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Title: Modeling Analysis for IVHS Architecture Evaluation

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ABSTRACT:

For the Federal Highway Administration (FHWA)-sponsored Intelligent Vehicle Highway Systems (IVHS) systems architecture study, proposed architectures will be evaluated against a defined criteria set. A subset of these criteria will be evaluated quantitatively through modeling. In order to perform this quantitative analysis, a proposed physical architecture will be developed into an evaluatory design for a common scenario, or geographic region. This paper outlines a plan for analyzing the evaluatory design through traffic and communication simulation. Modeling requirements and a survey of candidate traffic and communications simulations are presented, followed by a discussion of leading candidates and a recommendation for model selection.

KEYWORDS: Intelligent Vehicle Highway Systems, Simulation, Smart Highways, System Architecture, Transportation Modeling

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INTRODUCTION

1.1 BACKGROUND

MITRE is supporting the Federal Highway Administration (FHWA) in their efforts to define a national Intelligent Vehicle Highway Systems (IVHS) architecture. As currently envisioned, this will be accomplished by funding competing contractor teams. Through a process of consensus building and technical analysis .of competing approaches, the national IVHS architecture will be chosen. The task of identifying and differentiating a promising lVHS architecture from competing approaches necessitates the ability to quantitatively measure the costs and benefits of implementing competing architectures. Since it is not possible to quantify the performance of a physical architecture, representative evaluatory system designs of the proposed architectures will be defined. The proposed physical architecture is developed into an evaluatory system design for a set of supplied roadway topology and travel demands corresponding to a specific geographic region, or scenario. Using these evaluatory system designs that are generated based on provided scenario data, an analyst may employ a set of modeling techniques to perform a quantitative evaluation of the architecture and directly compare the results against a competing architecture using the same baseline data. In this approach, special care must be taken to ensure that one is comparing architectures rather than implementation details.

1.2 PURPOSE

A set of criteria for architecture evaluation has been defined as a part of the national IVHS architecture procurement. A subset of those criteria that will be evaluated through modeling are detailed in table l-l.

Some issues will not be directly modeled. For example, no explicit human factors/ ergonomics aspect will be modeled, since architectures can support a wide range of ergonomic designs. Thus, ergonomic issues are primarily an implementation detail and not an architecture issue.

Similarly, Commercial Vehicle Operations (CVO) and Fleet Management operations will not be modeled explicitly since the impacts can be assessed without a detailed traffic simulation. While automatic toll collection in particular may yield benefits to the roadway system in terms of reduced travel times and emissions, this effect is considered architecture-independent.

Emergency vehicles are also not modeled explicitly in the traffic model. Decrease in response time may be inferred from a two-part analysis. First, response time is decreased by improved incident detection and dispatch time. This is part of the communications analysis.

Table l-l. Criteria Evaluated Through Modeling

1. Performance of variously equipped vehicles
    - Under recurrent and nonrecurrent congestion
    - Compared against a baseline case (100 percent background traffic)
2. User travel performance measures
    - Change in average user travel time
    - Reduction in user queue time
3. **Traffic system performance measures**
    - Change **in total system travel time**
    - Reduction in congestion
    - Reduction in VMT
    - Reduction in energy consumption
    - Reduction in pollution emissions
4. Penetration levels for effective performance
5. First user benefits
    - Network performance at low penetration levels
6. Adequacy of communication system capacity vis-a-vis expected demand
7. Technology limits on the size of market
    - Outbound and inbound communication

Second, emergency vehicles will experience at least the same reduction in travel time as other vehicles on the network in reaching the incident site. Additional benefits, from signal preemption and other traffic control measures, are not measured explicitly because of difficulty of adapting existing simulations to model this rather infrequent event. Thus, reduction in response time may be estimated relatively accurately without explicit modeling.

The criteria that will be modeled in the architecture evaluation effort center on capturing nuances of two distinct aspects of the proposed architecture implementation:

- The effect of architecture implementation on traffic conditions
- The ability of the architecture to support the communications load placed on the system

Criterion (1) is a measure of the benefits accrued because of the implementation of the architecture, while criterion (2) is a measure of the adequacy of the proposed communications system. Thus, an effective analysis will model both traffic and communications aspects of an architecture in detail. Given the long lead times and complexity of developing a single model for both traffic and communication modeling, using separate models for these two aspects is recommended.

