Aspects of IVHS Architecture Design

Pravin Varaiya
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley CA 94720

17 September 1991

This paper is prepareddfor discussion at the IVES System Architecture Workshop, University of Michigan. Ann Arbor, October 24-25, 1991. I am grateful to Steve Shladover, Tony Hitchcock, and other participants of the PATE seminar on AVCS for discussions; however, they do not necessarily endorse all the views expressed here.

Abstract

IVHS systems influence four kinds of decisions that drivers make during their trip. The corresponding tasks that IVHS systems carry out are route and flow control, congestion control, vehicle coordination, and spacing. A comparison of two scenarios shows how IVHS influence over vehicle behavior can range from *minor* (under a strategy limited to providing information and advice) to major (under full automation which preempts driver control). The four IVHS tasks have three differentiating features: time scale or the time available to carry out the task; spatial scope or the impact of executing the task on the traffic system; and information span or the extent of information needed to carry out the task.

An IVHS architecture organized in a hierarchy of four layers - network, link, coordination. and regulation - is proposed. This hierarchy resolves in a natural way the three differentiating features. The architecture can accommodate a wide range of automation strategies from the simplest, which limits itself to providing driver information. to the most complex. which achieves total control of the vehicle. The architecture permits the incorporation of new functional capabilities over time, and encourages a decentralized implementation of IVHS tasks.

An open architecture specification is urged as a means to promote rapid development of IVHS and to ensure the interworking of independent, subsystem implementations. It is also suggested that IVHS standards should be specified in a formal-mathematical language to simplify later problems of design validation and conformance testing of products.

1 Introduction

Engineers face daunting challenges as they attempt to meet a growing demand for travel at a time when the traditional response of building more roads is less acceptable because it is too costly or too damaging to the environment.

There is a growing consensus that an appropriate combination of intelligent vehicles and intelligent highways may assist drivers in ways that lead to greater capacity and safety without building new roads. However, there is a wide diversity of opinion about the form of this ‘intelligence’. This diversity has several dimensions including:

- Function – the range and extent of transportation and driving functions that should be automated;
- Architecture – the functional decomposition of IVHS systems, the assignment of tasks to various subsystems, the information flows between subsystems, and their interfaces;
- Design – the appropriate forms, including the division of intelligence between vehicle and highway, in which control, computing and communication technologies should be combined to realize this architecture;
- Evolution - the timing of system development, the extent to which earlier architectures should be capable of accommodating new functions;
- Evaluation – the effectiveness, costs and benefits of different NHS proposals.

§2 presents a framework for describing IVHS functions, their relation to key decisions that drivers make, and the degree of influence that IVHS can have on those decisions. This framework provides a quick comparison of different IVHS proposals.

§3 proposes one IVHS architecture. The architecture arranges subsystems tasks in a hierarchy that corresponds to the functions introduced in §2. The architecture supports

- Uniformity – it accommodates a wide range of IVHS automation capabilities;
- Evolution – it permits the incorporation of new functions;
- Decentralization – it encourages an implementation in which the tasks are carried out in a decentralized manner; consequently most of the intelligence is in the vehicle.

§4 urges the specification of an open architecture, i.e. the formulation of standards in the form of reference models for each layer of the architecture hierarchy. It also urges the consideration of formal-mathematical methods for standards specification, design validation and conformance testing.

§5 argues that significant safety and capacity gains from IVHS will only be achieved by much larger degree of automatic vehicle control (AVC) than most proponents of IVHS are at present willing to contemplate. We recommend, therefore, that IVHS architectures be designed with the explicit requirement that they be able to accommodate AVC functions.

2 IVHS functions

Table 1 lists a sequence of six decisions made by an automobile driver in the course of **a** trip.[1] The decisions are divided into three phases - pretrip, in-trip, and post-trip. IVHS systems seek to improve these decisions and NHS subsystems must carry out corresponding tasks. Generally speaking, driver decisions may be influenced by four strategies of intervention - providing information, offering advice, taking direct control of the decision, and changing incentives by pricing, eg. tolls.

