Proceedings of the 1992 Winter Simulation Conference
ed. J. J. Swain, D. Goldsman, R. C. Crain, and J. R. Wilson

MODELING CONCEPTS FOR INTELLIGENT VEHICLE HIGHWAY SYSTEMS (IVHS) APPLICATIONS

Victor J. K. Hsin
Paul T. R. Wang

The MITRE Corporation
McLean, Virginia, U.S.A.

ABSTRACT

The Federal Highway Administration (FHWA) in cooperation with other government agencies, private industry, and academia, has established the Intelligent Vehicle Highway Systems (IVHS) program to use advanced computer and communications technology to increase throughput on existing roadways, to improve the safety of the traveling public, and to improve productivity of vehicle operations. Communications and vehicle traffic control are two major technologies used directly or indirectly to support the above IVHS program. This paper describes vehicle traffic and communications system modeling concepts used to analyze IVHS applications. The modeling concepts for IVHS traffic analysis section focuses on issues, solutions, and the design principles of an object-oriented model. The modeling concepts for communications system analysis section discusses Commercial Vehicle Operations (CVO) related architecture alternatives and performance analysis considerations. The paper summarizes the experience gained from our simulation/analysis and discusses the future direction for IVHS modeling studies.

1. INTRODUCTION

As stated in FHWA (1991), congestion on the nation's highways is becoming a major national problem, with delays and accidents on the nation's freeways costing billions of dollars in lost wages and direct costs. Continued expansion of the nation's highway system is, by itself, no longer an adequate option for reducing traffic congestion; therefore, the Federal Highway Administration (FHWA) has established the Intelligent Vehicle Highway System (IVHS) program to use advanced computer and communications technology to increase throughput on existing roadways, to improve the safety of the traveling public, and to improve productivity of commercial vehicle operations. The IVHS program has evolved to include five major system areas: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Commercial Vehicle Operations (CVO), Advanced Vehicle Control Systems (AVCS), and Advanced Public Transportation Systems (APTS). Each of these five focuses on different applications of IVHS technologies to highway system needs. Many technologies have been utilized to support the above five system areas. Among them, communications and vehicle traffic management are two critical technologies employed to support the IVHS applications.

Many papers in the literature have discussed the issues related to the IVHS vehicle traffic simulation, but only a few papers, i.e., McGurrin/Wang (1991) and Rodriguez-Moscoso/Chin/Santiago/Roland (1989), have mentioned object-oriented approaches. In the areas of communication system modeling, currently only a few papers, e.g., Ijaha et al. (1991), Catling et al. (1991), and Wall et al. (1991), discuss IVHS-related communications modeling; however communications systems modeling concepts have been studied substantially for applications other than IVHS in the past, which provide a valuable input for IVHS modeling studies.

This paper describes the concepts for vehicle traffic and communications system analysis for IVHS applications. Section 2 describes the vehicle traffic modeling concepts and focuses on the object-oriented traffic simulation and design principles of the Traffic and Highway Objects for Research, Analysis, and Understanding (THOREAU) model. The modeling concepts for communications system are discussed in section 3. Section 4 summarizes the experience gained from simulation/analysis and discusses the future direction for IVHS modeling.

2. IVHS VEHICLE TRAFFIC MODELING CONCEPTS

2.1 Vehicular Traffic Analysis Modeling Overview

Traffic models encompass both analytic and simulation models. Analytic models incorporate various equations derived from decades of traffic engineering experience and the analysis of the various relationships between traffic flow, vehicle speed, vehicle density, roadway capacity, driver behavior, and travel time. Analytic equations are commonly used in urban transportation capacity analysis, traffic flow analysis, shock wave analysis, and traffic queueing analysis. A simple relation exists between the average traffic flow, F; average vehicle density, D; and average vehicle speed, V is F=DV. This is a conservation of flow equation, and is similar to the Ohm's law in electricity, E=IR, and Little's result $L=\lambda W$ in queueing theory. For more elaborate relations between road way capacity, travel time, vehicle speed, vehicle density, and traffic flow, the Highway Capacity Manual by the Transportation Research Board (1985) and Traffic Flow Fundamentals by Adolf D. May (1990) provide good sources of references.

