Comparison of Advanced Traffic Management and Traveler Information System Architectures for Intelligent Vehicle Highway Systems

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One of the important efforts in the intelligent vehicle highway systems (IVHS) program is the development of a system architecture to guide development and implementation decisions. Five alternative architectures for advanced traffic management and advanced traveler information systems are compared. These architectures were created to focus on several key architectural issues. The qualitative evaluation focuses on characteristics of the alternative architectures that affect performance, cost, and risk. Additionally, the evaluation stresses issues connected with starting up IVHS services and evolving to more advanced systems and addresses institutional concerns.

The U.S. Department of Transportation through FHWA has established the intelligent vehicle highway systems (IVHS) program to use advanced technology to improve the efficiency of the nation's highway transportation resources (*1*). IVHS can be defined as advanced communications, navigation, sensors, control systems, and information systems that can be used to increase throughput on existing roadways, to improve the safety of the traveling public, and to improve the productivity of commercial vehicle operations. The IVHS program is divided into six major areas:

- Advanced traffic management systems (ATMS),
- Advanced traveler information systems (ATIS),
- Advanced vehicle control systems (AVCS),
- Advanced public transportation systems (APTS),
- Commercial vehicle operations (CVO), and
- Advanced rural transportation systems.

One of the early requirements in the IVHS program is a system architecture to guide development and implementation decisions. The architecture provides the framework, or structure, for defining the functions that provide IVHS services. It also defines the information flows and interfaces between functions. The system architecture, in addition, describes the way the IVHS functions are divided among subsystems in the vehicle, at the roadside, or in one or more traffic management centers (TMCs).

A process for defining and implementing an IVHS architecture is shown in Figure 1. The basic steps are to

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- Define goals and objectives for IVHS systems,
- Identify alternative functions that meet these objectives,
- Synthesize alternative architectures that may provide these functions,
- Assess and refine the alternatives,
- Select an acceptable architecture, and
- Design and implement the systems in accordance with the architecture.

Numerous organizations have developed definitions of IVHS goals and identified candidate solutions (*1*). Yablonski has provided an extensive discussion of IVHS services and functions (*2*). Several alternative architectures have been documented in earlier work (*3*). The assessment and refinement process shown in Figure 1 must be carried out in an iterative fashion and will require several iterations to come to an acceptable architecture.

This paper describes initial results for Steps 3 and 4 of the architecture development process: the synthesis and assessment of five alternative IVHS architectures. The alternative architectures are partial architectures because they have been limited to providing only major ATMS and ATIS functions and do not include the provision of AVCS, APTS, or CVO services. They can be described as end-state architectures because they have been defined to support the provision of fully developed ATMS and ATIS services. The alternatives have been named strawman architectures for two reasons. The first is that they were created to focus initially on several key architectural issues, rather than encompass all the ATMS and ATIS functions and services. The second is that the evaluation of these initial architectures will lead to modified and improved architectures.

There is some question about how to actually evaluate system architectures because they are not fully defined designs. They only provide structures for implementing the required services. Hence, it is not clear that one can, or should, carry out a traditional analysis of the benefits and costs for an architecture. It was therefore decided to carry out a qualitative comparison of several important characteristics of the architectures that would directly affect their eventual performance and costs. This evaluation is discussed more fully in a report by Cheslow et al. (*4*).

With current technical and institutional uncertainty, it is not possible to state specifically that one future end-state architecture is best. Instead, the evaluation described here

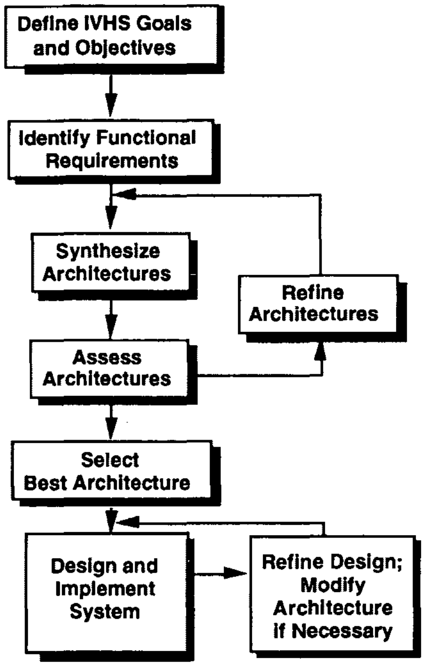


FIGURE 1 IVHS architecture selection process.

provides some initial conclusions about which types of end-state architectures are promising. Further analyses of IVHS architectures, as well as related research and development and operational tests, will eventually provide the necessary quantitative information to allow the determination of the best architecture.

A summary of the five strawman architectures is presented next, beginning with a description of the key architectural attributes that define them. A complete discussion of these alternatives, along with the approach used to develop them, is documented in earlier work (*3*). These five architectures highlight various functional approaches to providing ATMS and ATIS services, ranging from highly centralized to fully distributed. The architecture that finally evolves may not be identical to any of the original strawman architectures; it may combine features of two or more of the alternatives or may add features not found in any of the five.