The contractor teams will use traffic and communication models to prepare the quantitative measures of effectiveness for these criteria in their reports to the architecture manager. In addition, MITRE will use these models to perform verification and validation of some of the results provided by the contractor teams. This document reviews and recommends specific modeling and analysis tools. MITRE will be responsible for maintaining this set of models, and will make changes to the model source code in order to accurately represent the proposed architectures. All source code changes will be approved by the architecture manager. Contractor teams will be required to use a set of selected traffic models to provide for uniformity and comparability of results. However, the contractor teams may use any communication model, subject to government approval. This document also makes a recommendation for the communication model to be used in the independent validation and verification effort that will be conducted by MITRE. This report builds on several MITRE technical reports dealing with M-IS architecture, both in terms of potential frameworks (Cheslow et al., 1992a) and qualitative analysis (Cheslow et al., 1992b).

1.3 ORGANIZATION OF THE REPORT

This document is broken into five sections. In section 2, the relationship of traffic and communications modeling is discussed in terms of an overall quantitative architecture evaluation plan. In section 3, a discussion of requirements for the traffic model(s) is presented. In section 4, modeling requirements for communications evaluation are presented. In section 5, recommendations are presented for both the traffic and communication models.

SECTION 2

QUANTITATIVE IVHS ARCHITECTURE EVALUATION

2.1 A PLAN FOR QUANTITATIVE IVHS ARCHITECTURE EVALUATION

A traffic model and a communications model will be used in tandem for architecture evaluation. The traffic model provides a measure of the benefits accrued to the system because of the architecture's implementation, both in terms of system and user travel time reduction. The traffic model will use an update period and missed message rate supported by analysis from the communications model. In turn, data from the traffic model on localized flow conditions will be used to determine the demand on the communications system.

The approach is illustrated in figure 2-l. In the upper left of the "Scenario Data" box diagram are government-defined data files describing a specific geographic region in terms of roadway networks, associated trip tables, and other data. This data will be supplied to the contractor teams in a ready-to-use format for the recommended traffic and simulation models.

Contractor team deliverables are indicated in the upper right of figure 2- 1. The contractor teams will supply an evaluation design plan for each scenario. This plan will describe the location and function of all system components. Each evaluatory design will be based on a physical architecture. The physical architecture is derived from a functional architecture that is derived from a mission statement incorporating the required IVHS user services. The plan, together with a set of contractor-selected traffic management controls and procedures, are inputs to the traffic model.

In addition to the scenario data and the evaluation design, the traffic model is also dependent on the proposed architecture's communication system capacity parameters. A communication system that is unable to handle the communication demands on the network will not be able to provide timely, accurate updates on network conditions, resulting in decreased traffic management effectiveness.

The communications model has a similar set of inputs, drawn from the set of DOT-supplied scenario data, the contractor-supplied evaluatory design plan, and a dynamic profile of communication demand. The communication demand profile is comprised of the number, location and type of messages generated within the system. The demand profile is thus dependent on the number of vehicles passing certain portions of the roadway network and related to the output of the traffic simulation. For example, under high market penetration, the dissemination of certain route guidance instructions may considerably influence the experienced traffic patterns on the network, resulting in locally heavy communication demands. Under different traffic management strategies the result may be more evenly distributed communication demands.