Analytic models are very useful for deriving results involving random processes and equilibrium states. Consequently, such models have been used quite successfully for macroscopic traffic flow analysis and roadway capacity planning. However, at the microscopic level, the behavior of individual vehicles is governed by deterministic signal patterns, headway distribution, and roadway geometry; it is extremely difficult to derive analytic equations to describe precisely the microscopic aspects of roadway traffic because of the complexity, dynamics, and interdependency of traffic controls at various intersections and freeway junctions. Alternatively, simulation may be used with some degree of confidence to examine the microscopic as well as macroscopic aspects of travel time, vehicle speed, vehicle density, traffic flow, and signal control mechanism. Over the years, many good traffic simulation models have been developed. For examples, TRANSYT-7F (FHWA, 1986) and the TRAF family of models including NETSIM (FHWA, 1989), FRESIM (Halati, Torres, and Cohen, 1991), NETFLOW, and FREFLOW (FHWA, 1988). NETFLOW, FREFLOW, and TRANSYT-7F are macroscopic traffic simulation models while NETSIM, and FRESIM are microscopic traffic simulation models. Macroscopic models simulate analytic flow/density/speed relations while microscopic models simulate signal control, turn movements, vehicle-following, and other individual vehicle maneuvers. Recently, several "mesoscopic" models have been developed. These track the movement of individual vehicles, as microscopic models do, but model their movements using macroscopic flow equations. Two such model are Integration (Rilett, Van Aerde, and MacKinnon, 1991) and Dynasmart (Jayakrishnan, Irvine, and Mahmassani, 1991).

2.2 IVHS Traffic Analysis Modeling Issues

As IVHS is an umbrella term and the IVHS architecture is still evolving, with many alternatives and unresolved issues, related traffic simulations should provide rapid and quantitative analysis of benefits and tradeoffs. Therefore, to adequately model IVHS alternatives, the key modeling issues are modularity, flexibility, scope, run time, and validation. To establish its credibility, a model must be validated against established results and operational field data.

Modularity. Modularity in traffic simulation refers to the basic structure on which vehicles, network, control, data, and functional elements are organized in a modular fashion to allow rapid identification and modification of model components.

Flexibility. Flexibility refers to the relative easiness of model alteration and expansion to accommodate alternative designs, implementations, or proposed solutions such as route guidance, actuated signal control, or ramp metering. Flexibility in IVHS modeling also include the ability to generate various traffic scenarios such as toll collection or incidents, with little programming effort. Great attention should be given at model design time to achieve the desired flexibility. Modularity alone is necessary but not sufficient to assure flexibility.

Scope. Since IVHS technology encompasses both local and area wide traffic control mechanisms and strategies, the scope of traffic models will include microscopic signal control and vehicle turn movements simulation, and macroscopic traffic flow simulation over an entire metropolitan area. For ATMS analysis, the central issue is how to optimize traffic signal control to reduce total trip delay and implement optimal incident recovery strategies. For ATIS analysis, the main concern is to provide optimal routes for individual trips and good route guidance instructions to drivers. A key measurement of IVHS benefit is trip time. Consequently, both microscopic node simulation and trip-specific mesoscopic link simulation must be included.

Run-Time. The ability to model a large area traffic network consisting of thousands of links, nodes, and vehicles pose a great challenge. Efforts and solutions to reduce simulation run time should be rigorously pursued.

Validation. Validation is an essential part of model development. Models may be validated directly or indirectly. After a model is calibrated for certain input parameters, its output can be compared directly with data from controlled field tests to determine the level of confidence. A model may also be validated indirectly through comparisons of outputs from models for which credibility has been established either directly or indirectly. There are various types of validation, including face validation (the results look right), validation of the internal algorithms and validation of quantitative outputs.

2.3 Solutions To IVHS Traffic Analysis Modeling

This section describes the solutions to these issues used or planned for the THOREAU model.

Object-Oriented Simulation. Given the above issues, the objective is to achieve flexibility and model traffic flow at both microscopic and mesoscopic levels. We will argue that object-oriented simulation is essential to provide the required modularity and flexibility through the concepts of inheritance, polymorphism, and data encapsulation. For example, a link object consisting of name, a length field, orientation, and end nodes can be inherited by either a pocket, lane, street, or a freeway segment object. Another example is a vehicle object which can inherit all attributes of both an image object and a dynamic object to facilitate graphic animation. Similarly, UTCS (FHWA, 1985) signal controllers can be implemented as a traffic-light object with certain number of detector objects that are assigned to appropriate link objects.

Discrete-Event Simulation. A second concept recommended for IVHS traffic simulation is the use of discrete-event simulation instead of time-step simulation. In a time-step driven simulation, processing time is wasted between two steps if no new event occurs; while in a discrete event driven simulation, which is typically supported by special simulation languages such as Simscript or MODSIM, the simulation clock advances asynchronously to the next pending event without delay. Thus, discrete event simulation will run at its maximum possible speed limited only by hardware and software constraints. THOREAU takes full advantages of discrete event simulation using object-oriented simulation language MODSIM II marketed by the CACI Company.

