 94804
Tel. numbers: (510) 231-9559 (office), (510) 231-9512 (facsimile)
Email address: tan@robotics.eecs.berkeley.edu

Education
University of California, Berkeley
Ph.D. Electrical Engineering (November 1990)
Advisors: Professors Pravin Varaiya and Felix Wu
M.A. Mathematics (December 1987)
Advisors: Professors Morris Hirsch and Charles Pugh
B.Sc. Electrical Engineering (December 1982, graduated with High Honour)

Experience
Research
PATH, University of California, Berkeley
Assistant Research Engineer, 11/96 - now.
Research on signal estimation problems for applications to precise vehicle navigation and position control of automated vehicles. Students co-supervised with Prof. P. Varaiya: Kirill Mostov, PhD in EE, May 2000. Students co-supervised with Prof. R. Horowitz: Sungsu Park, PhD in ME, December 2000; Sing Yiu Cheung, MS/PhD student in ME
AVCSS Research Project Manager, 11/96 - now.
Manage the Advanced Vehicle Control & Safety Systems (AVCSS) research program. Monitor and evaluate all PATH sponsored AVCSS research projects. Review AVCSS research reports. Formulate PATH AVCSS RFP, conduct proposal evaluation, and develop funding recommendations.

Electronics Research Lab., University of California, Berkeley
Research Assistant, Department of Elec. Engrg. & Comp. Sci.
Power System Stability Analysis, 1/85 - 12/85.
The Effects of Small Noise on Nonlinear Dynamical Systems, 1/84 - 12/84.
Research Assistant, Department of Mathematics.
Qualitative Analysis of Nonlinear Dynamical Systems, 1/87 - 12/87.

Teaching
University of California, Berkeley
Tutor, Dept. of Elec. Engrg. & Comp. Sci., and Department of Mathematics, 1/86 - 12/87.

University of California, Davis
Visiting Lecturer, Department of Elec. Engrg. & Comp. Sci., 9/92 - 12/92.
Industrial Polotec Inc., Santa Clara, CA  
Research Engineer, 9/94 - 10/96.

Publications
I Resources

Most of the resources are requested for the category of personnel. Professors Horowitz and Sengupta will charge one summer month for this project in the first year and half month in the second year. Dr. Chin-Woo Tan at California PATH Headquarter will be collaborator with Professors Horowitz and Sengupta on this subject. The requested computer hardwares are necessary to develop, simulate and test enhanced protocols and regulation control software. We plan to extensively utilize the simulation hardware and computer resources located in PATH’s RFS.
### J Progress Reports

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>MOU 373/Task Order 4207: Development and Implementation of a Vehicle-Centered Fault Diagnostic and Management System for the Extended PATH-AHS Architecture</th>
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<tr>
<td>Principal Investigator:</td>
<td>Professors R. Horowitz, K. Hedrick and M. Tomizuka</td>
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<td>Starting Date:</td>
<td>September 1999</td>
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<td>End Date:</td>
<td>December 2001</td>
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In the space below, describe research progress relative to original research plan. Explain any deviations from plan.

The following tasks were executed in this project:

1. Nonlinear observers/filters were designed and tested in simulations to detect the previously unconsidered faults.
2. Residual processor has been extended and tested in simulations to identify the unconsidered faults in MOU 312.
3. The fault management scheme has been redesigned to handle the faults in the regulation layer level without degraded model maneuvers. Integration between fault detection and identification schemes and the management system has been implemented and tested in the SmartAHS simulator using SHIFT.
4. An extended fault management scheme has been designed to include detecting and handling the “soft” faults. A tire/road friction estimation scheme has been designed and tested in simulations. Such an estimation scheme can be combined with the emergency braking controllers to enhance the safety and performance of both manual and automated vehicles.
5. A fault diagnostic scheme, both longitudinal and lateral, has been implemented and tested on vehicles in RFS. The experimental results verify the validity of the design.

In the space below, list all project deliverables completed to date (research reports, software, publications, etc.).

**Software:**
1. MATLAB software for simulation and testing of nonlinear observer/filters for fault diagnostics and residual processor for fault identification.
2. MATLAB software for simulation and testing of friction estimation and emergency braking controller.
3. Real-time implementation of fault diagnostics and identification of longitudinal and lateral control systems.
4. SmartAHS simulation software for integration of fault detection and identification and fault handling systems for longitudinal vehicle control systems.