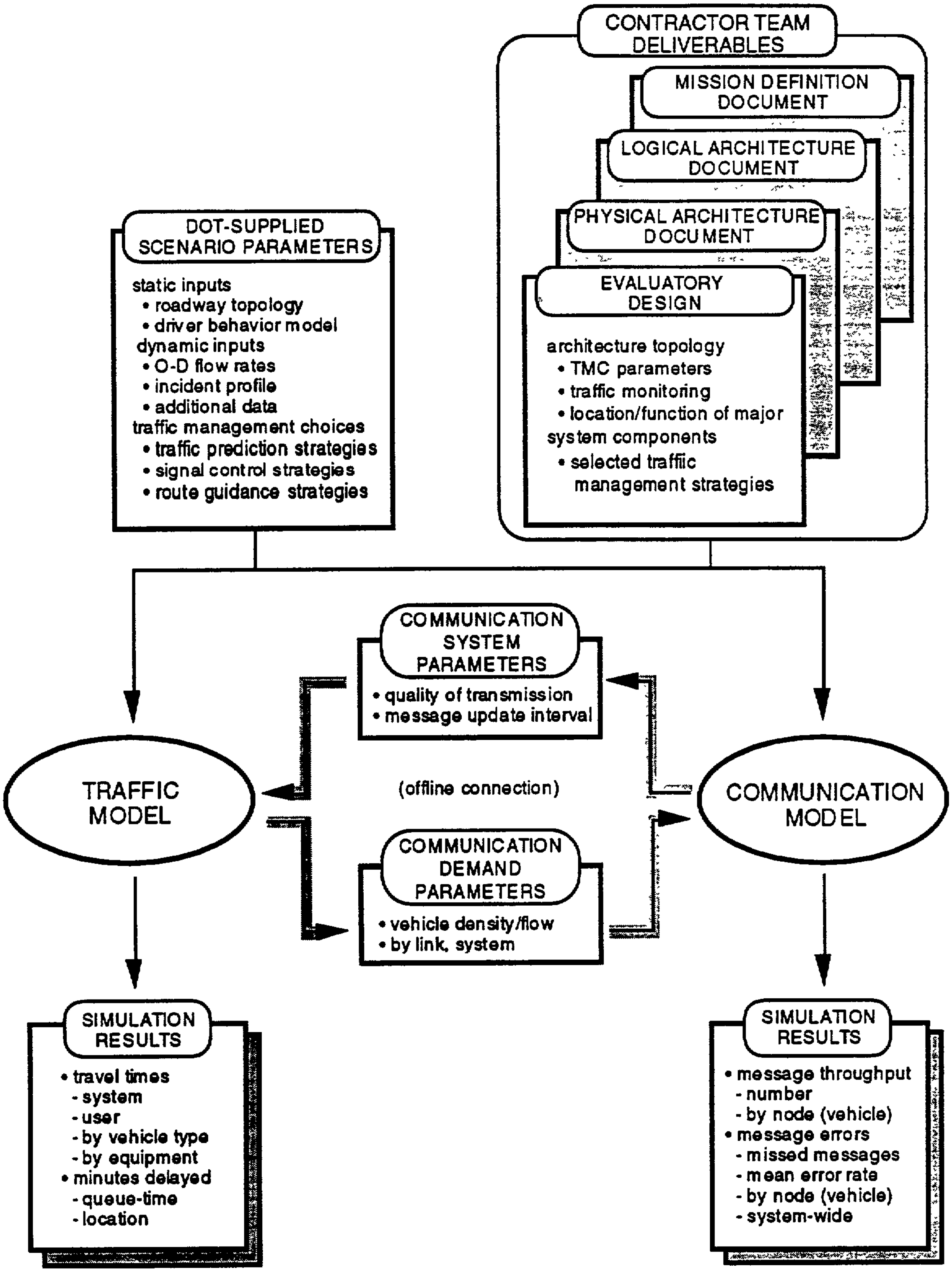

Figure 2-1. Quantitative Architecture Evaluation Plan

Analysis of the interaction between traffic flow and communication demand can be accurately modeled using the two models. In order to take advantage of Commercial Off-the-Shelf Software (COTS), existing simulation packages will be run separately with data exchanged between them off-line.

A model or set of traffic models will be included with the scenario data for the contractor teams to work with. Thus the selection of these models is critical to the accuracy of the analysis these teams will perform. The contractor teams will be required to use the provided traffic models to ensure comparability of results. For the communications model, the contractor teams may choose a model if one is particularly well-suited for evaluating their architecture, since the results are used to determine sizing and feasibility, not to compare architectures. A single communications model will be identified for use in Independent Validation and Verification (IV&V) efforts to be conducted by MITRE.