State-Transition and Keyword Approaches. Other modeling concepts used in THOREAU model development include a state-transition vehicle-following approach and the adoption of keyword model specification. A vehicle is always in one of the four states: stop, acceleration, deceleration, or moving at a uniform speed. Transition to the next state is determined from the current headway, related offset to the start of a link segment, current speed, and the state of the preceding vehicle or the approached intersection if the vehicle is a lead vehicle. State-transition vehicle-following approach can be checked for completeness using a state diagram (Figure 1). A keyword style model specification abandons FORTRAN style fixed format input file structure. Instead, model inputs are defined as pairs of keyword and value. New keyword pairs can be added easily to incorporate new model elements. Both a state-transition approach and keyword input file specification fit naturally with object-oriented programming practice.

A High-Speed Parallel Computing Platform. To achieve reasonable run time for large scale IVHS traffic simulation, parallel computing using either a distributed or parallel computing platform should also be considered. While object-oriented simulation should reduce significantly the model development time, it will not reduce model execution time, and may increase it. Therefore, it may require additional effort to implement key algorithms in C or other programming languages. For example, the Floyd and modified Floyd algorithms

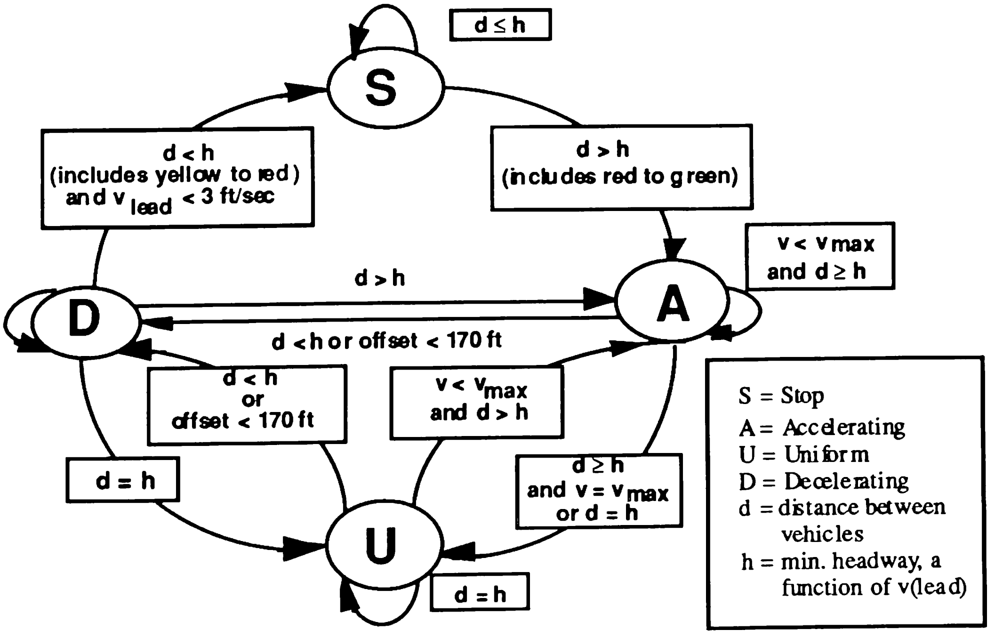

Figure 1: Vehicle State Machine

used for computing shortest paths between node pairs may be coded directly in C instead of MODSIM to reduce run time. We are planning to investigate these options in the coming year.

2.4 THOREAU Validations and Applications

THOREAU is the product of a 1991/92 MITRE sponsored research project called Vehicular Traffic Analysis Capability (VTAC) (McGurrin and Wang, 1991) to develop an object-oriented, trip specific, microscopic, and mesoscopic traffic simulation model designed for comparative IVHS analysis of IVHS concepts. THOREAU is coded in MODSIM II, an object-oriented simulation language marketed by the CACI Company. MODSIM II provides an ideal platform for speedy development of THOREAU with graphic animation capability to check out microscopic vehicle-following maneuvers, UTCS intersection controllers, and turn movements with stop signs or signal control. Measures of effectiveness (MOE) implemented in THOREAU include trip time, link time, delay at intersections, frequency of route changes, and counts of major events such lane changes, stops for traffic lights etc. All MOEs are cumulated individually and globally.