KEY ATTRIBUTES OF THE STRAWMAN ARCHITECTURES

The architecture definition process focused on three critical system elements that highlight major differences among the alternatives. These three elements are

- Vehicle-infrastructure communication alternatives,
- Location of the route selection function, and
- Degree of coupling between route selection and traffic control.

Although a single vehicle-infrastructure communication alternative is associated with each strawman architecture, the applicability of each of the communication alternatives to all of the architectures will be addressed in the paper. Further discussion of architectural issues can be found in other papers (*3, 5*).

Vehicle-Infrastructure Communications

A critical implementation issue for the IVHS program is the choice of an effective and economical approach for communicating traffic information and safety advisories to vehicles and collecting traffic flow information and assistance requests from vehicles. The strawman architectures have used four communication alternatives:

- Two-way localized beacons,
- Two-way wide-area coverage radio systems,
- Two-way cellular-like radio systems, and
- One-way broadcast radio systems utilizing an FM subcarrier.

These four options were chosen to represent a range of technological capability. Each approach has its specific advantages and disadvantages for supporting IVHS functions and services. With one exception, the communication options that were selected represent alternative ways of providing two-way communication services. Two-way communications between the traffic management infrastructure and vehicles will be required to enable the transmission of vehicle probe reports and assistance requests by vehicles and to receive traffic information and either traffic network link times or recommended routes from the infrastructure. Satellite-based communications were not considered for the strawman ATIS/ATMS architectures. In addition, alternatives for communication among the infrastructure components have not been considered. The following paragraphs summarize each of the four communication alternatives.

1. Localized beacons on the roadside support short-range, two-way transfer of traffic and routing information to or from vehicles that are near the beacon. The term beacon is used generically in this paper to mean any localized two-way communication device. Communication between the vehicle and the infrastructure can occur only at beacon sites. A variety of communication wavelengths, including infrared, radio, and microwave, could be used for the actual beacon implementation. Localized beacons have been chosen as a communication option because of their potential for spatially distributing the communication loads on the infrastructure. This approach can permit more location-specific information to be presented to vehicles within range of the beacon and would allow a large number of vehicles to be handled with a relatively small use of the electromagnetic spectrum.

2. A wide-area radio broadcast system is another alternative for two-way communications between vehicles and the infrastructure. The communication range is sufficiently large to cover a substantial portion of a metropolitan area (or critical segments of Interstate highways or rural areas). One or more dedicated pairs of radio frequencies is used to transmit and receive traffic information. This option represents a centralized communication system approach to providing two-

way communication coverage to or from any location within the area of interest. A wide-area radio system would broadcast the same traffic information to all vehicles within receiving range, relying on in-vehicle processors to separate out the relevant data on the basis of the vehicle location and planned route of travel. Each vehicle would also send (broadcast) information to the TMC.

3. A digital cellular radio system also supports two-way communications between vehicles and the infrastructure. The systemwide communication coverage is sufficiently large to serve a metropolitan area. However, the coverage area is broken into smaller cells, each served by a base station and a transmitter of lower power than that used with the wide-area radio option. This system provides more communication capacity for a given allocation of frequencies than does wide-area radio. A set of communication channels is reused many times throughout the network. This option represents a more distributed communication architecture than one based on wide-area radio.

Although analog cellular phone systems still dominate the market today, digital cellular systems will soon be common. Digital technology is assumed for this paper because of the significant capacity advantage it offers over analog. Two implementations of the cellular system infrastructure and spectrum are possible: (a) fully shared with conventional cellular applications (e.g., phone use), or (b) partially shared, with a limited number of channels dedicated for traffic purposes only. A partially shared system might use special data channels using communications protocols that eliminate the need for call setup and tear-down.

4. A one-way FM subcarrier broadcast can be used to send traffic information from the infrastructure to properly equipped vehicles. This is the only communication alternative considered that does not support two-way communications (e.g., does not support vehicle probe reports). This communication option was selected because it provides an efficient and relatively low-cost means of broadcasting traffic information to many users. Similar to the wide-area radio system described above, an FM subcarrier offers a means by which identical traffic information can be transmitted to all cars within receiving range.

Location of the Route Selection Function

Another distinguishing feature of the architectures is the location of the route selection function. Route selection provides recommended routes that are inputs to the route guidance function in the vehicle. Route selection involves the calculation of a "best" route of travel—selected according to an objective function—between a specified origin and destination (O-D) pair, on the basis of dynamic data, static data, or a combination of both. Operationally, the route selection algorithm would have to be periodically rerun to account for changing traffic conditions.

Two alternative locations for route selection have been considered for the strawman architectures: in-vehicle and in the infrastructure. The additional assumption has been made that infrastructure-based route selection is performed centrally at a single facility (e.g., the TMC). This latter assumption is important to the concept of coupling between route selection and traffic control, as described in the next section.