2.2 ARCHITECTURE DIFFERENTIATION

While a detailed quantitative look at the potential benefits of general IVHS implementation is a worthwhile task, it is not the same task as architecture evaluation. Different architectures may support the same or differing sets of route selection algorithms, traffic control policies and other traffic management strategies. While it may be true that potentially proprietary “software”/control issues may be critical to the success of IVHS in general, for architecture evaluation, we are concerned only that the architecture supports or does not support a generic kind of strategy.

For example, a route guidance algorithm that performs accurate link travel time prediction may provide significant travel time reductions against nonpredictive algorithms at high market penetration levels. While this is an important research topic, if this algorithm can be applied across several architectures, each architecture should be evaluated using it. The differentiation issue is one of support, that is, whether or not the architecture supports the implementation of a class of predictive route guidance algorithms. The contractor teams will not be expected to expend resources developing new route guidance strategies or traffic management techniques.

Because of this emphasis, a set of generic, nonproprietary control strategies will be provided for the contractor teams to use. A contractor team must justify that their architecture supports the strategy, and may include additional results using alternate strategies. If alternate strategies are employed, these strategies must be made available to all contractor teams for use if desired.

SECTION 3

TRAFFIC MODELING FOR ARCHITECTURE EVALUATION

This section describes the requirements for the traffic model within the architecture evaluation effort. First, potential modeling analyses are discussed in terms of both the scope they take and the detail they require. The requirements are defined and justified, followed by a survey of potential traffic models. The section concludes with a note on background (unequipped) vehicle modeling and model calibration.

3.1 MODEL SELECTION AND SCENARIO SCOPE

The FHWA plans to specify three scenarios in the solicitation for the national architecture: urban, inter-urban, and rural. Contractor teams will prepare an evaluatory design describing the function and location of major system components for each scenario. In addition, contractor teams are required to address changes to this design in a series of five-, ten-, and twenty-year evolutionary snapshots.

Modeling analyses must be performed to generate quantitative measures of effectiveness for the identified evaluation criteria. These analyses may differ greatly in terms of their scope. Scope is defined here as a general measure of complexity, combining both requisite geographic coverage area and level of detail. In general, one can think of the analyses for each of the scenarios as falling into two camps, one on a strategic, the other tactical.

A ***strategic*** analysis focuses on a larger geographic area with less detail. A strategic analysis will also deal with relatively large numbers of vehicles (tens of thousands) in the system. Most traveling is done on highways and major arterials. A key analysis done at the strategic level is measuring the benefit of route guidance and trip planning technology. The analyst may measure benefits against such architecture-sensitive parameters as coverage area and market penetration effects. This type of strategic analysis generates a set of functional requirements that are different from that of tactical analyses.

A ***tactical*** analysis focuses on a smaller geographic area and attempts to model it in detail. An example of a tactical analysis is the detailed modeling of a small network of multi-lane, signalized intersections where vehicles are tightly clustered and traveling at a range of speeds. The analyst may want to compare the localized effects of various signal control strategies, or examine the benefits accrued by installing surveillance equipment at specific points in the network Tactical analysis focuses on detailed vehicle-vehicle interactions, not on overall system performance.

COTS traffic models are specifically built to model either regional traffic networks or small sets of localized detailed intersections. Those that claim to model both often emphasize one aspect at the expense of the other. This de facto separation is acknowledged within the traffic modeling community as a trade-off between the level of detail to be modeled and the scope of the network to be modeled. While ideally one might want to model the regional traffic network at the highest level of detail, the current state-of-the-art in modeling does not make this kind of unified analysis viable.

The range of COTS traffic simulation software is illustrated in figure 3-1. Macro-level models are usually employed for regional networks and use continuous flow-density functions to model traffic. Micro-level models model vehicles using car-following logic and gap acceptance, but are limited computationally to small networks and hundreds of vehicles. Meso-level models fall in-between Macro- and Micro-level models, and most often feature flow-density equations in conjunction with queuing models. Given the long lead times and complexity of developing a new traffic model, using COTS traffic simulation software for the architecture evaluation effort is recommended.