Three THOREAU models have been successfully constructed and validated against known traffic models. The first model is a microscopic proof-of-concepts model called MiniTown. MiniTown depicts two intersections with 14 one-way arterial streets (links). A total of 30 distinct trips are generated from six entry links. MiniTown was used to check out vehicle maneuvers at intersection, signal controllers, and headway histograms for tightly coupled vehicles. The results of trip time and node delay from MiniTown were compared with results obtained from equivalent NETSIM and HCS models (McGurrin and Wang, 1991). Headway and speed relations for tightly coupled vehicles are compared with predictions from the Pitt's equation (JTF Associates, 1990), used in several well-established traffic models. Figure 2 shows the close match of the THOREAU simulation against the Pitt's equation.

A second model, Troy, depicts the roadway traffic in Troy, Michigan. The Troy model consists of 440 one way links and 65 fixed time intersection controllers, 36 uncontrolled intersections, and one freeway. The Troy model is used to check out dynamic routing using shortest time paths for drivers with ATIS devices. A third model consisting of 700 arterial streets, two freeways, and 250 UTCS intersection controllers has been constructed for central Orlando, Florida. The central Orlando model is used to check out UTCS actuated intersection controllers. Field trip data generated by the TRANPLAN, a transportation capacity planning tool, were used for both the Troy and Central Orlando models in IVHS-related studies. THOREAU simulation results will be calibrated and validated against field test data from the IVHS pilot programs such as TravTek in Orlando, Florida, and Fast-Trac in Troy, Michigan.

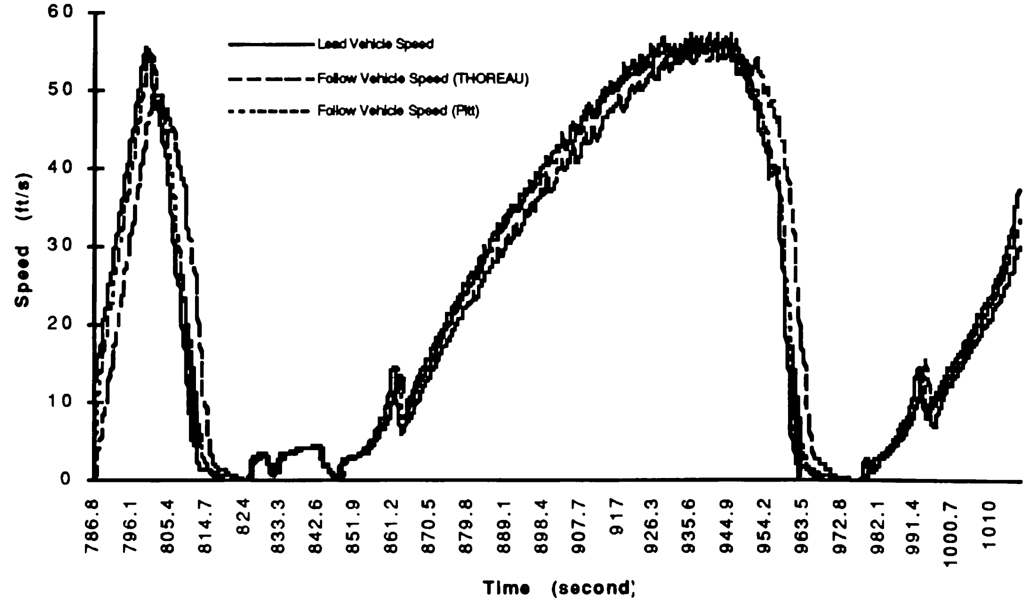

Figure 2: Comparison of THOREAU and Pitt

2.5 Summary of the Vehicle Traffic Analysis Modeling Concepts

Since object-oriented vehicle traffic simulations such as THOREAU can significantly reduce the model development time, model developers will be able to concentrate more on the validation and simplification of the design. Therefore, less errors and more robust models can be expected. In general, object-oriented simulations may not reduce model execution time as compared to models coded directly in other high order languages. It may require specific coded routines in other non object-oriented languages to achieve run time reduction. Due to speed limitations THOREAU can not currently model large networks with a large number of objects such as the Los Angeles Basin or the Greater Orlando, Florida area. High-speed distributed/parallel processing may provide a solution to this problem. MITRE is in the process of initiating a two-year project to port THOREAU to a distributed/parallel computing platform. Several alternatives are being considered, including converting THOREAU to either parallel MODSIM 2.0 or SIM++ under Time Warp. Both parallel MODSIM and SIM++ are also object-oriented simulation languages, marketed by the Jade Simulations International Corporation. Similar to MODSIM 2.0, an experimental implementation of MODSIM for parallel computing on a BBN Butterfly machine using JPL Time Warp Operating System is also available from the CACI Company.

