Control Design of an Automated Highway System

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Invited Paper

This paper describes the design of an automated highway system (AHS) developed over the past ten years at the California PATH program. The AHS is a large, complex system, in which vehicles are automatically controlled. The design and implementation of the AHS required advances in actuator and sensor technologies, as well as the design, analysis, simulation, and testing of large-scale, hierarchical, hybrid control systems. This paper focuses on the multilayer AHS control architecture and some questions of implementation. It discusses in detail the design and safety verification of the on-board vehicle control system and the design of the link-layer traffic-flow controller.

Keywords*—Automated highways, hierarchical control, hybrid systems, road transportation, stability, velocity control.*

I. INTRODUCTION

This paper describes the control architecture of an automated highway system (AHS), developed over the past ten years at the University of California Partners for Advanced Transit and Highways (PATH) program, in cooperation with the State of California Department of Transportation (Caltrans) and the United States Federal Highway Administration (FHWA). This multilayer AHS architecture was first described in [43] and [42], and this paper discusses aspects of design and verification at several of those layers. The AHS architecture envisions a fully automated control system that leaves few vehicle driving decisions to the driver.

It is argued in [42] that full automation can greatly increase highway capacity while improving safety. A key to greater capacity is the organization of traffic in groups of up to 20 tightly spaced cars called *platoons.*[1] Although the spacing between these platoons is large (about 60 m), platooning decreases the mean intervehicle distance to achieve a capacity of up to 8000 vehicles per hour per lane, as compared with a capacity of 2000 in today's highways with manually controlled vehicles. Because the maintained distance between cars within a platoon is small (1–2 m), in the event of a collision the relative impact velocity (and, hence, the impact energy) between colliding vehicles is small. As a consequence, platooning can increase safety. An additional benefit is that the tightly spaced vehicles reduce aerodynamic drag. As a result, fuel consumption and vehicle emissions are lower [45], [5]. To maintain close proximity while traveling at relatively high speeds (90 Km/h), the vehicles must be fully automated, since people cannot react quickly enough to drive safely with such small headways.

Because of its size, complexity, and large impact on everyday life, the design of an AHS control system that is safe, reliable, and practical poses major challenges, both in the development of new advances in communication, computer, sensor, and actuator technologies and in the synthesis and analysis of intelligent, hierarchical, large-scale hybrid control systems. Reference [39] provides an overview of the advanced vehicle control system (AVCS) research at the PATH program in 1990, while [23] describes the PATH AHS architecture design in 1994, focusing on the physical and coordination layers of the architecture. This paper emphasizes progress since 1994.

We also present new results on the safety and performance analysis of the hybrid system formed by the combined action of the coordination and regulation layer control systems and some results on the control of the combined system formed by the link, coordination, and regulation layers of the AHS architecture.

Table 1 summarizes the functions of the five-layer PATH AHS architecture and the mathematical framework used in the design of each layer. Section II presents an overview of the architecture and describes each layer. Section III discusses the design and safety verification of the hybrid on-board vehicle control system. Section IV discusses the link layer control system. Section V summarizes the main

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[1]Although we speak of cars, we mean all vehicles including trucks and buses. It is likely that an AHS will be initially deployed for trucks and buses.

Table 1
The Five Layers and Their Main Functions

Layer	Functions	Model
Network	Control entering traffic and route traffic flow within AHS network	Capacitated graph
Link	Compute and broadcast activity plans (i.e. the routes, maneuvers to be exectuted, speed, platoon size) for each vehicle type in each section	Fluid flow model with distributed control
Coordination	Communicate and coordinate with peers and select one maneuver to be executed	Finite state machine
Regulation	Execute maneuvers such as join, split, lane change	Feedback laws based on linear models
Physical	Decouple lateral and logitudinal control	High order nonlinear differential equations

points of the paper and contains some remarks about the future of AHS.

The PATH AHS research program began in 1989 with Caltrans support. In order to carry out AHS research, PATH developed basic tools for hybrid system design, simulation, and verification. Among these, the hybrid system simulation language and run-time system SHIFT [11] and related theoretical and software tools have been used in other intelligent control projects.

In 1994, the U.S. Department of Transportation formed the National Automated Highway Systems Consortium (NAHSC) with a charge to investigate alternative AHS designs, to test some key elements of AHS technology, and then to develop one detailed design.[2] In August 1997, NAHSC successfully demonstrated key AHS technologies, including an eight-vehicle platoon-based system, on I-15 in San Diego, CA. More than 1700 people enjoyed rides in automated vehicles. The NAHSC engaged up to 100 full-time engineers, including the PATH team of 15. Despite its success, the NAHSC was dissolved in 1998. With support from Caltrans, PATH continues to develop AHS technology and related spinoffs. There are active AHS programs in Europe and Japan today.

II. AHS Control Architecture

In order to understand the problems faced in the design of an AHS control architecture, imagine driving your car on an AHS. You queue the car at an AHS entrance gate. The integrity of the car's on-board control system is checked there and its destination recorded.[3] You relinquish control, and the car joins a platoon entering the AHS. Upon executing an entrance maneuver [16], the platoon begins its journey on the AHS. From then on your car executes, under AHS control, a series of maneuvers [42], including splitting from and joining platoons and lane changing, as it navigates through the highway network. As your car approaches its destination, it executes an exit maneuver, either as a free agent (i.e., a one-car platoon) or as part of an exiting platoon. At the AHS exit gate, your ability to handle your car is checked and control is returned to you.

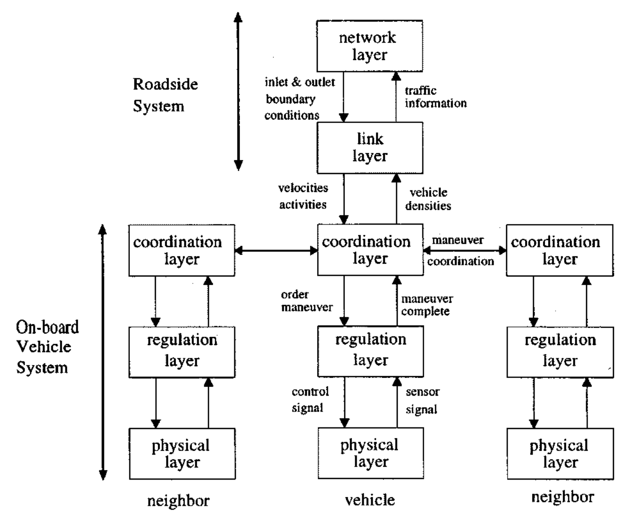

Fig. 1. The five-layer AHS control system architecture.

This scenario indicates the many control functions that the AHS must carry out. The architecture organizes these functions in a layered hierarchy. The influence of the control architecture in the design of a complex system like the AHS cannot be overestimated. A good architecture simplifies controller design and testing through the functional decomposition in self-contained layers, and well-specified interfaces simplify software design and code development.

A. Normal Operation

Fig. 1 shows a block diagram of the five-layer PATH AHS *normal mode of operation* control architecture [42]. (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.) Also indicated in the figure are the most important data that are exchanged at the layer interfaces. Starting from the top, the layers are called network, link, coordination, regulation, and physical. Except for the network layer, detailed models and corresponding control systems for each layer of this architecture have been specified and tested to varying degrees

[2]The core members of the NAHSC were Bechtel, Caltrans, Carnegie-Mellon University, Delco, General Motors, Hughes, Lockheed Martin, Parsons Brinckerhoff, PATH, and Federal Highway Administration.

[3]You may change the intended destination during the trip.

of realism.[4] We briefly describe each layer and its main functions, starting from the bottom.

The *physical layer* comprises all the on-board vehicle controllers of the physical components of a vehicle. These include the engine and transmission, brake, and steering control systems, as well as the different lateral and longitudinal vehicle guidance and range sensors.[5] The main function of the physical layer is to decouple the longitudinal and lateral vehicle guidance control and to approximately linearize the physical layer dynamics [23], [35]. By lateral guidance, we mean the task of keeping the vehicle in the center of its assigned lane and controlling its motion when commanded to change lanes [24]. By longitudinal guidance, we mean the task of controlling the forward motion of the vehicle along a lane [41]. The decoupling of the longitudinal and lateral modes simplifies the design of the regulation layer.[6] A detailed nonlinear differential equation model of a single vehicle's physical layer can have 30 dimensions.

The *regulation layer* is responsible for the longitudinal and lateral guidance of the vehicle, and the execution of the maneuvers ordered by the coordination layer. At this level of the hierarchy, for purposes of design and analysis, the vehicle is modeled as a particle, whose longitudinal dynamics is described by a second- or third-order linear continuous time system with control and state saturation [18], [41].