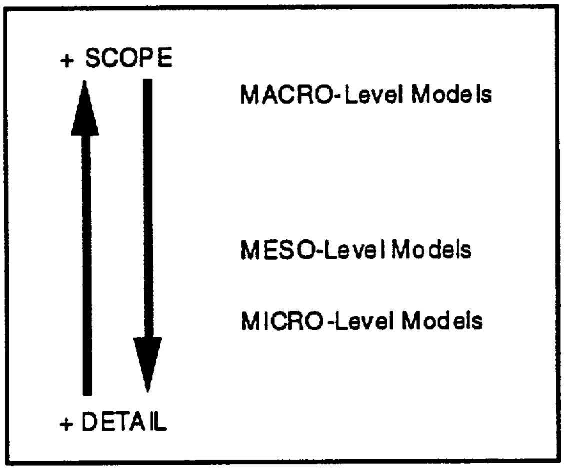

Figure 3-1. Model Scope and Detail

For architecture evaluation, there are several issues that lend strength to the argument that scenarios should be evaluated at both strategic and tactical levels. Part of the evaluation effort is the identification of the travel time reduction realized through the implementation of an architecture. A tactical analysis may be used to demonstrate effectiveness at the individual link level, but the impact on network-wide performance cannot be accurately extrapolated from the tactical level to the strategic level, especially for user services such as route selection. Similarly, because of the limitations in COTS traffic simulation software, a strategic analysis is not appropriate for capturing detailed effects at network "hotspots," for example, incident locations, surface-street intersections and freeway ramps.

For example, given the urban scenario, contractor teams will be expected to demonstrate the effectiveness of both Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) technologies. Route guidance is best analyzed at a strategic level. Signal control is best analyzed at a tactical level. One model or a set of models must be identified to facilitate analyses at the strategic and tactical level.

3.2 MODELING REQUIREMENTS AND JUSTIFICATION

In this section, the modeling requirements for overall traffic modeling efforts are presented and justified. The requirements list is summarized in table 3-l.

The first 11 requirements are general requirements; that is, any model used in the architecture evaluation should support these capabilities. The remaining 11 requirements are broken down by strategic and tactical requirements. To facilitate the analyses required for architecture evaluation, a set of models must be identified, each of which satisfy the general requirements, and whose union satisfies all of the strategic and tactical modeling requirements.

3.2.1 General Model Requirements

This section describes the 11 general model requirements. Any strategic- or tactical-level model used for architecture evaluation should satisfy these requirements. Each requirement is stated and justified.

1. Models Generalized Network Topologies

   Requirement: It shall be capable of modeling various geometric configurations corresponding to roadway networks. The model shall be capable of representing networks corresponding to grid networks, stars, corridors, and other structures.

   Justification The evaluation effort will require evaluating several scenarios. In order to accurately reflect and capture the effectiveness of implementing the architecture in each scenarios, a model capable of handling various topologies is required.

2. Mature Model Using Proven Dynamic Methodology

   Requirement It shall be a proven, mature model recognized within the modeling community, fully tested and debugged. The model shall simulate changes in network-wide and localized traffic conditions realistically, using proven modeling techniques. The model shall be capable of capturing the effects of traffic dynamics such as variable link loadings and queue lengths, as well as changes to key parameters such as link capacity, origin-destination flow rates, and traffic control strategies.

Table 3-1. Traffic Model Requirements for Architecture Evaluation

General Model Requirements

1. Generalized Network Topologies
2. Mature Model Using Proven Dynamic Methodology
3. Individual Vehicle Modeling and Routing
4. Multiple Vehicle Classes
5. Flexible Route Selection
6. Driver Behavior Model
7. Detailed Incident Model
8. Infrastructure-to-Vehicle Communication Limitations Model
9. Inexpensive Computer Platform
10. Standard Input Formats and Editing Interface
11. Source Code Access

Strategic-Level Model Requirements

12. Integrated Networks
13. Networks of Extensive Scope
14. Timeliness of Delivered Data Model
15. Output Suitable for Benefits Evaluation
16. Flexible Traffic Management Strategy Model
17. Dynamic Network State and Origin-Destination Flow Model

Tactical-Level Model Requirements

18. Outputs Sufficient for Use in Determining Communication Loads
19. Detailed Surface Street Intersections Model
20. Detailed Freeway Link and Ramp Model
21. Vehicle-Vehicle Interaction Model
22. Surveillance Model

Justification: The traffic model must be accurate and recognized so that the results obtained are believable. An accurate assessment of the benefits of implementing the architecture cannot be made without an accurate traffic model.