In fully distributed route selection the function occurs within individual vehicles (but without coordination with other vehicles). The driver requests a route and receives route guidance instructions from the in-vehicle system. When the vehicle is within a TMC's coverage area, the in-vehicle route selection processor is provided with dynamic traffic information from the TMC. This traffic information would consist of changes in link travel times, incidents, and other temporary restrictions (exception-type data). The in-vehicle system could also operate without reliance upon external (infrastructure) support when outside a traffic information coverage area or when dynamic traffic information is not available. In this case, traffic information used for route selection would consist of static information stored in the vehicle's map data base.

In contrast, with centralized route selection, individual vehicles transmit specific origin (or current location) and destination data to the infrastructure. This information is then used to select routes for the equipped vehicles that have provided O-D information. Each of these vehicles receives individualized route advice to support its trip. The vehicles will periodically send updates of their current location and, if necessary, receive new routing instructions for the remaining set of road links to be traveled. A vehicle might or might not utilize a map data base to assist the display of the selected route to the traveler.

Degree of Coupling Between Route Selection and Traffic Control

Coupling refers to the extent to which route selection and traffic control decisions are interdependent and coordinated. We consider three alternative levels of coupling:

- Fully coupled: TMC has real-time knowledge of equipped vehicles' O-D information and simultaneously optimizes both traffic controls and the routes of all equipped vehicles;
- Uncoupled: Traffic control optimization is carried out without real-time knowledge of vehicles' O-D and route information; and
- Partially coupled: TMC uses real-time knowledge of the routes selected by equipped vehicles, as well as their O-D information, for optimizing traffic controls.

With a fully coupled system, the TMC jointly determines the optimal settings for all traffic control devices and the optimum routes for all vehicles equipped to carry out route guidance. The capability requires complete knowledge of the origins (or current locations) and destinations at the TMC of equipped vehicles, which would be used with other traffic data obtained from traffic sensors and vehicle probes. Figure 2*a* provides a simple representation of the joint optimization process. The TMC would concurrently perform several functions:

- Prediction of future traffic loads and link times on the road network;
- Optimization of settings for traffic control devices; and
- Route selection for all equipped vehicles.

In an architecture with no coupling, the vehicles do not provide either destination or intended route information to

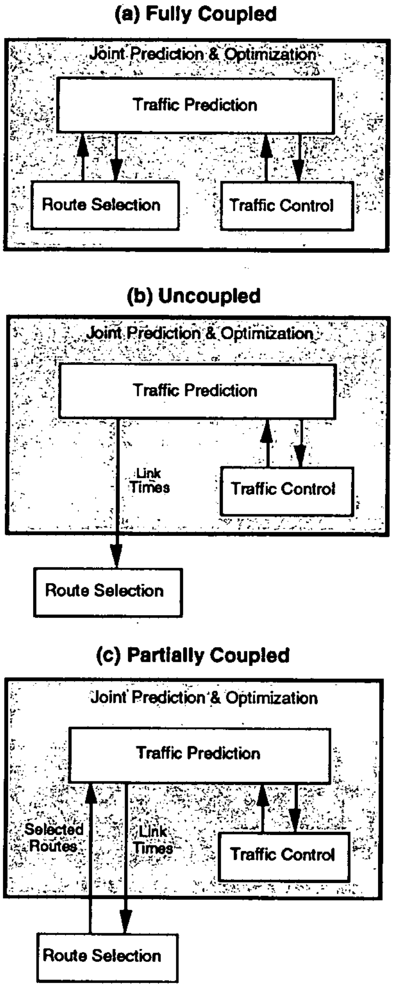


FIGURE 2 Degree of coupling between route selection and traffic control.

the TMC. The TMC only uses real-time information from traffic sensors, including vehicle probes, and historical traffic data to predict traffic loads on the network. It then optimizes the traffic control system on the basis of these (limited) traffic predictions. The link times from this process are passed to an independent route selection processor. The traffic control settings are not affected by information about selected routes; however, the traffic control optimization can affect the route selection process (through the link times). Figure 2*b* characterizes the traffic control and route selection functions for an uncoupled architecture. With no coupling, route selection could occur in either vehicles or the infrastructure.

With partial coupling, the TMC obtains planned destinations and selected routes from equipped vehicles. This information differentiates the partially coupled architecture from an uncoupled one. The TMC uses traffic sensor and vehicle probe information to estimate current link travel times. Using these inputs, as well as the selected routes and destinations, the TMC can predict traffic loads and optimize traffic control systems. Figure 2*c* provides a representation of the route selection and traffic control optimization process for a partially coupled control architecture. Partial coupling can exist with route selection in either the vehicles or the infrastructure.

Other ATMS and ATIS Functions

Although the development of the strawman architectures focused on three key issues, the architectures include several additional ATMS and ATIS functions. Except for the level of coupling of route selection and traffic control, each architecture is assumed to be able to provide the same traffic management functions. The main ones are as follows:

- Surveillance,
- Traffic data preprocessing and fusion,
- Traffic assignments and prediction,
- Dynamic traffic control (i.e., signal and sign control),
- Incident identification, and
- Traffic and safety advisories.

The ATIS services that are provided by the architectures are as follows:

- In-vehicle trip planning (excluding dynamic public transit information),
- Position location,
- Route selection,
- Route guidance for the selected route,
- Assistance requests, and
- Traveler information services.