The regulation layer must carry out two longitudinal control tasks. The first task is that of a vehicle follower[7] in a platoon and consists in maintaining a prescribed constant spacing from the preceding vehicle [40].[8] The second task is that of a platoon leader or free agent and consists in safely and efficiently executing a maneuver commanded by the coordination layer. These maneuvers (and their names) are: regulating the platoon velocity to a desired value, while maintaining a safe distance from the preceding platoon (*leader law*); joining with the preceding platoon (*join law*); splitting a platoon (*split law*); and splitting from a platoon while maintaining safe distances from neighboring platoons in the adjacent lanes, in order subsequently to change lanes (*split-to-change-lanes law*) [14], [28], [2], [3]. The two lateral control tasks of the regulation layer are to keep the vehicles in its assigned lane or to change to an adjacent lane. The latter task is called the change lane maneuver. The third set of regulation layer tasks are the AHS entry and exit maneuvers [16].

[4]Testing involves limited verification of the design, limited experimental validation, and extensive simulation. Verification comprises formal proofs of correctness and performance analysis; experimental validation is carried out on various test tracks with actual vehicles; and simulation is based on SmartPATH and SmartAHS simulation packages, the latter being written in SHIFT.

[5]The physical layer also includes the intervehicle radio communication system with its medium access and network protocols, and the integration of the communication and control systems. The communication system itself is properly modeled as a hybrid system, but it is not discussed here.

[6]For heavy trucks, the two modes are coupled and the design is more difficult.

[7]We use these names: the lead car in a platoon is its *leader*, and the rest are *followers*. A one-vehicle platoon is a *free agent*.

[8]In adaptive cruise control, by contrast, the feedback law maintains a constant headway or time, equal to spacing divided by speed, from the preceding vehicle [26].

We refer to all these longitudinal and lateral tasks and maneuvers as *activities*. Thus, the regulation layer at any time is engaged in one activity and switches to another activity in response to commands from the coordination layer.

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*. It communicates and coordinates its actions with its peers—the coordination layers of neighboring vehicles—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 [42]. The coordination layer stores and updates all relevant information regarding the vehicle's current state such as its identity, current location, activity, and assigned activity plan.

A vehicle's identity includes the vehicle identifier (perhaps its licence plate number), its type (e.g., bus, private car, emergency vehicle), origin and destination, etc. The location information includes the lane and section of the highway link where the vehicle is currently traveling, as well as it position within the platoon.

The assigned activity plan depends on the vehicle's type and current activity. For platoon leaders and free agents, the activity plan includes the vehicle's desired velocity, maximum platoon size, and the permit to attempt to join another platoon or change lane (including to and from exit and/or transition lanes). A follower's plan consists in maintaining the follower law or to split or split-to-change lane (i.e., become a leader). This plan depends on the vehicle's destination and its current location. The plan is periodically updated by the link-layer controller. We emphasize that the scope of the information regarding the vehicle's location and its current activity plan is local within a section of a highway link. Using this information, and by coordinating its actions with its peers, the controller selects *one* activity from a finite set, which it commands the regulation layer to execute.

There is one *link-layer* controller for each 0.5–5-km-long segment of the highway, called a link. Its task is to control the traffic flow within the link so as to attain its full capacity and minimize vehicle travel time and undesirable transient phenomena, such as congestion. A link is itself subdivided in sections, one per lane. A link receives and discharges traffic flow from and to neighboring links, as well as AHS entrances and exits. The controller measures aggregated vehicle densities in each of the link's sections. These densities are specific to vehicle type, including origin and destination, and whether the vehicle is a platoon leader, follower, or changing lanes. It broadcasts commands in the form of a specific activity plan for each vehicle type and section to the vehicle coordination layer controllers.[9]

The link-layer controller receives commands from the network layer in the form of demands on the inlet traffic flows

[9]Observe that there are far fewer such commands than the number of cars in each section.

at the AHS entrances, and outlet flow constraints at the AHS exits, as well as desired inlet-to-outlet traffic flow split ratios, in case a vehicle can take more than one route to reach the same destination, while traveling in that highway link [34]. The controller also monitors incoming traffic flow from neighboring links. At this level of the architecture hierarchy, the control system no longer monitors the response of individual vehicles. Instead, the state of the link is measured and described as *aggregated* space and time vehicle density profiles. Similarly, the control inputs are modeled as activity vector fields, i.e., activity and velocity commands that are functions of space and time. As a consequence, the link-layer dynamics are described by density conservation flow models [6], [29].

The task of the *network layer* is to control entering traffic and route traffic flow within 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 of the AHS control architecture is presently the least developed. An initial design can be found in [12].

We emphasize two points that are implicit in this description. First, the design of different layers are based on different models. The physical layer uses detailed differential equation models of a single vehicle, with its sensors and actuators. The feedback laws at the regulation layer are based on simpler, low-order linear systems. The coordination layer coordination protocols are designed as finite-state machines. The link-layer design is based on fluid flow models. At the network layer, the AHS is viewed as a capacitated graph. The model at a higher level is *not* an abstraction of a lower level model, as that term is normally used in the control and verification literature. There "abstraction" refers to aggregation, i.e., a "state" at a higher level represents a group of states at a lower level. The relation between a higher level state and the corresponding group of lower level states may only be heuristic (as in model reduction approaches) or it may be some invariant-preserving homomorphism. In the architecture above there is no such direct relationship between layers. Rather, the model at each layer is an "idealization" that is suited to the particular functions that layer carries out. Thus, for example, the coordination layer chooses particular activities, but "activity" is an ideal construct that is not visible at the physical or network layers. But a coordination layer activity does have a counterpart in a feedback law at the regulation layer and in the activity plan at the link layer. It is a creative part of the architecture design to come up with the proper ideal models at each layer.

Second, as one goes up the hierarchy, the time scale of decisions and their spatial impact increase. At the physical layer, the time scale is 20 ms—the sampling time of the sensors and actuators. An action at this layer only affects the vehicle itself. At the regulation layer, the time scale is on the order of seconds, which is the time taken to execute a maneuver. A vehicle's maneuver affects not only itself but also neighboring vehicles. The coordination layer selects an activity about once a minute, and the choice of activity depends on its neighboring peers as well. The time constants of the flow equations used by the link layer are on the order of minutes—the time that a disturbance traverses a link. A link-layer decision has an impact on all vehicles on a link. Last, network-layer decisions, affecting AHS-wide traffic, may be examined every hour, in the absence of incidents. Of course, this increasing time scale only holds in this architecture that describes the normal mode of operations. Under degraded operations (not discussed here), the architecture is different.

The behavior of a vehicle engaged in an activity is described by the corresponding differential equation of the closed-loop system—the physical layer and the feedback law of the activity. Thus, the physical and regulation layers together are described by a discrete state variable—the current activity—and the continuous-state variable of the activity's differential equation. The transition from one activity to another is determined by the coordination layer. Thus, the three lowest layers of a vehicle form a hybrid system. The hybrid system of neighboring vehicles are coupled in two ways. The continuous-state variables are coupled since the follower law, for example, adjusts acceleration as a function of the relative spacing with the vehicle in front. The discrete state variables are coupled because peer coordination layers communicate with each other.

B. Degraded 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 that enable the AHS to function in a degraded mode of operation, while dealing with faults and adverse environmental conditions.

The design of a fault management system (FMS) for longitudinal control in the AHS architecture described in this paper was proposed in [32], [31], and [17] for degraded modes of operation induced by the presence of faults. The FMS detects the presence of a fault utilizing information provided by a fault detection and identification system [8], [9], [36]. The fault detection and identification (FDI) schemes process sensor measurement information together with state estimates produced by a set of observers, to detect the presence of a fault. The key to fault detection is that the set of measurements and estimated variables contain some level of redundancy. For example, vehicle velocity can be derived from the wheel speed sensor or from the engine speed sensor. When these two measurements are within a given range, the wheel speed and engine speed are assumed to be nonfaulty. If the difference between these two velocity measurements is relatively large, then a fault in one of the two sensors can be presumed. In the general case, all signal measurements and estimations are processed by a set of residual filters that generate a unique pattern of residuals for each different fault. The output of the FDI system is a set of binary numbers, each one of them associated with a faulty component.