3. Individual Vehicle Modeling and Routing

   Requirement: It shall have the capability to model at the individual vehicle level, including accommodating the provision of vehicle-specific routing. The model shall track and report the location of vehicles during the run of a simulation, and shall have the capability to alter vehicle parameters on-the-fly, including the vehicle route.

   Justification: Accurate assessment of the impact of the route guidance and traffic control strategies supported by the architecture is impossible without the ability to identify, route, and if necessary, reroute vehicles on the network.

4. Multiple Vehicle Classes

   Requirement: It shall model a variety of vehicle classes simultaneously. Vehicles may be placed in different classes based on both vehicle type (such as a truck or bus) and level of equipage. Transit operations shall also be modeled.

   Justification: An accurate traffic model should differentiate between vehicles based on size and performance. For architecture evaluation, a further distinction must be made by the in-vehicle equipment installed in each vehicle.

5. Flexible Route Selection Model

   Requirement It shall provide modular support for a range of route selection algorithms, as well as modular support for a range of real-time traffic prediction techniques. Further, the model should allow for the provision of different routes to vehicles based on in-vehicle equipage. This requirement includes the modeling of route selection based on centralized or distributed route calculation, effect of route selection vs. travel advisory only, and route selection for unequipped vehicles.

   Justification: A key discriminator between architectures is the route selection algorithms they support. Route selection methods will differ by vehicle class and evolutionary scenario, so a range of algorithms must be modeled.

6. Driver Behavior Model

   Requirement: The model shall provide a mechanism to capture the effects of driver behavior in light of information received by the driver, including drivers of unequipped (background) vehicles. This includes deviation from computed or supplied path because of poor position location or noncompliance. The requirement also includes the modeling of passive and aggressive driving styles in tactical models and platoon dispersion in strategic models.

   justification An important part of architecture discrimination is not only what information is passed to an individual vehicle, but what the driver does with that information. A driver behavioral model provides a mechanism for modeling both this information-use aspect, but also accommodates a variety of driving styles for accurate modeling.

7. Detailed Incident Model

Requirement: It shall have the capability to model a wide range of incidents on the network, including attributes such as variable severity, duration, and onset times.

Justification A critical aspect of architecture performance is in how quickly and effectively it can respond to reductions in roadway capacity, so a detailed model is required to accurately reflect the effect of that response.

8. Infrastructure-to-Vehicle Communication Limitations Model

Requirement It shall model the effects of architecture-specific communication limitations at specific points on the roadway network This requirement includes the effect of dead areas, the effect of sparsely-placed communication beacons, and imperfect reception.

Justification: This requirement sharpens the focus on distinguishing the effects on traffic flow of broadcast-based versus beacon-based communication systems.

9. Inexpensive Computer Platform

Requirement: It shall not require an expensive computer platform to model networks of the described scope and detail, i.e., it should run on workstations or smaller machines. The model shall not be unduly burdensome or cumbersome to use in the analysis of large-scale networks using this platform.

Justification: The evaluation effort will require that the model be used to analyze a wide range of scenarios, evolutionary snapshots, and incident profiles. Since many runs of the model will be required for a comprehensive analysis, this precludes models that demand long run times or require scarce computer resources.

10. Standard Input Formats and Editing Interface

Requirement The model shall accept standard input formats, particularly roadway topology data from widely used transportation planning packages such as TRANPLAN. In addition, the model shall have an easy-to-use interface for input file editing and debugging. Ease-of-use attributes include a graphical display for network editing, automated range-checking and error identification for input files.

Justification: An easy-to-use model will reduce the amount of time analysts must spend learning the specifics of the model, rather than analyzing the scenarios.

11. Source Code Access

Requirement MITRE shall have access to the source code for the model so that architecture-specific modules or parameter changes can be made.