Phase	Driver decision	IVHS goal	IVHS task	Strategy
Pre-trip	Trip generation, modal choice, etc	More efficient resource utilization	Demand shift	I, P
In-trip	Route choice	Reduce travel time	Route guidance and flow control	I,A,C
	Path planning	Smooth traffic	Congestion control	I,A,C
	Maneuver	Increase safety, flow	Vehicle coordination	I,C
	Following	Increase safety, flow	Proper spacing	I,C
Post-trip	Parking, etc	Add value	Efficient use	I, P

A = Advice, C = Control, I = Information, P = Pricing

Table-l: Driver decisions and IVHS functions

Henceforth we restrict attention to the four in-trip decisions. Note that as the strategy adopted to influence driver decisions shifts from giving information to offering advice to exerting preemptive control, the decisions become more automatic and predictable. and the burden on system 'intelligence' increases.

A better appreciation of this shift of responsibility from the driver to the IVHS system is gained by comparing a scenario of a highly automated IVHS system with that of a system which eschews direct control.

A highly automated IVHS scenario

Vehicles enter and leave the automated network of interconnected highways at various gates and travel through the network under system control. Upon admission, the driver announces the vehicle's ultimate destination. (The system may delay admission for purposes of flow control.) The system responds to the driver's request by assigning a nominal route through the network. This is a sequence like

$$R = (H_1, s_1, f_1), (H_2, s_2, f_2), \ldots$$

The interpretation is that the route is a sequence of segments. The first segment on highway H_1 starts at gate s_1 and ends at gate f_1 which connects to gate s_2 on highway H_2 and so on, as illustrated in Figure 1.

[1]This applies to a typical commute trip. Somewhat different decisions may be involved in vacation trips. trips by drivers of commercial vehicles, etc.

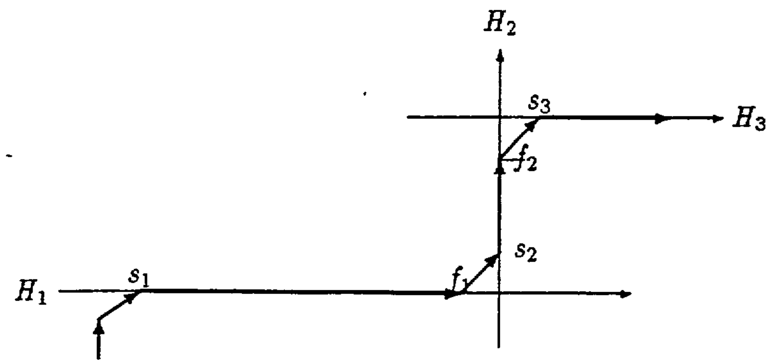

Figure 1: A route is a sequence of segments

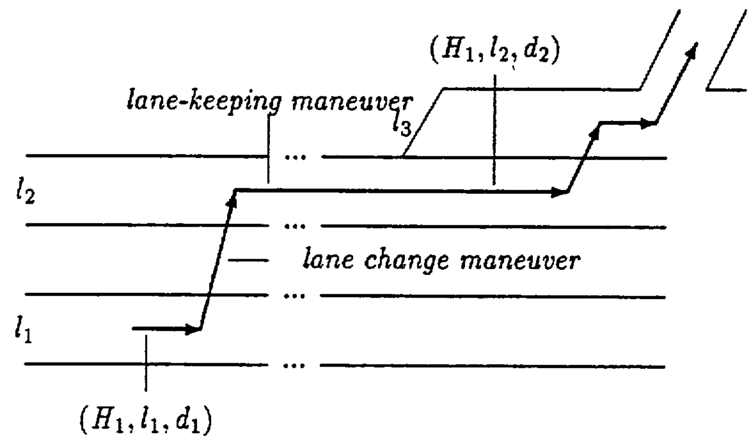

Figure 2: A path within a segment

We assume that the vehicle continuously senses the section of the highway on which it is traveling. A section is denoted by a triple (H, l, d) where H is the highway name, l is the lane number and d is the lane section number. A section is about 500 m long. It is used for congestion control as discussed below.

Suppose our vehicle enters H_1 through gate s_1 at section (H_1, l_1, d_1) and declares that it must exit at gate f_1. The system assigns a path (l_2, d_2, l_3). The interpretation is that the vehicle must change to lane l_2, travel along it until section d_2, and then change to lane l_3 from which it must exit at gate f_1. See Figure 2. As the vehicle travels along this segment the system announces target speeds $v(H, l, d)$ for each section of this segment. The vehicle must execute an actual trajectory that conforms to the assigned path at the announced target speeds.