Although THOREAU, Integration, or Dynasmart may provide the framework for simulations of IVHS implementation alternatives, the validation of a specific model and vendor specific algorithms will always be issues of concerns because a simulation will only be useful if it can be validated against statistics collected from operational field tests. Thus, validation of traffic simulations for IVHS are partially dependent on the accessibility of vendor specific algorithms used in ATIS and ATMS field tests.

3. IVHS COMMUNICATIONS SYSTEM MODELING CONCEPTS

3.1 Communications Architecture Considerations

Architecture Description. The communications alternatives and requirements that are needed to support the potential IVHS applications of the five system areas as mentioned earlier are very similar. Since CVO is the area which usually employs new technologies faster than other areas, due to a more rapid and direct return on investment, this paper will start with the CVO applications first, then extend the same concerns to other areas.

Figure 3 is an overview of the required components and communications interfaces for CVO applications. The figure shows the in-vehicle information management system (IVIMS) which contain communication links, and the components of the infrastructure. In order to model system performance, the characteristics of the applications, the communication alternatives, and information flow requirements must be defined.

Applications. CVO applications include the following categories:

- Registration, permits, routing, and inspection status
- Tax reporting and auditing
- Commercial Vehicle Tracking (CVT)
- Vehicle monitoring
- Driver Information
- Traffic Information

The above applications typically involve voice and data communications. Some applications (i.e., tracking, location) involving GPS or LORAN-C signals, may be classified as a special case of data communications with short message sizes in a fixed time frame. The communications considered in this paper is occur between vehicle and infrastructure. For some simple applications, the communications path may include only in-vehicle systems and road-side computers; for other applications, the path may also include, public or private data networks (e.s. X.25 or ISDN), and LANs in regional computer centers.

Communication Alternatives. The communication alternatives for the above applications consist of two major categories. One is wireless communication which is a major media for the communications between vehicle and infrastructure; another is the infrastructure-to-infrastructure communications, which may be provided by public or private providers and may involve land lines, satellites or radio. IVHS infrastructure communications standards have not been established; existing systems must be adapted for infrastructure communications among different agencies or traffic control centers. For vehicle to road-side communications, the alternatives include beacon, cellular, RF networks, and satellite technologies.

The CVO communication technology trade-offs include throughput requirements, coverage, number of sites, complexity, and cost (including acquisition, installation and operations for both the vehicle and infrastructure components). As the features of in-vehicle information and management systems increase, so will the quantity and density of data communications. The communication systems must allow this evolutionary growth to be handled gracefully to avoid the additional cost for replacement with new systems.

3.2 Performance Modeling Issues

To understand the behavior of the communication systems under study, performance models must be constructed. In general, the performance modeling process starts with information flow analysis and then