**Publications:**
5. X. Claeyx, J. Yi, R. Horowitz and C. Canudas de Wit. *A new 3D tire/road friction model for vehicle simulation*, in proceedings of the 2001 ASME IMECE.
<table>
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<tr>
<th>Project Title:</th>
<th>MOU 383/4208: Development of integrated meso/microscale traffic simulation software for testing fault detection and handling in AHS</th>
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<tr>
<td>Principal Investigator:</td>
<td>Professor R. Horowitz</td>
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<td>End Date:</td>
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</table>

In the space below, describe research progress relative to original research plan. Explain any deviations from plan.

The following tasks were executed in this project:

1. SmartAHS capabilities have been extended. An extended communication structure, a simplified sensor architecture, and a simplified set of regulation-layer components have been developed. Under certain conditions, the simplified set produces identical results as the full components, and increases simulation speed 4 to 5 fold.

2. The interface between the mesosimulator SmartCAP and microsimulator SmartAHS has been designed and implemented in SHIFT. A SmartAHS component was created to schedule and monitor all aspects of the interface between SmartCAP and SmartAHS. The SmartCAP activity model was extended to include platooning and join/split maneuvers.

3. The integrated meso/microscale simulation software for stationary regions has been developed and tested for different scenarios. A MATLAB-based visual interface was created which allows the user to view both levels of the simulation simultaneously, by including both macro (curves) and micro (vehicles) data in the same plot. It uses MATLAB’s GUI capabilities so that users can easily manipulate (e.g. zoom, rotate, change) the output.

4. A redefinition of the project objectives led to the replacement of the final task, which was originally the development of a moving interface between SmartCAP and SmartAHS. It was decided that a more direct and useful application of the meso/micro simulator would be in analyzing the interaction of an AHS with connecting manual traffic arterials at high-volume AHS entry and exit locations. One microscale manual traffic simulator, along with a macroscale simulator, will be selected, respectively, to model manual traffic near to and far away from the AHS entrances and exits. We have examined several microscopic and macroscopic models of manual traffic, including VISSIM and the cell transmission model, and are considering them as candidates for integration with the meso/micro simulator.

In the space below, list all project deliverables completed to date (research reports, software, publications, etc.).

**Software:**

1. Extended SmartAHS simulation software including link, coordination, regulation, and physical layers and extended communication structure, and simplified sensor structure.
2. SHIFT-compatible version of extended SmartCAP macro-simulator.
3. Integrated meso/microscale simulation software for stationary region.

**Reports:**


**Publications:**

<table>
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<tr>
<th>Project Title:</th>
<th>MOU329/TO4224: PATH Laboratory</th>
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<tr>
<td>Principal Investigator:</td>
<td>Professor Raja Sengupta &amp; Dr. Chin-Woo Tan</td>
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In the space below, describe research progress relative to original research plan. Explain any deviations from plan.

**Wireless Communications**

Research completed to date

(I) Wireless Token Ring Protocol: We designed a wireless token ring protocol (WTRP) for wireless ad-hoc networks supporting safety-critical applications. This remains to date the world’s only protocol that is capable of providing the access latency control required by safety applications in a mobile ad-hoc wireless environment. We have also completed a full implementation of the protocol on Lucent WaveLAN radios.

(II) Geographic Addressing, Routing, and Multicasting: A geographic routing and addressing algorithm, the first of its kind, is designed to allow the rapid and scalable delivery of position sensitive data to large groups of vehicles that are connected to the Internet.

(III) First Contact Protocol: A preliminary design of the protocol has been completed.

(IV) Light Vehicle-to-Vehicle Communication protocol for first generation ITS DSRC: In response to the need emerging from the ITS DSRC standards debates, we have designed an intelligent broadcast protocol and completed some simple stochastic analyses of this protocol.

**Work in Progress**

Task 1: WTRP Implementation for QNX operating system and integration with demonstration vehicles (March 2002)

Task 2: Implementation of the geographic multicasting protocol (on-going)

Task 3: First contact protocol refinement and implementation (on-going)

Task 4: Intelligent broadcast protocol for first generation ITS DSRC (on-going)

**Inertial Navigation Systems**

We have developed several algorithms to correct various error sources embedded in the GPS and INS data. We are in the process of developing the necessary signal processing (software) module to process the accelerometer outputs.

**Work in Progress**

Task 1: Signal Processing Module of an IMU: The signal processing algorithms are being implemented in C and simulated using Matlab.

Task 2: Integration of GF-INS and GPS: The main task of the integration is to design a state estimator that attenuates the GPS measurement error and provides an accurate estimate of the INS state error. This has been completed. We are also developing a User Interface using the QNX.

In the space below, list all project deliverables completed to date (research reports, software, publications, etc.).


References