The vehicle's trajectory can be decomposed into a sequence of lane-change and lane-keeping maneuvers. Before it engages in a lane-change maneuver, the vehicle's control system exchanges messages with those of neighboring vehicles to ensure there is space in the adjacent lane, that this space will be kept available until the lane-change maneuver is complete, or, if such space is not available, the neighboring vehicles will accelerate or decelerate to create such space. (The sequence of message exchanges is called a protocol.) Once agreement with its neighbors has been reached, the automatic vehicle control system (AVCS) executes the lane-change. In a lane-keeping maneuver, the AVCS system seeks to maintain the target speed $v(H, l, d)$ as it follows the vehicle in front of it at a safe distance. [2]

Comparison of partial and full automation

Table 2 compares the implementation strategies for the four tasks in the fully automated IVHS system with the strategies that might be adopted in a partially automated system. The fully automated system exercises a degree of control which effectively preempts driver actions, whereas the partially automated system seeks only to influence those actions by giving information and advice.

Task	Fully automated IVHS	Partial automated IVHS
Route guidance, Flow control	Assign route, Admission control	Provide travel time information; ramp-metering
Congestion control	Assign path, section target speeds	Indicate incidents, advisory speeds
Vehicle coordination	Automated protocols	Legal **rules** and social protocols
Spacing control	Automatic vehicle control	Collision warning

Table 2: Implementation strategy in full vs partial automated systems

The fully automated system assigns the route that the vehicle must follow; the partially automated system predicts travel times which the driver may take into account in route selection. Both systems may control admission.

The fully automated system seeks to avoid the propagation of congestion by assigning the target speed in each section. The partially automated system attempts to achieve this effect by posting advisory speeds or information about incidents. In this case, both systems provide the same advice; the fully automated system guarantees that vehicles will conform to the advice, in the other system drivers may ignore this advice.[3]

The safe execution of a lane change maneuver. requires the coordinated movement of neighboring vehicles. Partially automated IVHS may offer no assistance to drivers who must assume, as they do at present, that the neighboring drivers follow legal rules and social

[2]In [1]. during a lane-keeping maneuver, the vehicle must also try to stay in a platoon. The platoon size is announced by the system. Simple models suggest that organizing traffic in platoons offers a large increase in capacity [2. 3. 4].

[3]The effectiveness of congestion control under full automation is discussed in [2], while [5] discusses the effectiveness under partial information. Using a simulation model of the Santa Monica (SMART) corridor in LA, [6] concludes that savings ‘under recurring congestion conditions were found to be insignificant and in the order of **10** min for a **40** min trip under induced incident congestion.”

conventions. Fully automated systems achieve guaranteed coordination through formal protocols.[4]

Finally. in a lane keeping maneuver, partial automation may improve safety by alerting the driver to the threat of a collision; fully automated systems minimize collisions by automatic reaction to information about the relative speed and distance between adjacent vehicles.[5]

It is important to note that the two scenarios compared above span a large range of alternative strategies. For instance, in addition to travel time information, the IVHS system may offer static or dynamic route guidance.[6] Similarly, greater safety may be achieved by adding collision avoidance control which overrides driver actions under specified conditions.

Generally speaking in moving towards greater intelligence, one trades off increased complexity of the IVHS system for greater predictability and control of vehicle behavior which can be used to achieve increased safety and capacity.

3 IVHS architecture

In §2 we identified a set of four 'in-trip' decisions that drivers must carry out assisted by the IVHS system. In this section we examine the corresponding IVHS tasks in greater detail. Three features have a crucial impact on the design of IVHS subsystems which will implement those tasks. They are:

- Time scale - the time available to carry out the task;
- Spatial scope - the impact of executing the task on the traffic system;
- Information span - the extent of information needed to carry out the task.

Table 3 shows that the four tasks differ significantly in terms of these features.

4 Such protocols have been designed and proved to be correct under specified conditions, see [7, 8]. For work based on 'artificial intelligence' see [9, 10, 11].

5 Much research has been carried out on automatic longitudinal and lateral control [12, 13, 14, 15]. A representative Japanese work is [16]. European researchers use the term 'cooperative driving' for what we call 'vehicle coordination'. For examples of their work see [17, 18].