The FMS design presented in [32] and [31] utilizes, in addition to the sensor structure, two additional hierarchical structures to manage and process the information flow during a degraded mode of operation: the capability and performance structures. The former encodes discrete changes in the system capability due to hard faults in the vehicles and roadside hardware. The latter encodes gradual degradation in system performance due to adverse environmental conditions and gradual wear of AHS components. The capability structure is implemented by a set of finite-state machines whose function is to map the set of binary numbers produced by the FDI system into another set of binary numbers. This new set indicates the availability of each regulation layer control law and coordination layer maneuver, according to the pattern of faults that is detected by the FDI system. Communication faults can be posed in this same hybrid systems framework. Each received packet is fed to a finite-state machine, and their composition allows one to determine when a fault is present.

The information collected by the capability and performance structures regarding fault detection and AHS capability evaluation is sent to the fault handling module. In the on-board vehicle control system, the fault handling module acts as a supervisory unit to the coordination layer controller. It classifies faults by severity and initiates appropriate alternative control strategies or degraded maneuvers. In some cases, the redundancy features normally available in FDI are exploited, and faults are handled under the normal mode of operation, by using the information provided by the observers in the control algorithms and adjusting the controller parameters. In other cases, a specific degraded maneuver is executed to allow the faulty vehicle to exit the highway or stop in a safe manner. Interested readers are referred to the references cited above and to [44] for further details.

III. On-Board Vehicle Control System

The overall on-board vehicle control system comprises the control systems for the coordination, regulation, and physical layers. Its primary objective is to safely control the vehicle while efficiently executing its activity plan. By "safely," we mean that the vehicle should not collide under normal circumstances, in the absence of major hardware malfunction. By "efficiently," we mean that the vehicle should complete the maneuvers in its activity plan in a manner that tends to optimize the capacity and traffic flow of the AHS. This involves completing maneuvers, such as join, split, or change lane in the minimum possible time, and performing platoon follower and leader laws while maintaining as high a speed and as small a distance from the preceding vehicle as practicable. However, since the on-board vehicle control system does not have the overall AHS capacity and traffic-flow information (it does not even maintain detailed information on the vehicle's origin-to-destination trip plan), overall AHS optimality is not monitored or guaranteed at this layer.

The physical layer includes all physical components of the vehicle and their controllers. Its main function is to decouple the longitudinal and lateral vehicle guidance control and to approximately linearize its dynamics. Reference [23] and the references therein describe this layer in detail, and it will not be discussed further.

The on-board vehicle control system is a *hybrid control system* [20]: a discrete event dynamical system (the coordination layer) supervises and interacts with a continuous-time dynamical system composed of the regulation and physical layers. Thus, it is necessary to develop a design and verification methodology that guarantees the safety and efficiency of the overall on-board vehicle hybrid control system. This design goal is accomplished in three steps.

1) Activity Plan Definition: The control design task is simplified by restricting an activity plan to choices from a limited set of atomic maneuvers: leader, follower, join, split, split-to-change-lane, change-lane, AHS entry, and AHS exit. Moreover, execution of the maneuvers is further restricted by insisting that a) only leaders (and free agents) can initiate maneuvers, while followers maintain platoon formation at all times; b) leaders can only execute *one* maneuver at a given time; c) maneuvers are coordinated with the relevant leaders of neighboring platoons; and d) only after agreement is reached between these leaders is a maneuver initiated [42]. These restrictions dramatically simplify the tasks of the link and coordination layers.

2) Coordination Layer Design: The coordination layer control system is realized as a hierarchy of coupled finite-state machines. The coordination of each maneuver is 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 is formally specified, and its logical correctness is verified using software verification tools, such as COSPAN [21]. The overall state machine has more than 500 000 states [25], [42], [37].

3) Regulation Layer Design: The regulation layer control system is designed so that the execution of every maneuver initiated by the coordination layer follows 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, produces the same sequence of events as that dictated by the coordination-layer design in which the entire continuous-time behavior of the vehicle during a maneuver is represented by a single state. (See Fig. 3 for an example of the join maneuver.) In addition, when a maneuver is completed, it must be done safely and efficiently. Thus, the regulation layer must perform in a manner that is consistent with the coordination-layer model.

For longitudinal maneuvers, consistency is accomplished by casting the execution of the maneuver as an adversarial game between two agents, the lead and trail platoons involved in the maneuver. The trail platoon's control objective is to safely accomplish the maneuver in minimum time, while the lead platoon's objective is to make the trail platoon collide. Necessary and sufficient conditions, as well as the optimal feedback control laws, are derived so that the games are either won by the trail platoon, or otherwise, the maneuver is safely aborted. Using these results, the maneuver is initiated only when it can be safely completed, and is aborted otherwise [14], [3], [28], [30], [33], [19]. We illustrate this worst case design methodology for the join maneuver.

A. Join Maneuver

In the join maneuver, two consecutive platoons, traveling on the same lane, join to form a single platoon. As schematically depicted in Fig. 2, trail platoon $\mathbf{A}$ joins with lead platoon $\mathbf{B}$ to form the combined platoon $\mathbf{BA}$.

1) Coordination Layer Design: For the join maneuver to be initiated, the leader of the trail platoon, vehicle A_L has to engage in a join protocol with the leader of the lead platoon, vehicle B_L. The protocol design process assumes that each vehicle can detect neighboring vehicles within a certain range and that it can communicate with them. The protocol is designed in two stages. First, the protocol is described as the informal state machine shown in Fig. 3.

Note that these state machine descriptions are informal, since their states and transitions refer to actions and conditions that may depend on the regulation layer, on information from sensors on-board the vehicle, and on information from roadside monitors. These events are external, and therefore, are not part of the protocol machines. In the second stage of the design, the distinction between internal machine states and external events is enforced in each protocol machine, and they are specified in the formal language COSPAN [21]. The COSPAN software is then used to verify the viability and logical correctness of the product state machine formed by all the coupled protocols. See [25], [42], and [37] for details.

2) Regulation Layer Design: As soon as a join protocol is established between the coordination layer controllers of platoons leaders A_L and B_L, they declare themselves busy (see Fig. 3) and will not establish protocols with other vehicles until the join is either completed or aborted. When the join maneuver is initiated, the regulation layer controller of the trail platoon leader A_L switches to the *join control law,* while that of lead platoon leader B_L maintains the *platoon leader control law.* All other vehicles in the platoons maintain the *vehicle follower control law* [18], [14].

As depicted in Fig. 2, the join maneuver is initiated from a nominal leader law interplatoon spacing Δx_{LEAD} of approximately 60 m maintained by the leader law. The join maneuver is completed when the spacing between vehicles A_L and B_F becomes equal to the follower law switching interplatoon spacing Δx_S, which is equal to or slightly larger than the vehicle follower spacing $\Delta x_{\mathrm{FOLLOW}}$ of 1–2 m. At this instance, the regulation-layer controller switches from the join law to the vehicle follower law. It should be emphasized that the join and follower controllers not only have different control laws but, in addition, the follower controller makes use of an intraplatoon local area communication network to transmit to each member of the platoon the current values of the acceleration of its leader and of the vehicle that precedes it. This information is not available to the join controller.

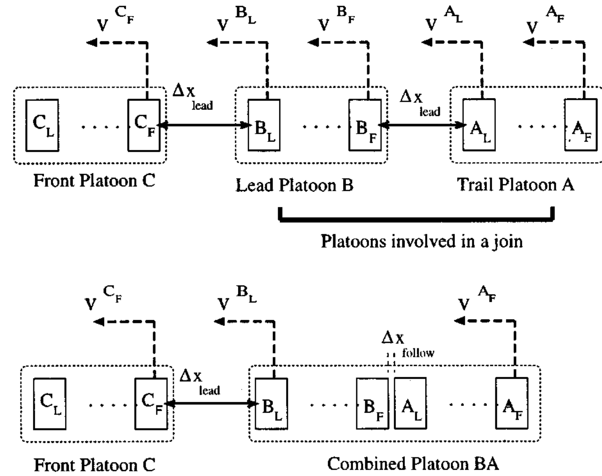

Fig. 2. Vehicles are moving right to left. In the join maneuver, the trail platoon $\mathbf{A}$ joins the lead platoon $\mathbf{B}$ to form the combined platoon $\mathbf{BA}$. The maneuver can affect the platoon $\mathbf{C}$, in front of $\mathbf{B}$.

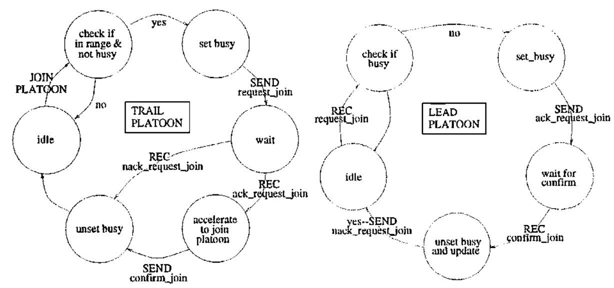

Fig. 3. These informal state machines specify the design of the join maneuver protocols. The machine on the left is for the leader of the trail platoon that initiates the maneuver request, and the machine on the right is for the leader of the front platoon that responds to the request.