Justification As no single model meets all the requirements outlined for the architecture evaluation, some customizing work may have to be done. To ensure that all contractor teams are working with equivalent models, MITRE will be managing all model modifications.

3.2.2 Strategic-Level Model Requirements

This section describes the six strategic-level model requirements. At least one model selected for architecture evaluation should satisfy these requirements. Each requirement is stated and justified.

12. Integrated Networks

    Requirement: It shall be capable of modeling a variety of facility types simultaneously and accurately, including freeways, collectors, arterials, and residential streets. The model shall have unidirectional links modeling unique attributes including link length, free flow speeds, number of lanes and peak hour capacity. The model shall also be able to include a variety of interchanges and intersections between roadway facilities.

    Justification: The evaluation will include integrated networks.

13. Networks of Extensive Scope

    Requirement: The model shall be able to run large-scale traffic models. As architectures will be evaluated in scenarios that are extensive in both geographic area (rural, inter-urban) and level of detail (urban), the model will support the simulation of large numbers of vehicles (50,000+ vehicles) on complex networks (1,000+ links) in time frames of peak demand.

    Justification: The evaluation includes assessment of benefits for large geographic areas.

14. Data Latency Model

    Requirement: The model shall provide a mechanism for incorporating variable delay in reporting current or predicted traffic conditions. This delay is the sum of the time required by the TMC to assess network conditions, compute appropriate communication and control strategies, and distribute that information.

    Justification: Architectures can be discriminated based on their ability to respond to changing network conditions. This requirement facilitates modeling the effectiveness of that response.

15. Outputs Suitable for Benefits Evaluation

    Requirement The model shall collect statistics providing primary measures of benefits criteria.. This detail will include data on trip times organized by vehicle type, level of equipage, time of departure, origin-destination pair, and compliance/noncompliance with route selection. The model will also provide figures on system-wide performance, including time in queue.

    Justification: Required for the evaluation of user and system benefits criteria.

16. Flexible Traffic Management Strategy Model

    Requirement: It shall provide modular support implementing alternative traffic management control strategies across the network. This includes control plans for signals and ramp meters, among other controls. It shall model a range of control strategies, including fixed timings, actuated controls, and centralized control algorithms.

    Justification: Architectures may be differentiated on the sophistication of the traffic management strategies they support.

17. Dynamic Network State and Origin-Destination Flow Model

    Requirement It shall support the modeling of networks that have multiple origins and destinations. In addition, the model shall accommodate dynamically changing rates of flow between these origins and destinations, and run for a simulation horizon long enough to capture the effects of these changes in flow.

    Justification: An accurate dynamic traffic model should include dynamic flow rates at origins, and effectively model the roadway network in various states not necessarily corresponding to system equilibrium.

3.2.3 Tactical-Level Model Requirements

This section describes the five tactical-level model requirements. At least one model used for architecture evaluation should satisfy these requirements. Each requirement is stated and justified.

18. Outputs Suitable for Use in Determining Communication Loads

    Requirement: The model shall collect statistics for use in determining dynamic communication loads on the IVHS architecture. This includes dynamic traffic counts by vehicle class, average vehicle speed, and traffic density at selected nodes and links.

    Justification Required for the evaluation of the adequacy of communication system criteria.

19. Detailed Surface Street Intersection Model

    Requirement It shall contain a detailed surface street intersection model. This includes the ability to model multi-phase signalized intersections featuring variable turn pocket depths and protected/unprotected turning movements. This requirement also includes the ability to model unsignalized intersections featuring the effect of stop and yield signs and a variable delay for unprotected turning movements into traffic. Under congested traffic conditions, the model should include dynamic queue length determination and lane blocking effects.

    Justification: Accurate architecture evaluation requires detailed modeling of critical portions of the roadway system, particularly signalized intersections, in order to quantify ATMS impacts. The major component of arterial delay is often intersection delay.

20. Detailed Freeway Links and Ramp Model

    Requirement: It shall contain a detailed freeway model including the explicit modeling of on- and off-ramps. This requirement also includes the ability to model variable ramp flow and control, as well as link-to-link spillback effects.

    Justification Accurate architecture evaluation requires detailed modeling of critical portions of the roadway system, particularly freeway links and ramps.