THE STRAWMAN ARCHITECTURES

Five strawman architectures have been selected that reflect logical combinations of the three key architectural attributes described above. Table 1 gives the salient features that distinguish the architectures from one another. Each alternative provides a different framework upon which required IVHS features and services can be assembled.

The first four architectures represent highly capable ATMS/ATIS architectures. Although these architectures differ in important ways, they all have essentially the same basic capabilities; specifically, they all include some form of vehicle routing, two-way communications, advanced traffic management, and so forth. The fifth alternative represents an architecture with less functionality, primarily because it does not provide an inbound (vehicle-to-infrastructure) communication link.

A descriptive overview of the architecture alternatives is provided below. Additional details can be found in earlier work (*3*). Figure 3 highlights for each of the strawmen the location of the route selection function, the primary functions provided, and the communication medium between the vehicle and the traffic management infrastructure. In Figure 3, the components of each architecture are classified into three categories:

- In-vehicle,
- Traffic management infrastructure, and
- Vehicle-infrastructure communications.

Strawman Architecture 1

Architecture 1 has route selection and guidance capability in the vehicle with no coupling between vehicle routing and the

TABLE 1 Overview of Strawman Architectures

Architecture 1	Architecture 2	Architecture 3	Architecture 4	Architecture 5
Uncoupled route selection/traffic control	Partially coupled route selection/traffic control	Fully coupled route selection/traffic control	Uncoupled route selection/traffic control	Uncoupled route selection/traffic control
		Centralized route selection (with real-time data)	Centralized route selection	
In-vehicle route selection	In-vehicle route selection	In-vehicle route selection (with static data) when real-time routing is unavailable		In-vehicle route selection
In-vehicle map database	In-vehicle map database	In-vehicle map database	No in-vehicle map database	In-vehicle map database
Two-way wide-area radio communications	Two-way localized (beacon) communications	Two-way cellular radio communications (digital technology)	Two-way localized (beacon) communications	One-way broadcast (FM subcarrier) to vehicles for communications

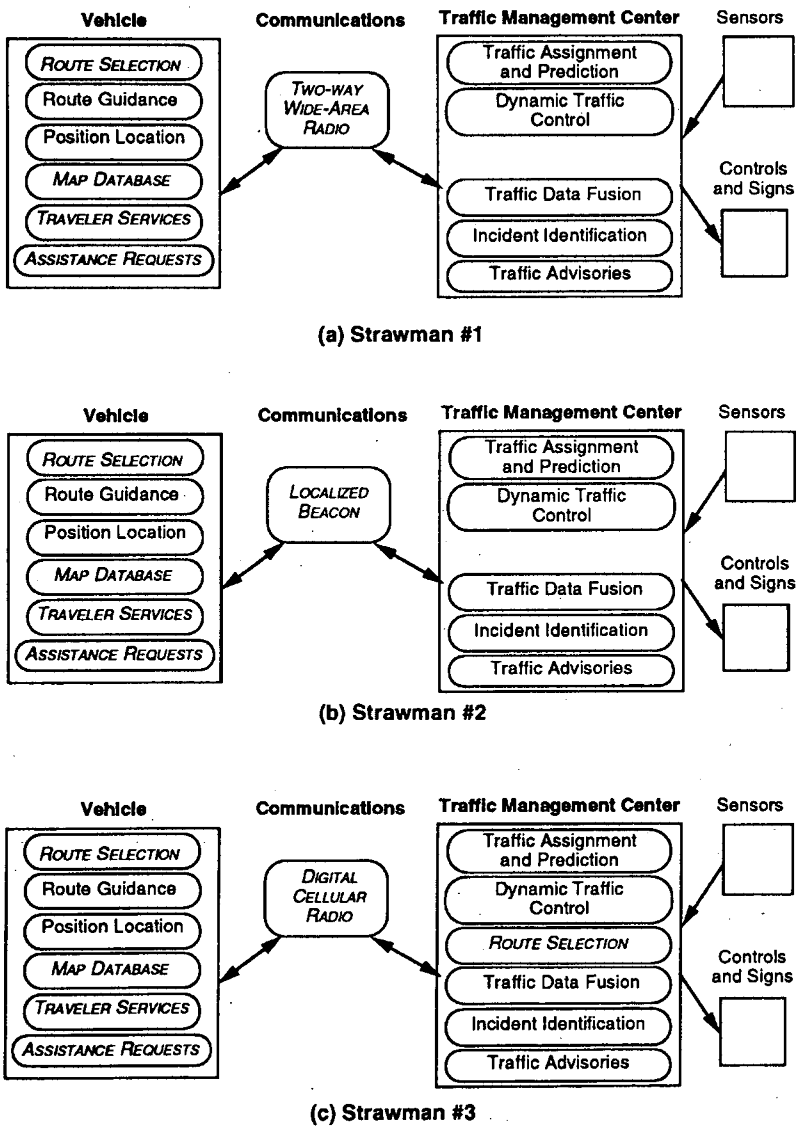
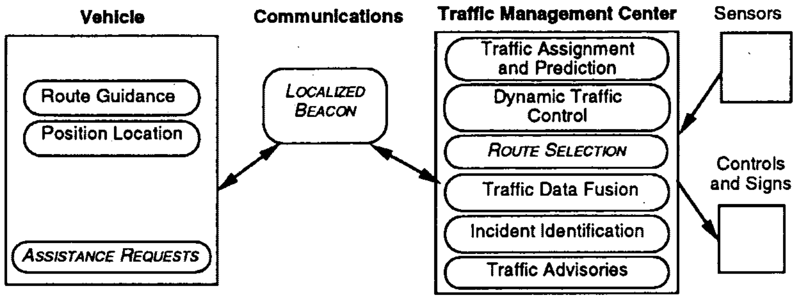
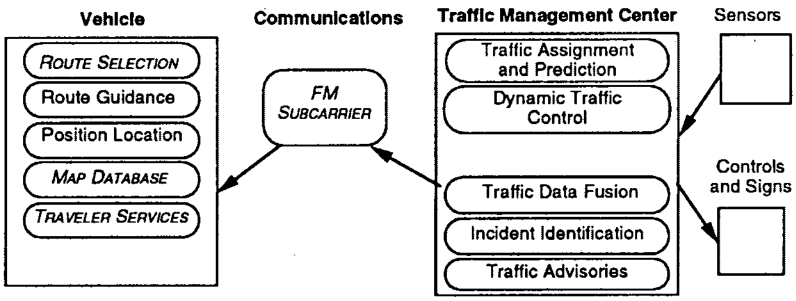