Since the join protocol is only established between vehicles A_L and B_L, the leader of the front platoon C_L can itself engage in a different maneuver that does not require coordination with vehicle B_L. As a consequence, the behavior of the last vehicle follower in the lead platoon B_F cannot be entirely predicted by vehicle A_L, since it depends on what C_L may do (e.g., B_F could suddenly be forced to brake if C_L applies full braking). Thus, the *join control law* has to be designed assuming that B_F is *not cooperating* with vehicle A_L. In fact, it must be assumed that B_F could behave in the *most harmful* way it possibly can to make A_L collide [14], [28], [2], [33]. This is an example of a worst case design mentioned above.

We now analyze the vehicle behavior during a join maneuver in more detail. Referring again to Fig. 2, we identify vehicles by consecutive integer indexes $\mathbf{V} = \{A_F, \ldots, A_L, B_F, \ldots, B_L, C_F, \ldots, C_L\}$, which are of ascending order in the direction of the traffic flow, e.g., $B_F = A_L + 1$. We denote the three platoons, respectively, by $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$, where, e.g., $\mathbf{A} = \{A_F, \ldots A_L\}$.

For any vehicle $P \in \mathbf{V}$, denote its longitudinal position, velocity, and acceleration, respectively, by x^P, v^P, and a^P. We assume that $v^P(t) \geq 0, \forall t \geq 0$ (i.e., vehicles do not travel backward). Define $\mathbf{T}_J = [t_o, t_f] \subset \Re_+$ as the interval of time during which the join maneuver takes place.

Let $a_{\rm MAX}^P$ and $a_{\rm MIN}^P$ be, respectively, the magnitudes of the maximum acceleration and deceleration that vehicle P attains *during the entire join maneuver*, i.e.,

$$-a_{\rm MIN}^P \le a^P(t) \le a_{\rm MAX}^P \qquad \forall t \in \mathbf{T}_J.$$

We assume given the acceleration magnitude $A_{\rm MAX}$ and deceleration magnitude $A_{\rm MIN}$, which can be achieved by *all* vehicles in the highway. We will design the regulation layer control laws such that

$$a_{\rm MIN}^P \le A_{\rm MIN} \quad \text{and} \quad a_{\rm MAX}^P \le A_{\rm MAX} \qquad \forall P \in \mathbf{V} \quad (1)$$

and the speed of all vehicles executing the leader law does not exceed the *maximum leader law travel speed* $v_{\rm LEAD}^{\rm MAX}$.

We model the longitudinal response of the vehicles as a double integrator and express the combined response of vehicle P and its preceding vehicle $P+1$ as

$$\Delta\dot{x}^P(t) = v^{(P+1)}(t) - v^P(t)$$
$$\Delta\ddot{x}^P(t) = a^{(P+1)}(t) - a^P(t)$$

where $\Delta x^P = x^{(P+1)} - x^P$ is the headway of vehicle P. Thus, for safety, we require that

$$\forall P \in \mathbf{V}, \forall t, \quad \Delta x^P(t) > 0. \qquad (2)$$

The key for designing longitudinal safe control laws is in deriving sufficient conditions that guarantee that the behavior of lead vehicle B_L and consequently follower vehicle B_F is sufficiently benign, so its most harmful behavior does not prevent platoon $\mathbf{A}$ from joining safely and efficiently. Note that to analyze the safety of the join maneuver, we must analyze the join, leader, and follower laws, since vehicles under the control of these three laws may potentially affect the outcome of the maneuver.

The task of the vehicle follower control law is to maintain a constant vehicle spacing of about $\Delta x_{\rm FOLLOW} = 1$ m (Fig. 2) between vehicles forming a platoon. Reference [23] discusses in detail the currently implemented control law designed in [41] and [40]. The key feature of this design is to maintain *platoon string stability* [38], [26], [40] so that spacing errors caused by lead car maneuvers are not amplified throughout the platoon. This is achieved by making the acceleration of the preceding vehicle, as well as the velocity and acceleration of the lead vehicle, available to each vehicle follower controller in the platoon. The robustness of the string stability to small processing lags can also be guaranteed by an additional term in the follower control law involving the position of the lead vehicle [22]. It is also shown in [40] that a sufficient condition for preventing vehicle collisions in a platoon, is to make the *platoon maximum deceleration ratio,* which is defined as the ratio between the maximum allowable decelerations of the last follower and the leader of the platoon, sufficiently large. For any platoon $\mathbf{P}$, $\mu^{\mathbf{P}}$ is defined as

$$\mu^{\mathbf{P}} = \frac{a_{\rm MIN}^{P_F}}{a_{\rm MIN}^{P_L}} \qquad (3)$$

where P_L and P_F are, respectively, the platoon leader and last vehicle follower. A sufficient condition to prevent collisions in platoon $\mathbf{P}$ is that

$$\mu^{\mathbf{P}} \ge \mu_{\rm MIN}(N^{\mathbf{P}}) > 1 \qquad (4)$$

where $\mu_{\rm MIN}(N^{\mathbf{P}})$ depends on the number of vehicles in the platoon, $N^{\mathbf{P}}$. It is shown in [40] that

$$\lim_{N\to\infty} \mu_{\rm MIN}(N) = \mu_{\rm MIN} < \infty \qquad (5)$$

and $\mu_{\rm MIN} = 1.12$ for most AHS normal conditions.

In the case of the leader and join control laws, we assume that, in addition to the platoon leader's own velocity and acceleration, only the spacing and relative velocity between the platoon leader and the last vehicle follower of the preceding platoon is available to the control system. Thus, no information regarding the acceleration of the last vehicle in the preceding platoon is available to the leader and join control laws. To design safe *join and leader control laws*, we make use of the following modeling abstraction.

- For a platoon leader vehicle $P_L \in \{A_L, B_L, C_L\}$, its maximum braking deceleration $-a_{\rm MIN}^{\mathbf{P}_L}$ can be achieved d^{P_L} seconds after a full braking command is issued.

The delay d^{P_L} may account for jerk saturation, if a third-order model is used for the vehicle dynamics, as well as other time delays or dynamics present on the system. For example, simple brake models often include pure time delays of about 50 ms. However, delays in the current braking system for PATH are greater than 150 ms. By redesigning the brake system, the delay can be limited to 20 ms [15]. Other less conservative modeling abstractions are possible [33], [1].

We now define the *leader maximum deceleration ratio*

$$\alpha^{P_L} = \frac{a_{\rm MIN}^{P_L}}{a_{\rm MIN}^{(P_L+1)}} \qquad (6)$$

which plays a crucial role in determining safe AHS operating conditions. Note that $\alpha^{P_L} > 1$ implies that the leader vehicle P_L is allowed to decelerate more than the vehicle preceding it, throughout the entire join maneuver.

The task of the join control law is to close the *interplatoon spacing,* from a nominal *leader law interplatoon spacing* $\Delta x_{\rm LEAD} \approx 60$ m to the *follower law switching interplatoon spacing* $\Delta x_S \ge \Delta x_{\rm FOLLOW} = 1$ m, as quickly as possible while maintaining safety (Fig. 2). Switching the vehicle follower law occurs when

$$\Delta x_{\rm FOLLOW} < \Delta x^{A_L} \le \Delta x_S \quad \text{and} \quad 0 \le -\Delta v^{A_L} \le \Delta v_S \qquad (7)$$

where $\Delta x^{A_L} = x^{B_F} - x^{A_L}$ and $\Delta v^{A_L} = v^{B_F} - v^{A_L}$.

The parameters $(\Delta x_S, \Delta v_S)$ denote the state space region where the follower law can be activated, and depend on the capability and operation range of the intraplatoon local area communication network used by the follower control law, as well as the transient response characteristics of the follower control law.

The following proposition provides sufficient conditions for the join between platoons $\mathbf{A}$ and $\mathbf{B}$ to be safe.