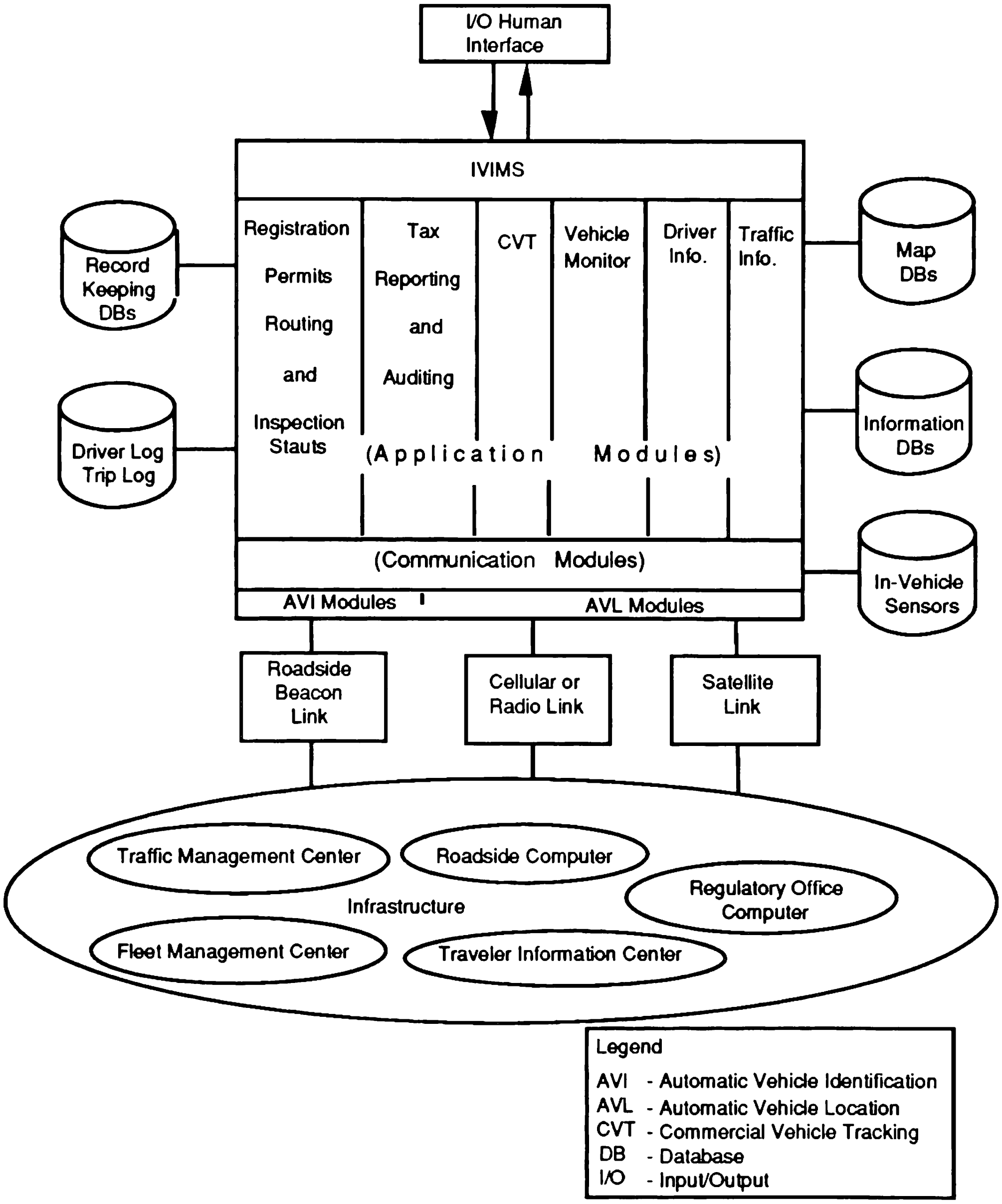

Figure 3: Vehicle-Infrastructure Communications Systems Structure

develops the related performance measures, and finally predicts the performance measures for a specific system design concept.

Information Flow Analysis An information flow analysis identifies the informations which must be exchanged between each set of communications entities, at a level of detail sufficient to provide a logical basis for the rational design and evaluation of processing, database, and communications systems. In order to insure that information flow requirements are defined in sufficient detail, it is first necessary to develop a framework, which specifies the necessary data fields, message, frequency, and database descriptive parameters. Performance requirements are specifications against which a system can be designed and evaluated to satisfy the information flow requirements for a certain application. The values to be taken on by some performance measures, e.g., Availability, Grade of Service (GOS), and Tolerable Error, may be specified by the user. Other performance measures (i.e., spectrum, sizes) may be specified by the designer or both. In all cases, the performance measures must take on those values that result in the satisfaction of the information flow requirements.

Performance Measures Determination. The IVHS communications systems related performance measures are the same as those for most other communications systems, only the actual parameters differ. These measures are discussed in the following paragraphs.

Reliability and *availability* are the most commonly used performance measurements for communications systems. Reliability is the probability that a part, component, subsystem, or system will perform for a specified interval under stated conditions with no malfunctions or degradations that require corrective maintenance or repair actions. Availability is the probability that a service/system will be available to the user for the transmission and reception of messages. The analysis of these two measures is based upon two basic parameters: Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR).

In general, the value for reliability is specified by users (or sometimes by both users and designers) and used by designers to develop a system to satisfy the users' requirements. The information from the full range of prospective users and developers is not available, however, the minimum MTBF requirements for the communications systems of the Heavy Vehicle Electronic License Plate (HELP) and Advantage I-75 operational test programs are 15,280 hours and 18,000 hours respectively. The IVIMS reliability measurement can be assumed to be 16,000 hours for the MTBF, which means only one failure is allowed within an approximate two-year operation.

The availability measurements are usually expressed as a combination of MTBF and Mean Time To Repair (MTTR). MTTR may be estimated by dividing the estimated total corrective repair time in hours by the total number of repair actions. MTTR includes all repair related normal elapsed time documented, but excludes extra delays caused by inefficient administration, supply, and transportation. The HELP and Advantage I-75 programs showed the MTTR with values ranging from one day to five days.