6 There is a large body of work on this exemplified by [19, 20. 21].

Task	Time scale	Spatial scope	Information span
Route and flow control	Hour - under large shift in demand or highway conditions	Changes in routes and flows affect entire network	Systemwide data on demand, highway conditions, flows
Congestion. control	Minute - target speeds updated after incidents and disturbances,	Changes in target speed affect traffic over few kms.	Data on incidents, disturbances over few kms.
Vehicle coordination	Minute - when vehicle does lane change	Affects neighboring vehicles	Predictions about neighboring vehicles, target section speeds
Spacing	Second - based on vehicle time constant	Direct effect limited to single vehicle	Data on neighboring vehicle speed, position

Table 3: Features differentiating four IVHS tasks

Observe that the tasks must be executed more rapidly, the spatial scope reduces, and the information span is more localized as we proceed from the first task to the fourth. This systematic variation in the features suggests a distribution of these tasks in the four layer hierarchy of Figure 3.

Starting at the top the layers are named: network, link, coordination, and regulation. Their functions correspond in order to the four tasks in Table 3, namely: route and flow control. congestion control, vehicle coordination, and spacing. The function of the physical layer is to provide relevant vehicle sensor data and to accept actuator (steering, throttle, braking) commands.

It seems natural, as the figure suggests, to distribute the tasks in each layer among several identical controllers. Then, there would be one controller per vehicle at layer 1 and 2, one controller per highway link (consisting of several km long section of highway) at layer 3, and one or a few controllers at the top layer 4.

If the tasks are distributed in this way the lines interconnecting the controllers in the figure represent communication links. Thus, the physical layer in a vehicle sends sensor data to its regulation layer and receives command signals from it. The regulation layer receives commands to execute lane change maneuvers from its coordination layer. The latter exchanges messages (protocols) with its peer controllers and receives target speeds from the link layer, and so on.

The hierarchy provides a uniform treatment of automation strategies since it leaves open the extent to which the tasks are automated. For example, the-commands received by the physical layer from its regulation layer may be automatic signals generated by the on-board vehicle control system or they may be generated by the driver. Similarly, the messages exchanged between adjacent (peer) coordination layers may be formal protocols or they may be informal messages that drivers exchange and interpret according to social convention.

The hierarchy can preserve an evolution of IVHS capabilities. That is, the extent to which each task is automated can vary over time depending on need and experience.

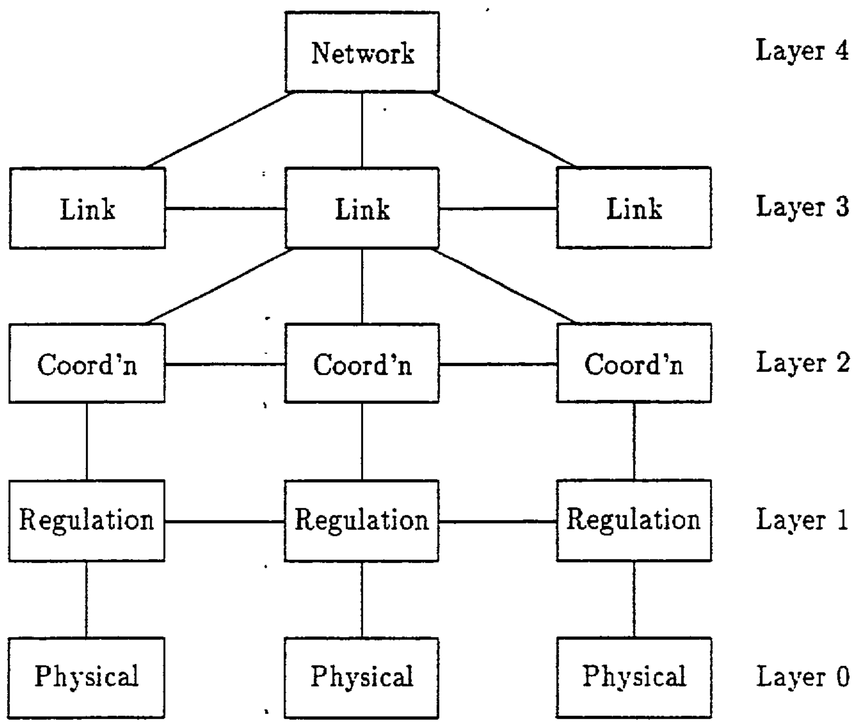

Figure 3: IVHS architecture

Finally, the proposed task distribution strongly encourages a decentralized implementation. For example, in principle, vehicle control signals may be generated in a centralized computer and communicated down through the hierarchy; but the more natural implementation is one where the control signal is generated by the regulation layer itself. A decentralized implementation would be more robust than a centralized one since the impact of failures would be spatially limited.