Proposition 1: Let $\Delta x^{A_L}(t) = x^{B_F}(t) - x^{A_L}(t)$ be the spacing between vehicles B_F and A_L and $\Delta v^{A_L}(t) = v^{B_F}(t) - v^{A_L}(t)$, where $v^{B_F}(t)$ is the velocity of vehicle B_F and $v^{A_L}(t)$ is the velocity of vehicle A_L. For given performance parameters $a^{A_L}_{\rm MAX}$, $a^{A_L}_{\rm MIN}$, d^{A_L}, and $\alpha^{A_L} \geq 1$, associated with vehicles A_L and B_F, it is possible to define the safety set $X^{A_L}_{\rm safe} \in \Re^3$ such that the join maneuver can be initiated at any time t_o when

$$(\Delta x^{A_L}(t_o),\, \Delta v^{A_L}(t_o),\, v^{B_F}(t_o)) \in X^{A_L}_{\rm safe} \tag{8}$$

and

$$(\Delta x_S,\, \Delta v_S,\, v^{B_F}(t_o)) \in X^{A_L}_{\rm safe} \tag{9}$$

where Δx_S and Δv_S are defined in (7), and will be completed safely.

Moreover, any join control law for vehicle A_L that applies maximum braking command $-a^{A_L}_{\rm MIN}$ when $(\Delta x^{A_L}(t), \Delta v^{A_L}(t), v^{B_F}(t)) \notin X^{A_L}_{\rm safe}$ maintains safety in the sense that $\Delta x^{A_L}(t) > 0$, i.e., vehicles A_L and B_F will not collide.

A precise definition of the safety set $X^{A_L}_{\rm safe}$ can be found in [2]. Proposition 1 follows directly from Theorem 1 in [2] if we use the definition of highway safety given by (2) (i.e., vehicles never collide). Reference [2] considered a more general definition of highway safety, where vehicles are allowed to collide with a relative velocity smaller than or equal to some prescribed value $v_{\rm allow} \geq 0$. Setting $v_{\rm allow} = 0$ in Theorem 1 in [2] results in Proposition 1.

Theorem 1 in [2] is an extension of the results derived in [28], which only considered the case when $\alpha^{A_L} = 1$. As a consequence, in [28] highway safety can only be proven in the more liberal sense that vehicle collisions with relative velocity larger than $v_{\rm allow}$ are avoided. It should be emphasized that the above safety conditions are also necessary in that, if vehicle A_L crosses the boundary of $X^{A_L}_{\rm safe}$ and does not immediately command full deceleration, it may collide with vehicle B_L.

Using the boundary of $X^{A_L}_{\rm safe}$, a feedback-based desired velocity profile for vehicle A_L is generated that satisfies safety and time-optimality requirements. A nonlinear velocity controller can then be designed to track the desired velocity profile within a given error bound. When safety is not compromised, this controller keeps the acceleration and jerk of the vehicles in the platoon within comfort limits. See [28] and [2] for details.

Fig. 4 shows the phase plane response of a join maneuver, using the performance parameter values for $a^{A_L}_{\rm MAX} = A_{\rm MAX}$, $a^{A_L}_{\rm MIN}$, $d^{A_L} = d_{\rm MAX}$, $\alpha^{A_L} = \alpha^{A_L}_{R_{\rm MIN}}$, and $(\Delta x_S, \Delta v_S)$ given in Table 2, for a constant $v^{B_F}(t) = v^{\rm MAX}_{\rm LEAD}$ and a interplatoon spacing of 60 m. The figure also shows the boundary of $X^{A_L}_{\rm safe}$. Under the stated conditions, the join maneuver is completed in about 16 s. The maneuver completion time can be decreased by increasing α^{A_L}. However, as we shall see, this is accomplished at the expense of increasing the interplatoon spacing.

A necessary condition for vehicles A_L and B_F not to collide during a join maneuver is that $\alpha^{A_L} \geq \alpha^{A_L}_{F_{\rm MIN}} > 1$, where

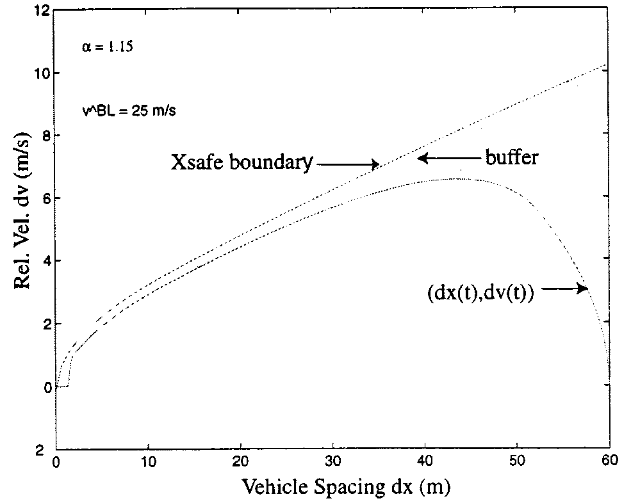

Fig. 4. Join maneuver phase plane response $(\Delta x^{A_L}, -\Delta v^{A_L})$ when $v^{B_F} = v^{\rm MAX}_{\rm LEAD}$. The boundary $X_{\rm safe}$ is used to design a feedback law that guarantees safety and efficiency.

$\alpha^{A_L}_{F_{\rm MIN}}$ is the minimum acceptable value for the leader deceleration ratio. Thus, the maximum deceleration that vehicle B_F may achieve during the join maneuver *must be smaller* than the one which vehicle A_L may achieve.

$\alpha^{A_L}_{F_{\rm MIN}}$ can be calculated as follows [2]:

$$\alpha^{A_L}_{F_{\rm MIN}} = \frac{a^{A_L}_{\rm MIN}(2\Delta x_S + \overline{a}^{A_L} d^{A_L})}{(a^{A_L}_{\rm MIN}(2\Delta x_S + \overline{a}^{A_L} d^{A_L}) - (\overline{a}^{A_L} - \Delta v_S)^2} > 1 \tag{10}$$

where $\overline{a}^{A_L} = (a^{A_L}_{\rm MIN} + a^{A_L}_{\rm MAX})\, d^{A_L}$ and $(\Delta x_S, \Delta v_S)$ must be chosen so that $\alpha^{A_L}_{F_{\rm MIN}} > 0$. The magnitude of $\alpha^{A_L}_{F_{\rm MIN}}$ depends greatly on the pure time delay d^{A_L}. For the performance parameters in Table 2, $\alpha^{A_L}_{F_{\rm MIN}} = 1.01$. However, $\alpha^{A_L}_{F_{\rm MIN}} = 1.08$ if $d^{A_L} = 150$ ms and $\alpha^{A_L}_{F_{\rm MIN}} = 2.34$ if $d^{A_L} = 500$ ms.

The task of the leader control law is to regulate the platoon's longitudinal velocity to a desired value, while maintaining a safe *leader law interplatoon spacing* from the preceding platoon. The desired velocity is part of the activity plan that the link layer transmits to the coordination layer.

Theorem 1 in [2] can also be used to derive a *leader law safety theorem* and corresponding leader feedback control law. See [28] and [2] for details.

3) Overall AHS Safety Results: By combining the results in Proposition 1 with the follower law safety results given by (3) and (4), it is possible to derive conditions for overall highway safety. Two *worst case scenarios* must be considered, depending on the range of the on-board radar and velocity sensors: 1) leader vehicle B_L *can* measure *at all times* the velocity of last vehicle follower C_F and vehicle C_F can decelerate at any moment with maximum deceleration $-A_{\rm MIN}$ and 2) leader vehicle B_L *cannot* measure the velocity of last vehicle follower C_F, which is not moving (i.e., $v^{C_F} = 0$). The results are summarized in the following proposition. Details are given in [2].

Proposition 2: Assume that the regulation layer controller of vehicle A_L in Fig. 2 is executing the join law and that of vehicle B_L is executing the *leader law* and that the set of AHS performance parameters μ_{MIN}, A_{MIN}, and A_{MAX}, as respectively defined in (5) and (1), a maximum overall braking delay of d_{MAX} for all vehicles in the AHS, a maximum leader law velocity $v_{\text{LEAD}}^{\text{MAX}}$ and a maximum longitudinal spacing and relative velocity sensor range $\Delta x_{\text{RANGE}}^{\text{MAX}}$ are specified. If the following condition is satisfied:

$$\alpha_{\text{MAX}}^{A_L} \geq \alpha^{A_L} \geq \alpha_{\text{MIN}}^{A_L} > 1 > \frac{1}{(\mu_{\text{MIN}})^2 \alpha^{A_L}} = \alpha^{B_L} \quad (11)$$

where $\alpha_{\text{MIN}}^{A_L}$ is given by (12), shown at the bottom of the page, where $\alpha_{\text{MAX}}^{A_L}$ is given by

$$\alpha_{\text{MAX}}^{A_L} = \frac{2A_{\text{MIN}}(\Delta x_{\text{RANGE}}^{\text{MAX}} - v_{\text{LEAD}}^{\text{MAX}}\, d_{\text{MAX}})}{\mu_{\text{MIN}}^2 (v_{\text{LEAD}}^{\text{MAX}})^2} \quad (13)$$

and $\overline{A}^{A_L} = (A_{\text{MIN}} + \mu_{\text{MIN}} A_{\text{MAX}})\, d_{\text{MAX}}$, then the join maneuver depicted in Fig. 2 is safe in the sense that $\Delta x^P > 0$ for all $P \in \mathbf{V}$.