Response time is the interval between the time that a user directs his terminal to transmit information or messages to a computer (at infrastructure) and the time the last character of the response appears on the screen or terminal. For vehicle to roadside communications, the response time intervals in CVO applications include time required to:

- Process the message at the IVIMS
- Transmit the message to the roadside computer
- Process the message at the roadside computer system
- Transmit the response message back to the originating IVIMS terminal

When the vehicle is moving, the response time interval must be able to allow the information exchange between the vehicle and roadside computers within the effective information exchange time frame. For example, if the vehicle is assumed moving at 100 mph, this corresponds to 147 feet per second. For limited range beacon systems, the information exchange must be completed within a second for an effective information exchange distance of 150 feet (current commercially available products can handle the information exchange in about 200 feet). Therefore, for a moving vehicle application, the assumption of 1/2 second for mean response time can be made. We also assume that about 99 percent of the time, the response time intervals are required to be less than 1 second. However, when the vehicle is not moving, the requirements can be relaxed. Since the human tolerable interactive time between terminals and computers is about 2-8 seconds as described in FSIMC (1989), all the information flow exchange must be accomplished within such time frame. We assume that the average response time of the IVIMS applications is 2 seconds and that 99 percent of all responses must be received within 5 seconds for non-moving situation.

Throughput is the quantity of information that can be passed from a sending device to a receiving device during a specified interval of time. Currently available products can handle a transmission rate of 500 kbps or higher; it is more than enough for IVIMS communication needs.

Blocking Factor, also called Grade of Service (GOS), is the probability that a call attempt will be unsuccessful, e.g., a busy signal. An acceptable factor for CVO applications has not been determined.

Performance Measures Prediction. To assess the potential effects on performance of changes of in the existing network characteristics, prediction techniques are needed. The prediction of the major performance measures of IVHS-CVO communication systems can be accomplished through analytic or simulation approaches.

Traditionally, analytical methods are used to model networks of this magnitude using a series of equations, numerical techniques, closed-form expressions, or heuristic algorithms that have a logical relationship manipulable according to formal rules. The main advantage of an analytical model is that once developed, it can be executed repeatedly under differing inputs conditions to determine performance sensitivity with little change in the model structure. The problem with the analytical approach is that it requires many simplifying assumptions. The results are highly dependent on the accuracy of these assumptions which may lead to substantial overestimates or underestimates of actual performance. Thus, attention has focused in recent years on the simulation method in order to improve on the accuracy and reliability of analytical methods. The primary drawback of this approach in the past has been the large amount of time required to produce the original model and also to alter the model for sensitivity studies. Recently many commercially released packages (e.g., COMNET II.5 of the CACI Products Company, CA; DNDS of the Connections Telecommunications Inc., MASS; or NPAT of the WANDL Inc., NJ) with the help of powerful work stations, have shown major improvements in this area.

Tool selection. Tool selection is a major issue in the modeling process. A graphical user interface (GUI) can significantly reduce the time and effort needed for building models and conducting sensitivity studies. An example is the use of iconic building blocks for nearly all types of network configurations. These building blocks include nodes of the network and links connecting the nodes. Nodes represent sources and destinations for network traffic while a link is a transmission facility which connects two or more nodes. To define a node, the user merely makes a menu selection, which pops up a dialog box indicating all the information that needs to be provided. To define connectivity, the user simply drags the mouse from one node to the next. Another time saving concern is that a change made to the network should be assimilated through the entire structure without having to change each individual entity. For example, changing the hardware or traffic structure of a node should also make the related changes on the links and routing algorithm.

Hsin and Ferrante (1990) have performed several studies to evaluate the effectiveness of computerized simulation techniques and tools. They analyzed a sizable network under a variety of traffic growth and crisis scenarios to evaluate their impacts on network performance. From that simulation experience, the computer-based simulation tool, COMNET II.5 has been proven a useful tool for analysis of wide area infrastructure communications, using existing standard protocols. Currently, the system contains limited analytical modeling capabilities, i.e., the abilities to incorporate different performance measurements (reliability, availability) and routing algorithms. However, the COMNET II.5 simulation tool may interface with some users' specific analytical models through "C" programs. Other, similar commercial communications modeling packages are also available, as are tools for modeling radio networks.

4. CONCLUSIONS

This paper has discussed modeling concepts for IVHS traffic flow and CVO communications system analysis. The concepts provide a useful mechanism to simulate real world IVHS environments. However, based on our experiences, some future work in the following areas might be helpful to improve the modeling quality and efficiency for more complicated IVHS application studies.

Parallel Processing for Modeling. Current microscopic traffic models cannot model large networks in resasonable time. Parallel processing for simulation models may provide the necessary reduction in run-time.