To achieve fully these advantages of uniformity, evolution, and decentralization it is necessary to go further and specify an open architecture.

4 Towards an open architecture

An IVHS architecture specifies

1. a functional decomposition of IVHS systems,
2. the assignment! of tasks to various subsystems, and
3. the information flows between subsystems.

The architecture is open if it provides

- a reference model for the external behavior of each subsystem, and
- subsystem interfaces to which information exchanges must conform.

Reference models only specify the external behavior. This permits different implementations to conform to the same reference model. Ideally, the reference models and interfaces are unambiguously spelled out and contain enough detail so that subsystems implemented in conformity with them can interwork. Perhaps the most important advantage of an open architecture is that the design and implementation of each subsystem need only consider the external behavior of other subsystems as defined by the reference models and interfaces. Thus an open architecture permits independent and parallel subsystem design. which reduces development time.[7] It also allows changes in one subsystem design to incorporate new technology without the need to change other subsystem designs.

Central to an IVHS open architecture specification, then, is the standardization of subsystem reference models and interfaces. Efforts to produce standards must steer between two conflicting requirements: sufficient and unambiguous detail must be given so that subsystems conforming to those standards can interwork smoothly, but the standards should not be so overspecified as to preclude conformance of innovative and more economical implementations.

‘The importance of this cannot be overestimated. The open architecture standards adopted in the data communications and personal computer fields has spurred innovations enormously.

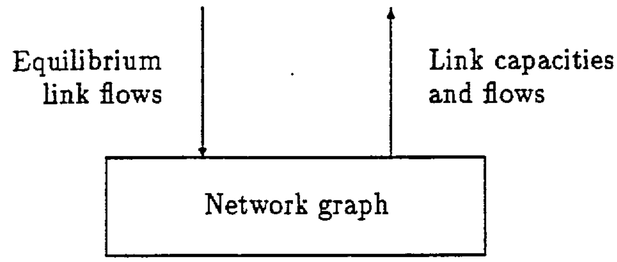

Figure 4: Link layer reference model

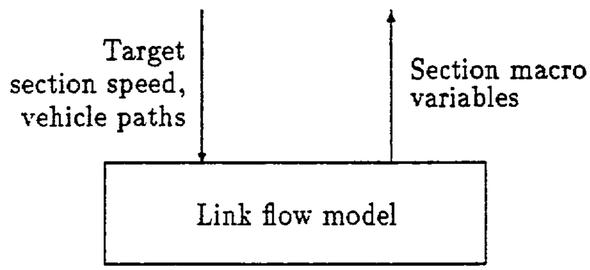

Figure 5: Coordination layer reference model

In the context of the architecture proposal summarized in Figure 3 there would be four layer reference models, one for each of layers 0,1,2 and 3, and three peer reference models at layers 1,2 and 3. We briefly discuss each set of reference models.

The *link layer reference model* provides an aggregate description of the flows in each link. It indicates to the network layer any significant changes in link capacities and flows. Thus this reference model can be formulated as a graph each of whose links is characterized by the current capacity and flows. (Such a reference model suggests that layer 5's route and flow control task can be formulated as a mathematical programming problem of network flow optimization.) See Figure 4.

The *coordination layer reference model* is a dynamic model describing the behavior of vehicles on a link.[8] The 'inputs' to the model are the section target speeds (set by the link layer); its 'outputs' are macroscopic variables of speed and density in different sections of the link. The congestion control policy of the link layer is based on this reference model. Examples of such models can be found in [2, 5]. See Figure 5.

[8]Recall that a link is several km long stretch of highway.