1) If vehicle B_L is measuring the velocity of vehicle C_F, the maximum interplatoon spacing that it will maintain is stated in (14), shown at the bottom of the page.
2) If vehicle B_L is not measuring the velocity of vehicle C_F, the maximum interplatoon spacing that it will maintain is

$$\Delta x_{\text{LEAD}}^{\text{MAX}} = \frac{\alpha^{A_L} \mu_{\text{MIN}}^2 (v_{\text{LEAD}}^{\text{MAX}} + \overline{A}^{B_L})^2 - (v_{\text{LEAD}}^{\text{MAX}})^2}{2A_{\text{MIN}}} \quad (15)$$

where $\overline{A}^{B_L} = ((1/\mu_{\text{MIN}}^2 \alpha^{A_L}) A_{\text{MIN}} + A_{\text{MAX}})\, d_{\text{MAX}}$.

Equation (15) is useful in determining the necessary range of the on-board longitudinal spacing and relative velocity sensor, since it specifies the maximum distance required by vehicle B_L to stop if it suddenly detects a stationary object in its path. Equation (13) is obtained from (15) by solving for α^{A_L}. The range of the longitudinal spacing and relative velocity sensors currently used by PATH is 90 m.

By using the results in Proposition 2, it is possible to calculate performance parameters that will yield a provably safe on-board vehicle control system. These values can also be used to perform AHS capacity studies. Table 2 shows the results of these calculations using nominal values for the performance of the equipment that is currently in use or will be used by PATH [18], [14], [28].

For the nominal performance parameters in Table 2, the calculated maximum required interplatoon spacing $\Delta x_{\text{LEAD}}^{\text{MAX}}$ is 30 m. This value is half the size of the value previously used to estimate attainable highway capacity increases from platooning [42]. These results therefore validate, from the safety point of view, the capacity estimates and the viability of the vehicle on-board control architecture design presented in [42]. A comprehensive capacity and safety study of AHS is found in [7], which includes both fully automated and mixed traffic systems. The on-board control system described in [14] and [28] has been experimentally tested [10] and fully simulated and tested on SmartPATH, a comprehensive AHS simulation software package [13]. In this paper, we have not discussed lateral control laws nor the effect that lane changes have on traffic capacity. The determination of a safe intervehicle longitudinal spacing, necessary for performing lane changes, can be carried out as an extension of the results presented in this paper, if vehicle lateral dynamics are neglected [2], [14]. Other approaches to the determination of safe intervehicle spacing that consider lateral control and vehicle movement across lanes can be found in [27].

IV. Roadside Control System

The roadside control system's primary objective is to optimize the capacity and traffic flow of the overall AHS. The models used in the link layer involve aggregated vehicle densities and traffic flows but not individual vehicles. Thus, vehicle safety, as defined in Section III, cannot be monitored, much less enforced. The roadside control system can control the network and link layers in ways that *tend* to increase vehicle safety, such as maintaining sufficiently low aggregated vehicle densities and decreasing the inlet traffic flow into links where aggregated traffic density is very large.

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, join, 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 (i.e., spatial density functions), and the notion of the individual vehicle is lost. The flow of a vehicle type, at a given location of the link, is the product of the density function with the corresponding activity vector field at that location. Changes in the link-layer controllers should in turn be modeled at the network layer, which is not discussed here.

The link-layer functions can be divided into two tasks. The first consists in the determination of a *desired* time-

$$\alpha_{\text{MIN}}^{A_L} = \frac{A_{\text{MIN}}(2\mu_{\text{MIN}}\Delta x_S + \overline{A}^{A_L} d_{\text{MAX}})}{A_{\text{MIN}}(2\mu_{\text{MIN}}\Delta x_S + \overline{A}^{A_L}\, d_{\text{MAX}}) - (\overline{A}^{A_L}\, d_{\text{MAX}} - \mu_{\text{MIN}}\Delta v_S)^2} \quad (12)$$

$$\Delta x_{\text{LEAD}}^{\text{MAX}} = \frac{\alpha^{A_L} \mu_{\text{MIN}}^2 (v_{\text{LEAD}}^{\text{MAX}} + \overline{A}^{B_L})^2 - (v_{\text{LEAD}}^{\text{MAX}})^2 A_{\text{MIN}} \overline{A}^{B_L}\, d_{\text{MAX}}}{2A_{\text{MIN}}} \quad (14)$$

varying density profile and a corresponding activity vector field, which together form the *desired flow field* of the link. This desired flow field must satisfy the topological and density capacity constraints of the current state of the infrastructure (e.g., which lanes are closed and in what sections), the exit flow-rate constraints (e.g., cars that must exit at a particular exit ramp, should be traveling, either as free agents or as part of an exiting platoon, on the lane adjacent to that ramp). It should also ideally optimize highway capacity and vehicle travel time, for a given set of entrance flowrate demands, and desired outlet flow-rate split levels. This task requires *global* state information (the density profile) of the entire link.

The second task consists in the determination of the *actual* activity vector field that is broadcast to the coordination layer on-board vehicle controllers, using local feedback information. The overall link-layer control block diagram is depicted in Fig. 5.

We illustrate the controller design methodology with an example; the reader is referred to [29] and [4] for more general formulations. Consider a one-lane automated highway parameterized by $x \in [0, L]$ and time t, schematically shown in Fig. 6. Two types of vehicles are traveling on this link: leaders and followers. Thus, the aggregated vehicle density is K: $[0, L] \times \Re_+ \rightarrow \Re_+^2$, with $K = (K_L, K_F)$, where $K_L(x, t)$ and $K_F(x, t)$ are, respectively, the leader and follower densities at location x and time t. Based on conservation of vehicles, the density profile evolves according to

$$\frac{\partial}{\partial t} K(x, t) = -\frac{\partial}{\partial x} \{V(x, t)K(x, t)\} + N(x, t)K(x, t) \tag{16}$$

where $V(x, t) \in \Re_+$ is the average vehicle velocity in location x, at time t, $\Phi(x, t) = V(x, t)\ K(x, t)$ is the flow field and

$$N(x, t) = \begin{bmatrix} -n^{FL} & n^{LF} \\ n^{FL} & -n^{LF} \end{bmatrix}, \qquad \begin{matrix} n^{LF} \geq 0, n^{FL} \geq 0 \\ n^{LF} n^{FL} = 0 \end{matrix} \tag{17}$$

where, e.g., n^{LF} is a flow proportion of follower vehicles that are becoming leader vehicles and the conditions in (17) are necessary to maintain conservation of total number of vehicles. Thus, $K(x, t)$ and the pair $[V(x, t), N(x, t)]$, respectively, are the density profile and activity field for the link at time t.

Fig. 6 also shows the inlet and outlet flows: $\Phi(0, t) = V(0, t)K(0, t)$ and $\Phi(L, t) = V(L, t)K(L, t)$. As discussed in Section II, $\Phi(0, t)$ can be the outlet flow of a preceding link or an AHS entrance flow, while $\Phi(L, t)$ can be the flow entering another link or exiting the AHS. In this example, however, we eliminate the effect of inlet and outlet conditions, by specifying the link to be a "loop," so that $\Phi(L, t) = \Phi(0, t)$.

A. Determination of the Desired Flow Field

One way to determine a desired flow field that optimizes traffic flow on the link is to use the results in [6]. The key idea consists in casting the desired flow field determination

Table 2
Nominal and Calculated Performance Parameters

Nom. Param.	μ_{MIN} m/s	A_{MIN} m/s^2	A_{MAX} m/s^2	d_{MAX} s	
	1.12	5	2.5	0.03	

Nom. Param.	v_{LEAD}^{MAX} m/s	Δx_{RANGE}^{MAX} m	Δx_{FOLLOW} m	Δx_S m	Δv_S m/s
	25	90	1	1.5	0

Calc. Param.	$\alpha_{F_{MIN}}^{A_L}$	$\alpha_{R_{MIN}}^{A_L}$	α^{A_L}	α^{B_L}	$a_{MIN}^{A_L}$ m/s^2	Δx_{LEAD}^{MAX} m
	1.01	1.13	1.15	0.7	4.46	30

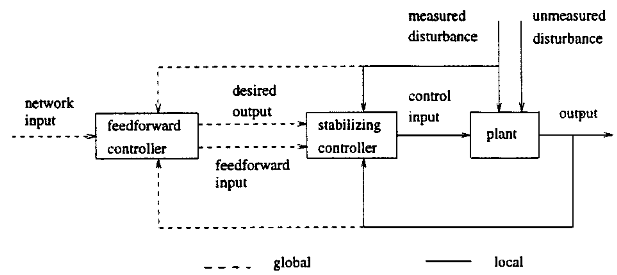

Fig. 5. The link-layer controller determines the desired density profiles over the link as well as the actual activity vector field broadcast to the individual vehicles.