FIGURE 3 Simplified diagrams of strawman architectures. *(continued on next page)*



(d) Strawman #4



(e) Strawman #5

Notes: *ITEMS IN ITALICS AND ALL CAPS, AS IN THIS SENTENCE, VARY AMONG THE ARCHITECTURES.*

ROUTE SELECTION varies in its location, i.e., whether it is performed in the vehicle or in the Traffic Management Center. (Also in Architecture 3, in-vehicle *ROUTE SELECTION* uses static data only.)

The choice of the *COMMUNICATIONS MEDIA* varies across architectures.

The (in-vehicle) *MAP DATABASE*, and the *TRAVELER SERVICES* and *ASSISTANCE REQUEST* functions are included in some architectures and omitted in others.

FIGURE 3 ***(continued)***

traffic control system. The in-vehicle system performs position location, route selection, and enroute guidance functions. Position location within the vehicle is based on land-based or satellite radio trilateration, dead reckoning, and map matching. The in-vehicle navigation and routing unit contains a map data base that supports traveler services and "yellow pages" data. A variety of trip planning and route selection options are available in-vehicle to support the traveler.

The in-vehicle unit communicates with the TMC via a wide-area radio system that may cover a metropolitan area, critical segments of Interstate highway systems, or other rural areas.

Strawman Architecture 2

Architecture 2 is similar to Architecture 1, with some important modifications. Like Architecture 1, all position location and routing functions are performed in the vehicle and all high-level traffic control functions in the TMC. However, Architecture 2 has partial coupling between the traffic control and routing functions. This level of coupling is accomplished by the transmission of selected routes to the TMC, where they are used to enhance the accuracy of traffic prediction and traffic control functions. In the TMC, the selected route data must be integrated (fused) with other traffic information.

A major difference between Architectures 1 and 2 is in the type of vehicle-to-TMC communications. This architecture uses two-way localized communications (beacons) instead of a wide-area network. This beacon system must have the capability of transmitting traffic data describing link times on all major roads in the network to all vehicles that have route selection capability. This will require large messages to be transmitted in a short time by the beacons.

Strawman Architecture 3

This strawman has full coupling of the traffic management and routing systems. The simultaneous determination of the traffic control and routing parameters requires that communication between the two processes take place frequently and efficiently. This is best accomplished if both processes take place in a single physical facility, namely a TMC. Therefore, this strawman has the selection of traffic routings determined centrally, rather than in individual vehicles.

Recommended routes are communicated to the equipped vehicles in Strawman 3. This is a major difference from Strawmen 1 and 2, in which link times are sent to equipped vehicles. For this strawman, the communication link is provided by two-way digital cellular radio. The routing data for each vehicle must be coded with the vehicle's identification (ID) so that the vehicle can select out the messages addressed to it.

An in-vehicle route guidance processor utilizes the recommended routes sent from the TMC to provide assistance to the traveler about directions and turns. Vehicle location is determined by the individual vehicles, and each vehicle is assumed to be able to perform in-vehicle navigation when routing recommendations are not available from the central facility.

Strawman Architecture 4

Architecture 4 has centralized route selection with an uncoupled traffic control system. Similar to Architecture 2, localized beacons are used for communications between the infrastructure and vehicles. In this architecture, communication from the infrastructure to the vehicles is required for any route guidance to be displayed, even using static data. With this centralized approach, a map data base is not required in the vehicle, potentially lowering the cost of the in-vehicle unit. Thus, Architecture 4 is highly infrastructure dependent.