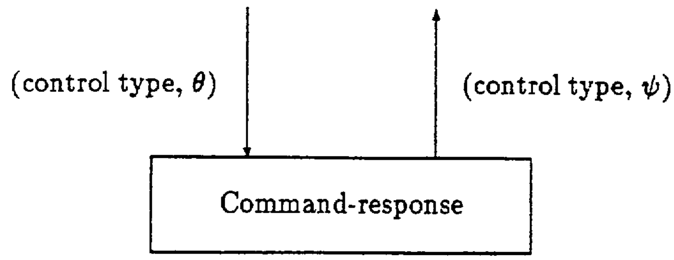

Figure 6: Regulation layer reference model

The *regulation layer reference model* is a 'command-response' model of the feedback controlled dynamics. The commands to execute various maneuvers are issued by the coordination layer. These commands can be encoded as parameters for each type of feedback control law. For example, there would be a command to change lane and a command to keep lane at a specified speed and headway. The parameterized response to each command would indicate how well the command was executed. Thus the regulation layer reference model takes the form:

$$(\text{control type}, \theta) \rightarrow (\text{control type}, \psi)$$

where 'control type' is 'change lane' or 'keep lane', and θ is the associated parameter vector.[9] See Figure 6.

Finally, the *physical layer reference model* is a model of the vehicle, actuator, and sensor dynamics. In the case of full automation this model might be given in terms of differential equations. In the case where the regulation layer task is implemented by a human driver, the model would be in terms that are intelligible and useful to the driver. See Figure 7.

These layer reference models define the relations between different layers in the hierarchy of Figure 3. In addition, that figure indicates interaction between peers at layers 1,2,3. Reference models for such peer interaction need to be specified. For example, the coordination layer peer reference model would specify how messages exchanged between neighboring vehicles should be interpreted in terms of their behavior. In [7], these models are in terms of state machines. In the case of partial automation, such models might specify the probable meaning of turn signals, brake lights, etc.

We end with several observations. A reference model for an architecture of the kind indicated by Figure 3 accommodates a variety of implementation strategies. That is its advantage. As details of implementation strategies get worked out, they will be reflected in standard reference models at different layers.[10] Consequently, as implementation strategies

[9] In the example above, θ would encode the the 'specified speed and headway'.

[10] This is similar to the situation in communications networks. The famous seven-layer OSI reference model applies widely, but there are different standards for different protocols which conform to the seven

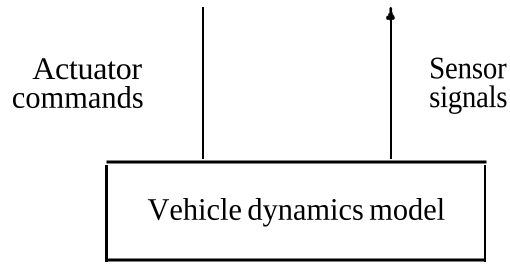

Figure 7: Physical layer reference model

evolve over time (presumably towards increased automation), the reference standards will change. One may insist that the new standards be ‘backward’ compatible. The reverse side of this coin is even more important in our view. Standards designed at an earlier point in time should be ‘forward’ compatible, that is they should accommodate the incorporation of new functions. This will be best achieved if the setting of standards is done not with a myopic view of IVHS prospects, but with a vision that incorporates the tremendous-advances in communication. control and computing technologies.

We offer one final remark about standards based on the lessons of the communication networks community. Standards are generally specified in a language that is a mixture of English (or some other natural language) and some formal language, (eg. state machines. pseudo-programming language). Built into such a semi-formal language is a wide latitude for interpretation. As a result, systems implemented by different organizations and conforming to the ‘same’ standard often are mutually incompatible. To minimize this incompatibility. the communication networks community is moving towards the adoption of formal languages in which standards should be formulated. The IVHS community can learn’ from this experience and strive towards the development of such formal languages at an early stage. This will serve three purposes: (1) it will impose a discipline on standards setting bodies to reduce ambiguities; (2) it will help those designing IVHS components and subsystems to check the validity of their designs; and (3) in the long run: it will help in the conformance testing of IVHS products.

5 Conclusions and recommendations

The predominant goals of IVHS are to influence drivers in ways that increases capacity and safety.” The strategy adopted to implement IVHS tasks can range from partial automation

layer model.

“Other goals relating to the impact of IVHS systems are reducing pollution and fuel conservation. increasing GNP as a result of reduced travel time-and safeguarding international competitiveness of C.S. industry.

(in which IVHS only provides information and advice) to full automation (in which most decisions are under computer control).