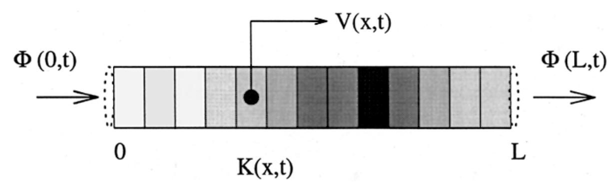

Fig. 6. One-lane mass conservation model of a link.

as a constrained optimization problem. Reference [6] considers one-lane highway links and shows, for a certain class of problems, that there is a stationary optimal flow $\hat{\Phi}^o(x) = v_{\text{LEAD}}^{\text{MAX}}\hat{K}^o(x)$, which optimizes the vehicle travel time across the link, where $v_{\text{LEAD}}^{\text{MAX}}$ is the maximum allowable leader law cruising velocity. Moreover, this optimal stationary flow field can be determined by solving a linear programming problem. For the simple system given by (16), the optimal $\hat{K}^o(x)$, which optimizes travel time and capacity, is a constant density profile given by the maximum allowable number of vehicles in a platoon.

B. Flow Stabilization Via Decentralized Feedback Control

Consider now the case when a desired flow density and activity field profile $\hat{K}(x, t)$ and a *stationary* desired activity field $[\hat{V}(x), \hat{N}(x)]$, satisfying the boundary conditions (presumably set by the network layer), have been determined. The problem then is to design decentralized feedback laws, that stabilize the actual flow field at the desired flow field.

As an example, consider a situation where it is desirable to create sufficiently large low occupancy areas, at particular instances and locations, in order to accommodate incoming traffic to the highway, as schematically depicted in Fig. 7.

Notice that the desired density profile $\hat{K}(x, t)$ depicted in Fig. 7 is not time-invariant, since the low-density occupancy

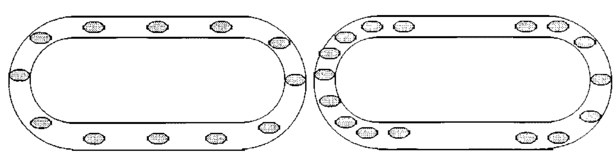

Fig. 7. Initial and desired link states.

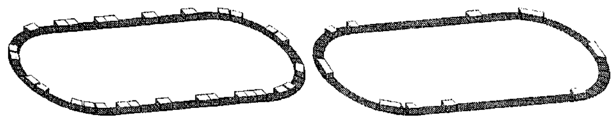

Fig. 8. Initial and desired link state achieved by the link, coordination, and regulation layers together.

regions are moving with the traffic flow. However, the desired activity field is. In fact, $\hat{V}(x) = v_{\mathrm{LEAD}}$ and $\hat{N}(x) = \mathbf{0}$.

We now describe the closed-loop decentralized feedback law developed by [29] and [4] that stabilizes the *actual* link density profile at the desired profile. We first define the density error profile as

$$\tilde{K}(x, t) = \hat{K}(x, t) - K(x, t) \tag{18}$$

and the error flow field

$$H(x, t) = \hat{V}(x)A(x)A^T(x)\tilde{K}(x, t) \tag{19}$$

where $A(x)$ is the nonsingular solution of the ODE

$$\frac{\partial A(x)}{\partial x}\, \hat{V}(x) + A(x)\hat{N}(x) = 0, \qquad A(0) = I \tag{20}$$

which is a function only of the *desired* activity field and can be computed *off-line.* Notice that the coordinate transformation matrix A is independent of x in the highway sections where $\hat{N}(x) = 0$. This is the case in the example shown in Fig. 7, where $A(x) = I$ through the highway. The activity field is given by

$$V(x, t) = \hat{V}(x) + V_f(x, t) \tag{21}$$
$$N(x, t) = \hat{N}(x) + N_f(x, t). \tag{22}$$

where $[\hat{V}(x), \hat{N}(x)]$ is the desired activity field. $V_f(x, t)$ and $N_f(x, t)$ are generated by decentralized feedback laws

$$V_f(x, t) = \zeta_v(x, t)K^T(x, t)\,\frac{\partial}{\partial x}\,\tilde{H}(x, t) \tag{23}$$

where $\zeta_v(x, t) \geq 0$ is chosen so that $V(x, t) \geq 0$. The elements of $N_f(x, t)$ are chosen such that

$$K^T N_f(x, t)H(x, t) \geq 0 \tag{24}$$

and (17) is satisfied. More general stabilizing control laws and proofs that the control laws given by (21)–(24) are stabilizing are found in [29] and [4].

Fig. 8 shows the results of a simulation study conducted using the SmartPATH AHS simulation software [13]. The highway link is an oval of approximately 5 km with about 100 vehicles traveling at a nominal speed of 25 m/s. Each vehicle in the simulation is under an on-board hybrid control system, as described in Section III. The "blocks" in Fig. 8 represent platoons and the size of the block is not strictly proportional to the size of the platoon. The left panel shows the initial state of the link, while the right panel shows the state of the link after $t = 120$ s. The hierarchical control system formed by the link, coordination, and regulation layers was effective in regulating the AHS to a prescribed desired density profile, while maintaining safety requirements.

V. Conclusion

This paper described the AHS control architecture developed at PATH, including some of the considerations that motivated the architecture, and some control synthesis and analysis techniques for the detailed design of the individual layers. We presented safety and performance results of the hybrid system formed by the coordination and regulation layers and discussed the control of the hierarchical system formed by the link, coordination, and regulation layers.

A key feature of the architecture is the separation of the various control functions into distinct layers with well-defined interfaces. Each layer is then designed with its own model that is suited to the functions for which it is responsible. The models at the various layers are different not only in terms of their formal structure (ranging from differential equations to state machines to static graphs) but also in the entities that have a role in them.

The AHS is a complex large-scale control system whose design required advances in sensor, actuator, and communication technologies (not discussed here) and in techniques of control system synthesis and analysis. It is a measure of the advanced state-of-the-art that these techniques have reached a stage that they could be successfully used in the AHS project.

There is a fairly large literature on AHS control, only some aspects of which are covered here. Missing are discussions of the physical layer (vehicle, actuator, and sensor models), follower and leader laws at the regulation layer, and studies at the link layer of the impact of lane changes on AHS throughput.

The NAHSC was formed to develop over a six-year period a design for an automated highway system that achieved much greater capacity and safety, taking into account alternative automation concepts and technologies. Over time, federal sponsors added another goal: to develop scenarios for AHS deployment and to build support for these scenarios among stakeholders, including local government, vehicle and insurance industries, environmentalists, etc. The first goal was an engineering challenge toward which the consortium made considerable progress in two years, as the August 1997 demonstration proved.

The second goal proved elusive. Full automation on dedicated lanes seemed then (and now) to be the only design that secures high capacity with safety. Implementing this design requires a large investment in urban highway infrastructure, which can be justified only with widespread ownership of automated vehicles. But such ownership is likely only if the complementary highway infrastructure is in place. Deployment scenarios seemed to founder on this "chicken and egg" problem. Nevertheless, the NAHSC conducted case studies, notably for Houston, that suggest that past growth in traffic is unsustainable in the future without AHS investment.

The NAHSC was dissolved in 1998. The U.S. Department of Transportation launched the Intelligent Vehicle Initiative, whose goal is the design of "intelligent" vehicles that improve safety, without capacity increases. The goal of increased capacity through automation has meanwhile been embraced by projects in Europe and Japan. The California Department of Transportation, with its counterparts from other states, has kept alive the goal of full automation, under the conviction that a large increase in capacity is the only way of meeting large increases in traffic. A demonstration of automation technologies for heavy trucks and buses is planned for 2002.

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REFERENCES

[1] L. Alvarez, "Automated highway systems: Safe platooning and traffic flow control," Ph.D. dissertation, Univ. California, Berkeley, 1996.

[2] L. Alvarez and R. Horowitz, "Safe platooning in automated highway systems, Part I: Safety regions design," *IVHS*, vol. 32, pp. 23–56, July 1999. (Vehicle System Dynamics Special Issue).