Even though both route selection and the determination of control system parameters are carried out centrally, there is no direct coupling between these two functions. These two functions do not have to be carried out at the same facility and conceivably could be handled by different organizations. For example, route selection could be performed by a private subscription service while traffic management is provided by a public agency.

Strawman Architecture 5

Architecture 5 has uncoupled route selection and traffic control with a one-way, FM subcarrier communication system to broadcast real-time traffic conditions from the infrastructure to vehicles. The broadcast is assumed to transmit in digital format. The same broadcast can be used for transmitting both routes and traffic information. The traffic management functions of this architecture are similar to those of Architecture 1, except that no vehicle probe data are collected.

The communication infrastructure is assumed to be developed primarily to provide information to vehicles with route selection and route guidance processors but also allows vehicles without these routing processors to obtain some of the transmitted information. Both equipment options can be accommodated with one overall architecture and are intended to operate together in the same area. In addition to carrying general traffic advisories and warnings, the one-way traffic channel is used to broadcast link travel times that can be used for routing purposes. The main limitations of this architecture, compared with the previous four architectures, are that it does not support assistance requests or vehicle probe traffic data.

INITIAL EVALUATION OF THE STRAWMAN ARCHITECTURES

The evaluation compared the capabilities of the five strawman architectures according to several important criteria. The evaluation was qualitative and relied on currently available information; however, it provides a structure that can be used as more quantitative information becomes available. Evaluation criteria that might be pertinent only for comparing detailed designs were generally avoided. The qualitative evaluation criteria that were used were chosen because they identify important characteristics of the systems and can provide initial insights about system benefits and costs.

The categories of evaluation criteria that were used to evaluate the strawman architectures are as follows:

- System performance (end state),
- System costs (end state),
- System risks,
- System evolution, and
- Institutional issues.

The evaluation focused on characteristics of the alternative architectures that affect performance, cost, and risk. Because the five architectures being compared are end-state architectures, the system performance and cost criteria that were used relate to the characteristics of fully developed systems. In using these criteria, it was assumed that the relevant technologies have matured to the (end) state implied by the architectures and that the market penetrations of the systems have grown to their highest (saturated) levels. Several criteria were chosen that relate to the technical, operational, and institutional risk of the architectures. These criteria address the risk of services or systems not being provided, as well as the risk of services not being efficiently utilized by either traffic managers or vehicle operators.

As part of the evaluation, several issues related to system evolution were also considered. These are connected with selecting a deployment strategy that could produce a desirable end-state IVHS architecture from feasible initial start-up conditions. Institutional concerns, such as equity and privatization, also were investigated. The major geographic focus of the evaluation was on large metropolitan areas because the strawman architectures emphasize route selection and traffic management functions.

Attempts have been made to give each of the alternative architectures a ranking for each of the qualitative criteria. A ranking is used as an ordinal comparison: an architecture has first-, second-, or third-level rankings, based on its relationship to other architectures. The detailed methodology used to obtain the rankings is described in the related report (*4*).

Because there are several evaluation criteria, each strawman architecture received several rankings. The rankings have not been combined into overall scores for the alternatives. However, a summary of the architecture rankings is provided in Table 2. Caution must be used when interpreting the results because several important criteria were not rated and because of the many assumptions made for those criteria that were rated. Also, an ordinal ranking gives no information on the magnitude of differences. This means that one is not able to estimate how closely, say, a second-ranked alternative is to a first.

Despite the incompleteness of the evaluation, a few generalizations can be derived from the rankings. Architecture 5 rated very well for each evaluation category except for system performance, operational characteristics. Its poor rating

TABLE 2 Summary of Rankings for Alternative Architectures

EVALUATION CRITERIA	ARCHITECTURE 1	2	3	4	5
SYSTEM PERFORMANCE					
Operational Characteristics					
Accuracy of Traffic Prediction Models	2nd	1st	1st	2nd	3rd
Efficiency of Traffic Control System	2nd	1st	1st	2nd	3rd
Efficiency of Route Calculations					
Accuracy of Position Location	1st	1st	1st	2nd	1st
Effectiveness of Information Delivery Methods					
Adequacy of Communication System Capacity					
System Reliability and Maintainability					
Capability During Communication Failure	1st	1st	1st	2nd	1st
Capability During TMC Failure	1st	1st	1st	1st	1st
Capability to Update Maps					
Performance in Poor Weather	1st	2nd	2nd	2nd	1st
Performance in Diverse Terrain/Structures	1st	1st	2nd	1st	1st
SYSTEM COSTS					
Vehicle Capital	3rd	3rd	3rd	1st	2nd
Vehicle Operating	3rd	3rd	3rd	1st	2nd
Communication System Capital	2nd	3rd	2nd	3rd	1st
Communication System Operating					
Traffic Management Capital	1st	2nd	3rd	2nd	1st
Traffic Management Operating	1st	2nd	3rd	2nd	1st
SYSTEM RISKS					
Equipment or Service Not Being Provided					
Communication System Risks					
Other System Risks	1st	2nd	3rd	2nd	1st
Service Not Implemented by Traffic Managers					
Complexity of TMC Risk	1st	2nd	3rd	2nd	1st
Failing to Meet Jurisdictional Interest Risk	2nd	2nd	1st	1st	2nd
Service Not Purchased or Used by Vehicle Operators	2nd	2nd	3rd	2nd	1st
Technology Places Limits on Size of Market					
Outbound Communications	1st	1st	2nd	1st	1st
Inbound Communications	2nd	1st	1st	1st	N/A