Performance Analysis Expansion. There is a need for a set of tools which can model the full communications path, including both mobile communications and new protocols.

ACKNOWLEDGEMENTS

We gratefully acknowledge valuable suggestions and comments made by Michael McGurrin, the IVHS Project Leader at MITRE. We also thank Edward Wells for editorial review and Cheryl Simpson for formating and graphics assistance.

REFERENCES

Catling, Ian et al., October 20-23, 1991, "Scenarios and Communications System Architecture for Integrated RTI/IVHS Applications, VNIS '91.

Federal Highway Administration, October, 1991, *An Overview of the IVHS Program through FY 1991*, McLean VA.

Federal Systems Integration and Management Center, March 1989, *Designing Data Communications Networks*, Washington, DC.

Federal Highway Administration, *NETSIM User's Manual*, U.S. Department of Transportation, 1989.

Federal Highway Administration, *Traffic Control Systems Handbook*, Section 3.8, PB86-131760, FHWA-IP-85-11, National Technical Information Service, U.S. Department of Commerce, April, 1985.

Federal Highway Administration, *TRAF User Guide*, FHWA-RD-88, U.S. Department of Transportation, 1988.

Federal Highway Administration, *TRANSYT-7F: Traffic Network Study Tool (Version 7F)*, U.S. DOT, Washington, D.C., 1986.

Halati, A., Torres, J. F., and Cohen, S. L., FRESIM - Freeway Simulation Model, Paper #9102202, Transportation Research Board 70th Annual Meeting, Washington, D.C., January, 1991.

Hsin, V. and F. Ferrante, December, 1990, "Concept for FTS2000 Performance Modeling," *The Telecommunications Review*, The MITRE Corporation, McLean, VA.

Ijaha, S. E. et al.,May 1991, "A Computer Modeling of Digital Microwave Transponding Links for Automatic Road-use Debiting Systems", Paper #910082,*ISATA'91 Conference Proceedings*, Florence, Italy.

Jayakrishnan, R., Irvine, and Mahmassani, H. S., "Dynamic Traffic Network Simulation--Assignment Modelling for Advanced Driver Information Systems, "Paper #912801, *Vehicle Navigation & Information Systems Conference Proceedings*, VNIS'91, October 20-23, 1991.

JFT Associates, "Freeway Simulation Model Enhancement and Integration," FHWA Contract DTFH61-85-C-00094, Pacific Palisades, CA, February, 1990.

May, Adolf D., *Traffic Flow Fundamentals*, University of California, Berkeley, Prentice-Hall, Inc., New Jersey, 1990.

McGurrin, M and Paul T. R. Wang, October 20-23, 1991, "An Object-Oriented Traffic Simulation with IVHS Applications", Paper #912797, Vehicle Navigation & Information Systems Conference Proceedings, VNIS '91, Dearborn, Michigan.

Rilett, L. R.,Van Aerde, M., and MacKinnon, G., "Simulating the TravTek Route Guidance Logic Using the Integration Traffic Model," Paper # 912824, *Vehicle Navigation & Information Systems Conference Proceedings,* VNIS'91, Dearborn, Michigan, October 20-23, 1991, pp. 775-788.

Rodriguez-Moscoso, J., Chin, S.M., Santiago, A. and Roland, R. "Object-Oriented Programming in Traffic Simulation", CONF-8902150-1, Oak Ridge National Laboratory.

Wall, Nigel et al., "Integrated Communications Architecture for Road Transport Informatics," Vehicle Navigation & Information Systems Conference Proceedings, VNIS'91, Dearborn, Michigan.

AUTHOR BIOGRAPHIES

VICTOR J. HSIN received the a Ph.D. in Operations Research and information Systems from the University of Texas at Austin. He is a lecturer at Johns Hopkins University and a member of the technical staff in MITRE's Intelligent Highway Systems Group. Before joining MITRE, he had been with AT&T Bell Laboratories from 1980-1985 and the GTE Corporation from 1985-1988.

PAUL T. R. WANG received the B.S. degree in mathematics from the Cheng Kung University, Taiwan, in 1966. He received the M.S. and PhD. degrees in computer and information sciences from the Ohio State University in 1973. From 1973 to 1983 he was with the General Electric Company, serving as a consulting engineer in the performance evaluation of the MARK III computer system architecture and operating systems. Since 1983 he has been with The MITRE Corporation. Currently, he is a Lead Scientist within MITRE's CAASD Modeling and Simulation Center. His interests include optimization, simulation, modeling, and queueing theory. He is a member of MAA.