The evidence suggests that a ‘partial automation’ strategy will not materially affect the goals of increased capacity and safety. Under partial automation, capacity is increased because travel time is reduced since drivers have more accurate and timely information about traffic conditions and advice about the best routes. Simulation and analytical studies, and data from demonstration experiments suggest little or no improvement under recurrent congestion and some improvement under incident induced congestion.[12] One may with confidence suggest an upper bound of 15 % on the capacity increase from partial automation. The capacity ‘bottleneck’ in a partially automated system will continue to be, just as it is today, the driver response characteristic. By contrast, studies based on admittedly simple models suggest capacity gains by a factor of two to three under full automation

There is little evidence about the gains in safety achieved by partial automation. The general wisdom is that up to 90% of accidents today are caused by the driver’ s inattention, faulty anticipation, and slow reaction.[13] These relate to tasks we have called ‘vehicle coordination’ and ‘spacing’. Partial automation strategies may include 'collision warning and avoidance’, and ‘intelligent cruise control’ but AVCS systems offer much more. They hold the promise of making vehicle movement much more predictable and regular, thereby reducing incidents and preventing accidents. Of course, the prospect of full automation- raises many other concerns including system reliability, public acceptance, and legal liability.

In summary, then, while partial automation can more readily be implemented, and involves few surprises of technical or social nature, its impact will also be minimal, and it is unclear whether the cost/benefit tradeoffs are favorable. Full automation offers more promise . . . and more uncertainties. The wisest course would seem to be one in which IVHS architecture standards, initially conceived for partial automation, be made to accommodate evolution to more complete automation. At the same time, a serious effort should be undertaken to reduce the technological and social uncertainties of full automation.

References

[1] P. Varaiya and S. Shladover, “Sketch of an IVHS systems architecture,” tech. rep., UCB-ITS-PRR-91-3, Institute of Transportation Studies, University of California,

[12]A simulation study based on the CACS project suggests that travel time in Tokyo could be reduced by 6 % [22]; U.K. researchers estimate an average benefit of 10 % from dynamic route guidance [23]; preliminary results from the Berlin route guidance experiment show no savings in average travel time under normal conditions [24]; simulations of the Santa Monica freeway (SMART) corridor suggest insignificant savings under recurrent congestion and savings on the order of 10 minutes for a 40 minute trip under incident induced conditions [25, 6]; a careful examination of data on driver response to advisory speeds posted by the Dutch Motorway Control and Signalling System showed no increase in capacity [26]; theoretical considerations also suggest little or no benefits from route guidance under recurrent congestion [27]; lastly. experiments using the CONTRAM simulation model show that single ‘ best route’ guidance can even lead to negative benefits [28]. I am indebted to H. Al-Deek for many of these references.

[13]Incidents' leading to accidents are probably caused by drivers in the same proportion.

Berkeley. CA 94720: February 1991.

[2] U. Karaaslan, P. Varaiya, and J. Walrand, "Two proposals to improve freeway traffic flow," in *Proceedings* of *the 1991 American Control* Conference, (Boston, MA), pp. 2539-2544, June 26-28 1991.

[3] S. Shladover, C. Desoer, J. Hedrick, M. Tomizuka, J. Walrand, W. Zhang, D. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown, "Automated vehicle control developments in the PATH program," *IEEE Transactions on Vehicular Technology,* vol. 40, pp. 114-130, February 1991.

[4] S. Yoo and T. Chira-Chavala, "Flow rate, vehicle delays, and infrastructural dimensions of HOV lanes due to implementation of longitudinal control systems." Preprint, Institute of Transportation Studies, August 1991.

[5] S. Smulders, "Control of freeway traffic flow by variable speed signs," *Transportation Research-B,* vol. 24B, pp. 111-132, 1990.

[6] H. Al-Deek and A. May, "Potential benefits of in-vehicle information systems (ivis): Demand and incident sensitivity analysis," tech. rep., UCB-ITS-PRR-89-1, Institute of Transportation Studies, University of California, Berkeley, CA 94720, 1989.

[7] A. Hsu, S. Sachs: F. Eskafi, and P. Varaiya, "The design of platoon maneuvers protocols for IVHS:" tech. rep., UCB-ITS-PRR-91-6, Institute of Transporation Studies, University of California, Berkeley, CA 94720, April 1991.

[8] A. Hsu. S. Sachs, F. Eskafi, and P. Varaiya, "The design of platoon maneuvers for IVHS:" in *Proceedings of the 1991 American Control Conference,* (Boston, MA), pp. 2545-2550, June 26-28 1991.

[9] A. M. Waxman J. LeMoigne, L. Davis, B. Srinivasan, T. Kushner, E. Liung. and T. Siddalingaiah. "A visual navigation system for autonomous land vehicles." *IEEE Journal of Robotics and Automation,* vol. 3, pp. 124-140, April 1987.