Note: (1st = best ranking for each criterion, e.g., best performance, lowest cost, lowest risk)

in the operational category can be attributed to its lack of inbound communication capability. Architectures 2 and 3 rate similar to one another, largely because they are the only architectures with some level of coupling. Architectures 1 and 4 also appear to rate similarly for the evaluation categories other than system costs.

CONCLUSIONS

Several conclusions were reached that, although based on qualitative analyses, generally appear to be well founded. The conclusions relate to both the key attributes of the architectures—route selection, traffic control, and communication—as well as to the complete architectures. Some ways to mix the architectural attributes to produce promising new alternatives are suggested, and several unpromising combinations of architecture attributes are identified. Some important observations about system evolution are also discussed.

Route Selection and Traffic Control

The location of route selection cannot be decided in isolation from other architectural decisions. The location may not directly affect the efficiency of selected routes but certainly has an impact on it—through the level of coupling between route selection and traffic control. If full coupling can be accomplished, collocating route selection with the traffic prediction and control functions and using system optimization may be the preferred approach.

Coupling of route selection and dynamic traffic control in an integrated process has potentially high payoff, but there is currently great uncertainty about coupling's technical and institutional feasibility. The technical uncertainty is related to the accuracy of traffic prediction models and the ability to provide needed processing requirements. Coupling places stringent requirements on all parts of the system architecture for very fast response times, including the communication system and the traffic sensors.

Institutional uncertainty is related to acceptance by traffic managers and vehicle operators. Traffic managers may be concerned about the overall complexity of the computer algorithms or the lack of manual control that they would have. Travelers may choose to ignore system-optimized routes that do not consider user preferences. This potential concern of users can be important even though the alternative—placing the route selection processor in the vehicle—would likely cost the user more. (This last observation might not hold if central routing information providers charge hefty fees to users of their routes.) Centralized systems can optimize routes for each user, rather than for the overall system, but then the potential benefits of full coupling would be lost.

Partial coupling may provide an approach that is acceptable to vehicle operators (because it has user-preferred routes) while also being acceptable to traffic managers. But partial coupling requires that traffic predictions be able to factor in user-selected routes quickly enough to change the estimated link times before a large number of vehicles make the same route diversions. Otherwise, the result could be instability of the traffic control system (thrashing).

Dynamic traffic control is an important component of all the strawman architectures. To be successful, it has to work well for most ATIS and ATMS services. The details of this function have not been examined in this evaluation, but one major aspect—traffic assignment and prediction—has been considered. The ability to make, and continuously update, predictions of traffic flows and link times for several minutes into the future using real-time data is a major requirement for providing dynamic traffic control. This requirement, in turn, depends on acceptable computer hardware and software, as well as a sufficient number of traffic sensors sending current data and a sensor-to-infrastructure communication system that has the speed and capacity to send frequent updates.

The more timely and accurate the traffic information that can be obtained, the better will be the traffic predictions. For this information to be truly valuable, however, the prediction function must be able to estimate traveler responses to the routing advice. One way for this to occur is to have a traveler behavior model embedded in the prediction model.

In all the strawman architectures, the traffic management processing function has been discussed as if it were performed in a single centralized facility. This was done for ease of comparison with in-vehicle processing. In fact, the processing connected with traffic management could be distributed among several centers; for example, one metropolitan center and several subregional ones. In this case, there would be additional architectural issues about how the optimization is coordinated, as well as by what means and how frequently information is transferred between centers. Of course, coupling with route selection would make more difficult any distributed processing of the traffic management requirements. Another variation of decentralized traffic management would be to carry out some of the tasks on the roadside in localized facilities. Again, coordination of the traffic control optimization would be an issue. However, it is likely that there would be some form of hierarchical control system with local controllers that function independently, within constraints set by a network-wide optimization plan.

Communications

No definitive conclusions were reached about the various communication systems in this initial evaluation. Each has different advantages and disadvantages that cannot be compared in a qualitative analysis. However, a quantitative analysis of communication load requirements has recently been conducted at MITRE (*6*) that provides more insight into this subject.

A major question about each architecture is the cost allocation of the communication services among the various owners of the IVHS components. Because service providers can charge user fees, the answer to this question will be resolved only when a particular implementation of the service is examined.

End-State Architectures

With regard to the five end-state architectures, but with all communication systems combined with the other key attributes, several conclusions can be reached. First, the requirement of passing link data to vehicles can best be met with a broadcast channel. This is a fairly weak conclusion, because cellular radio may use dedicated broadcast channels, and beacons may have a high enough data rate, when used with a structured flow of traffic, to also be able to transmit link data without practical problems.