[3] ——, "Safe platooning in automated highway systems, Part II: Velocity tracking controller," *IVHS*, vol. 32, pp. 57–84, July 1999. (Vehicle System Dynamics Special Issue).

[4] L. Alvarez, R. Horowitz, and P. Li, "Traffic flow control in automated highways systems," *IFAC J. Eng. Practice*, vol. 7, pp. 1071–1078, 1999.

[5] M. Barth and J. M. Norbeck, "Transportation modeling for the environment: Final report," Inst. Transportation Studies, Univ. California, Berkeley, PATH Res. Rep. UCB-ITS-PRR-96-6, 1996.

[6] M. Broucke and P. Varaiya, "A theory of traffic flow in automated highway system," *Transport. Res. C*, vol. 4, no. 4, pp. 181–210, 1996.

[7] J. Carbaugh, D. N. Godbole, and R. Sengupta, "Safety and capacity analysis of automated and manual highway systems," *Transport. Res. C*, pp. 69–99, 1998.

[8] R. K. Douglas, W. H. Chung, D. P. Malladi, R. H. Chen, J. L. Speyer, and D. L. Mingori, "Fault detection and identification with application to advanced vehicle control systems," Inst. Transportation Studies, Univ. California, Berkeley, PATH Tech. Rep. UCB-ITS-PRR-97-51, 1997.

[9] ——, "Integration of fault detection and identification into a fault tolerant automated highway system," Inst. Transportation Studies, Univ. California, Berkeley, PATH Tech. Rep. UCB-ITS-PRR-97-52, 1997.

[10] T. Connolly and K. Hedrick, "Longitudinal transition maneuvers in an automated highway system," in *Proc. ASME IMECE Conf.*, Atlanta, GA, 1996.

[11] A. Deshpande, A. Gollu, and L. Semenzato, "The SHIFT programming language and run-time system for dynamic networks of hybrid systems," *IEEE Trans. Automat. Contr.*, vol. 43, pp. 584–587, 1998.

[12] F. Eskafi, "Modeling and simulation of the automated highway systems," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Univ. California, Berkeley, 1996.

[13] F. Eskafi, D. Khorramabadi, and P. Varaiya, "SmartPath: An automated highway system simulator," Inst. Transportation Studies, Univ. California, Berkeley, PATH Tech. Memo. 92-3, 1992.

[14] J. Frankel, L. Alvarez, R. Horowitz, and P. Li, "Safety oriented maneuvers for IVHS," *J. Vehicle Syst. Dyn.*, vol. 26, no. 4, pp. 271–299, 1996.

[15] J. C. Gerdes and J. K. Hedrick, "Brake system requirements for platooning on an automated highway," in *Proc. 1995 Amer. Control Conf.*, 1995, pp. 165–169.

[16] D. Godbole, F. Eskafi, E. Singh, and P. Varaiya, "Design of entry and exit maneuvers for IVHS," in *Proc. ACC*, 1995.

[17] D. Godbole, J. Lygeros, E. Singh, A. Deshpande, and A. E. Lindsey, "Design and verification of communication protocols for degraded modes of operation of ahs," in *34th IEEE Conf. Decision and Control*, New Orleans, LA, Dec. 1995, pp. 427–432.

[18] D. N. Godbole and J. Lygeros, "Longitudinal control of the lead car of a platoon," *IEEE Trans. Veh. Technol.*, vol. 43, no. 4, pp. 1125–1135, 1994.

[19] D. N. Godbole, J. Lygeros, and S. Sastry, "Hierarchical hybrid control: A case study," in *Hybrid Systems II*, P. Antsaklis, W. Kohn, A. Nerode, and S. Sastry, Eds. Ithaca, NY: Springer-Verlag, 1995, pp. 166–190.

[20] A. Gollu and P. Varaiya, "Hybrid dynamical systems," in *Proc. 28th Conf. Decision and Control*, Tampa, FL, Dec. 1989, pp. 2708–2712.

[21] Z. Har'El and R. P. Kurshan, *Cospan User's Guide*: AT&T Bell Laboratories, 1987.

[22] J. K. Hedrick and D. Swaroop, "Dynamic coupling in vehicles under automatic control," in *Proc. 12th IAVSD Symp.*, Chengdu, China, Aug. 1993.

[23] J. K. Hedrick, M. Tomizuka, and P. Varaiya, "Control issues in automated highway systems," *IEEE Contr. Syst. Mag.*, pp. 21–32, Dec. 1994.

[24] P. Hingwe and M. Tomizuka, "Experimental evaluation of a chatter free sliding mode control for lateral control in AHS," in *Proc. Amer. Control Conf.*, 1997.

[25] A. Hsu, F. Eskafi, S. Sachs, and P. Varaiya, "Protocol design for an automated highway system," *Discrete Event Dyn. Syst.*, vol. 2, pp. 183–206, 1993.

[26] P. Ioannou and C. C. Chien, "Autonomous intelligent cruise control," *IEEE Trans. Veh. Technol.*, vol. 42, pp. 657–672, Nov. 1993.

[27] A. Kanaris, P. Ioannou, and F. S. Ho, "Spacing and capacity evaluations for different AHS concepts," in *Automated Highway Systems*, P. Ioannou, Ed. New York: Plenum, 1997.

[28] P. Li, L. Alvarez, and R. Horowitz, "AVHS safe control laws for platoon leaders," *IEEE Trans. Contr. Syst. Technol.*, vol. 5, pp. 614–628, Nov. 1997.

[29] P. Li, R. Horowitz, L. Alvarez, J. Frankel, and A. Roberston, "An AHS link layer controller for traffic flow stabilization," *Transport. Res. C*, vol. 5, no. 1, pp. 11–37, 1997.

[30] J. Lygeros, "Hierarchical and hybrid issues in the control of large scale systems," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Univ. California, Berkeley, 1996.

[31] J. Lygeros, D. Godbole, and M. Broucke, "Design of an extended architecture for degraded modes of operation of IVHS," in *Proc. Amer. Control Conf.*, 1995, pp. 3592–3596.

[32] ——, "Toward a fault tolerant AHS design," presented at the SAE Future Transportation Technology Conf., Costa Mesa, CA, 1995.

[33] J. Lygeros, D. Godbole, and S. Sastry, "A verified hybrid control design for automated vehicles," in *Proc. CDC*, 1996.

[34] M. Papageorgiou, "Dynamic modeling, assignment and route guidance in traffic networks," *Transport. Res. B*, vol. 24B, no. 6, pp. 471–495, 1990.

[35] H. A. Pham, J. K. Hedrick, and M. Tomizuka, "Combined lateral and longitudinal control of vehicles for AHS," in *Proc. Amer. Control Conf.*, June 1994.

[36] R. Rajamani, A. Howell, C. Chen, and J. K. Hedrick, "A complete fault diagnostic system for the longitudinal control of automated vehicles," in *Proc. ASME Winter Conf.*, Dallas, TX, Nov. 1997.

[37] S. Sachs, "Formal verification of discrete event and hybrid systems," Ph.D. dissertation, Dept. Elect. Eng. Comput. Sci., Univ. California, Berkeley, 1995.

[38] S. Sheikholeslam and C. A. Desoer, "Longitudinal control of a platoon of vehicles," in *Proc. 1990 Amer. Control Conf.*, vol. 1, San Diego, CA, June 1990, pp. 291–296.

[39] S. Shladover *et al.*, "Automatic vehicle control developments in the PATH program," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 114–130, Feb. 1991.

[40] D. Swaroop, "String stability of interconnected systems: An application to platooning in automated highway systems," Ph.D. dissertation, Dept. Mech. Eng., Univ. California, Berkeley, 1994.
[41] D. Swaroop, C. C. Chien, J. K. Hedrick, and P. Ioannou, "Comparison of spacing and headway control laws for automatically controlled vehicles," *Veh. Syst. Dyn.*, vol. 23, 1994.
[42] P. Varaiya, "Smart cars on smart roads: Problems of control," *IEEE Trans. Automat. Contr.*, vol. 38, no. 2, pp. 195–207, 1993.
[43] P. Varaiya and S. E. Shladover, "Sketch of an IVHS systems architecture," Inst. Transportation Studies, Univ. California, Berkeley, Tech. Rep. UCB-ITS-PRR-91-3, 1991.
[44] J. Yi, L. Alvarez, A. Howell, and R. Horowitz, "A fault management system for longitudinal control in AHS," in Proc. Amer. Control Conf., June 2000, to be published.
[45] M. A. Zabat, N. S. Stabile, and F. K. Browand, "Estimates of fuel savings from platooning," in *Proc. ITS America Annu. Meetings*, 1995, pp. 1203–1208.

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