[10] M. Markarinec, *An accident avoidance system* for *an autonomous highway vehicle.* PhD thesis, Northwestern University, 1989.

[11] E. Freund, Ch. Buhler, U. Judaschke, B. Lammen, and R. Mayr, "A hierarchically structured system for automated vehicle guidance!" in *22nd International Symposium on Automotive Technology and Automation,* Vol 1, (Automotive Automation' Ltd., Croyden, England): pp. 351-359,1990.

[12] S. Sheikholeslam and C. A. Desoer, "Longitudinal control of a platoon of vehicles," in *Proceedings of the 1990 American Control Conference, Volume 1,* (San Diego, CA), pp. 291-296, March 1990.

[13] D. McMahon, J. Hedrick, and S. Shladover, "Vehicle modeling and control for automated highway systems," in *Proceedings* of *1990 American Control Conference,* (San Diego, CA), pp. 297-303, 1990.

[14] K. Chang, W. Li, A. Shaikhbahai, and P. Varaiya, "A preliminary implementation for vehicle platoon control system," in Proceedings *of the **1991** American Control Conference*, (Boston, MA), pp. 3078-3083, June 26-28 1991.

[l5]. T. Hessburg, H. Peng, M. Tomizuka, W. Zhang, and E. Kamei, "An experimental study on lateral control of a vehicle," in *Proceedings of the 1991 American Control Conference,* (Boston, MA), June 26-28 1991. To appear.

[16] S. Tsugawa and S. Murata, "Velocity control for vehicle following through vehicle/vehicle communication," in *22nd International Symposium on Automotive Technology and Automation, Vol* 1, (Automotive Automation Ltd., Croyden, England), pp. 343-350, 1990.

[17] F. Broqua, G. Lerner, V. Mauro, and E. Morello, "Cooperative driving: Basic concepts and a first assessment of "intelligent cruise control" strategies," in *Advanced Telematics in Road Guidance. Proceedings of the DRIVE Conference,* pp. 908-929, Elsevier, February 4-9 1991.

[18] A. Kemeny and J. Piroird, "A simulator for cooperative driving," in *Advanced Telematics in Road Guidance. Proceedings of the DRIVE Conference,* pp. 930-942, Elsevier, February 4-9 1991.

[19] J. Buxton, S. Honey, W. Suchowerskyj, and A. Tempelhof, "The Travelpilot: A second-generation automotive navigation system," *IEEE Tmnsactions on Vehicular Technology*. vol. 40, pp. 41-44, February 1991.

[20] R.. von Tomkewitsch, "Dynamic route guidance and interactive transport management with ALI-SCOUT," *IEEE Transactions on Vehicular Technology,* vol. 40, pp. 45-50, February 1991.

[21] M. Tsuzawa and H. Okamoto, "Advanced Mobile Traffic Information and Communication System – AMTICS." Vehicle Navigation and Information System Conference, Toronto. Canada, September 11-13 1989.

[22] F. Iiobayashi, "Feasibility study of route guidance," *Transportation Research Record.* vol. 737, pp. 107-112, 1979.

[23] J. Sparmann, "LISB route guidance and information system: First results of the field trial." Vehicle Navigation and Information System Conference, Toronto, Canada, September 11-13 1989.

[24] H. Al-Deek, M. Martello, A. May, and W. Sanders, "Potential benefits of in-vehicle information systems in a real freeway corridor under recurring and incident induced congestion," tech. rep., UCB-ITS-PRR-88-2, Institute of Transportation Studies, University of California, Berkeley, CA 94720, 1988.

[25] S. A. Smulders, "Control of freeway traffic flow," tech. rep., Center for Mathematics and Computer Science, Report OS-R8806, Amsterdam, 1988.

[26] H. Al-Deek and A. Kanafani, "Some theoretical aspects of the benefits of en-route vehicle guidance," tech. rep., UCB-ITS-PRR-89-2, Institute of Transportation Studies, University of California, Berkeley, CA 94720, 1989.

[27] N. Hounsell, M. McDonald, and L. Breheret, "The modelling of dynamic route guidance," in *Advanced Telematics in Road* Guidance. *Proceedings of the DRIVE Conference*, pp. 89-98, Elsevier, February 4-9 1991.