It has also been concluded that passing selected routes from a traffic management facility to vehicles should not be performed by a wide-area broadcast system, because there is not a good match between the large data transmission requirement and channel capacity. The broadcast channel would have to send all routes to all vehicles (although each vehicle could pick off only the data that it needed).

An inbound broadcast channel, such as that provided by wide-area radio, does not appear to be a good match for sending selected route data from vehicles to a TMC, such as is required with partial coupling in Architecture 2. This is because of communication system access limitations, which, even with a stringent access protocol, could prevent some routes from being sent. These observations imply that wide-area radio, by itself, should not be considered for Architectures 2, 3, or 4. (In fact, it was considered only for Strawman 1.) It also appears that an inbound broadcast channel is not the best mode for sending probe data.

Another conclusion is that an architecture that supports infrastructure-based route selection without an in-car electronic map should include a beacon type of communication system to serve as location fixes. Although it would be possible to design a mapless system without beacons, it does not appear to be a promising approach.

It may have been observed that Architecture 4 appears to have route selection, as well as traffic management, occurring in a central traffic management facility, while not having these two functions coupled together. The original idea behind the strawman was that there would be a desire to carry out route selection centrally by traffic managers most likely on the basis of system optimization. But there would be a constraint, either institutionally or technically, in coupling with traffic control. This constraint might occur because the two functions are carried out in two different facilities, or by two different organizations, or even because the traffic management is carried out in a distributed manner among several levels of TMCs. Although it has not been possible to consider any of these variations, at least some of them need more investigation.

The utility of each of the architectures for the APTS, CVO, and AVCS service areas was examined briefly in the related report (*4*). One conclusion is that it is generally possible to have separable architectures for these additional services—

even for AVCS services in a vehicle that also performs the route guidance function. In addition, the communication requirements for ATIS services that are performed outside the vehicle appear to differ from those that are performed within the vehicle. When a full range of IVHS services must be provided, it may turn out that multiple communication systems must be utilized. One exception is that, within some frequency ranges, a broadcast to vehicles could also be received inside buildings. FM subcarrier, for example, fulfills this requirement.

System Evolution

The potential for evolutionary development of an architecture is one of the most important issues to consider in an evaluation, especially for a system such as IVHS. Because of the technical and institutional uncertainties of the IVHS program, an end-state architecture should be defined so that it can "gracefully" evolve from a simpler, less costly, and less risky one. An architecture that provides a range of services and functions could be developed to make some functions available in the near term, whereas others would be added later. This evolutionary approach would allow improvements in performance over time, as the number of users increases. A start-up architecture should be conceptualized to provide significant initial benefits, while being capable of evolving without the need to discard major system components.

One attractive start-up architecture is Strawman 5, which has only a one-way communication channel; however, it includes a capability to broadcast traffic link data to vehicles that have in-vehicle route selection equipment. This strawman has little risk and relatively small cost, but is does not provide the same level of functionality as the other architectures. However, this start-up architecture does not have to be a dead-end architecture, because an additional vehicle-to-infrastructure communication link could be added to provide for the transfer of either probe data, as in Architecture 1, or probe and route data, as in Architecture 2. The system would have to be designed to allow for easy in-vehicle equipment upgrades for users that wish to add the additional communication functionality. An in-vehicle route selection approach would be maintained as the system evolved.

Another evolutionary possibility focuses on having centralized route guidance along with system optimization in the end state, as in Architecture 3. The start-up architecture could be a version of Architecture 4, which has no coupling, and could be based on a cellular or a beacon communication system. It is not known at this time which communication system would require a higher start-up cost.

It also may be possible to start with a capability built around in-vehicle route selection and evolve to centralized route selection with system optimization. The details of this evolution are not completely clear. The physical components of the communication capability, if they were based on beacons or cellular, might not have to evolve appreciably. However, the information exchange protocols would have to be modified (if the end-state capability were not already provided for in the beginning). In the end state, vehicles would continue to utilize map data bases but would use in-vehicle route selection only with static data, for example, when centrally determined routes are not available. The TMC would have to make major improvements to its hardware and software to provide the new capabilities.

Institutional Issues

Some preliminary observations can be made about two important institutional issues that should be important evaluation concerns: equity and privatization. In considering the costs of both alternative communication equipment and of the data that could be made available to vehicles, it has been determined that there are likely to be fees charged by either the communication operators or the information providers. These fees may be set only to transfer the cost from a service provider to a service user. But there is also the possibility that fees will be set to accomplish other ends, such as profitability, equity among various travelers, pricing low to buy into a market, and so on. In other words, the fee structures can easily dominate considerations of equity of benefits and costs of IVHS services.

The type and size of fees will depend on which IVHS services are operated publicly and which ones are operated privately. Hence, the issues of equity and privatization should not be dealt with independently. However, they are not architecture issues per se; they are implementation issues. There can be a range of public and private roles for each of the strawman architectures that has been considered so far. Hence, it appears that the level of privatization, by itself, cannot be used to discriminate among architectures.

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