21. Vehicle-Vehicle Interaction Model

    Requirement: It shall model in a detailed way how vehicles interact with each other, particularly with respect to car following, lane changing, and changes in speed or acceleration.

    Justification: A detailed vehicle interaction model of vehicles is required for the evaluation of AVCS benefits, as well as the ability of vehicles to accept and respond to route selection strategies varying traffic densities.

22. Surveillance Model

    Requirement It shall support the modeling of various generic surveillance equipment supported by specific architectures, including the ability to model variable detection rates and support a range of incident detection algorithms. Further, the model should also capture the effects of placing surveillance equipment at different locations along a roadway segment.

    Justification: Architectures may be differentiated by the sophistication of the surveillance they can provide to the system, and the traffic model can provide insights and support for contractor team claims for response time and incident detection time.

3.2.4 Issues Not Explicitly Modeled

Some issues are modeled implicitly from the requirements listed in figure 3-l. The modeling of transit operations is included as a part of requirement 4. Weather and environmental modeling is implicitly included under several requirements. Those effects that cause incidents are included as a part of requirement 7. Those effects that degrade TMC-to-vehicle communications are included as parameter changes in requirement 14. Weather effects that cause a network-wide slowdown effect can be included as parameter changes to the vehicle-to-vehicle interaction model, among others. Terrain and obstruction effects are captured in requirement 8.

3.3 TRAFFIC MODEL SURVEY

MITRE reviewed seventeen models for consideration in the architecture evaluation. Some of these models, such as those from the TRAF family, were developed by the FHWA, others such as DYNASMART were developed in universities, and still others such as CONTRAM were developed abroad. For this reason and because of different levels of model maturity, the amount of information that we were able to obtain varies from model to model. The TRAF family of models consists of six models that were developed by the Federal Highway Administration. It includes NETSIM, FRESIM, and CORSIM, which are all microscopic simulation models, and it includes NETFLOW, FREFLO, and CORFLO, which are macroscopic models. CORFLO, which is described in further detail in this section, is made up of the three sub-models of FREFLO, NETFLO 1, and NETFLO 2. Models that were reviewed are:

- HCS
- FREFLO
- FRESIM
- PASSER II
- TEXAS
- NETSIM
- CONTRAM
- THOREAU
- ROGUS/RG CONTRAM
- FREQ
- INTRAS
- QUEWZ
- PASSER III
- TRANSYT -7F
- INTEGRATION
- CORFLO
- DYNASMART

Each of these models was assessed based on each of the 22 traffic model requirements listed in table 3-1. The model requirements are divided into the three groups of general requirements, strategic-level requirements, and tactical-level requirements. The results of this model evaluation effort are presented in figure 3-2. For each model and for each requirement, one of six symbols indicates how well that model meets the requirement. The symbols used and their meaning are as follows:

? There is not enough information to judge the model.
○ The model does not meet this requirement.
◒ The model would require major modifications to meet this requirement.
◓ The model partially meets this requirement; extent of modification unknown.
◉ The model could meet this requirement with some minor modifications.
● The model meets this requirement.

As can be seen from figure 3.2, while none of the models fully meets all of the model requirements, some of the models clearly come closer to meeting them all, or to meeting all the requirements from one of the three groups. By using a combination of models and by possibly making some modifications to them, all the requirements could be met. Those

REQUIREMENTS / MODELS	HCS	FREQ	FREFLO	INTRAS	FRESIM	QUEWZ	PASSER II	PASSER III	TEXAS	TRANSYT-7F	NETSIM	CORSIM	INTEGRATION	CONTRAM	CORFLO	THOREAU	DYNASMART	ROGUS
General Model Requirements																		
1. Generalized network topologies	○	◓	◓	◓	◉	○	○	○	○	◓	●	●	●	●	●	●	●	●
2. Mature model using proven dynamic methodology	○	◓	◓	◍	○	○	○	○	◓	○	●	◍	●	●	◓	◓	◓	◍
3. Individual vehicle modeling and routing	○	○	○	○	○	○	○	○	○	○	◓	●	●	◍	○	●	●	●
4. Multiple vehicle classes	○	○	○	◓	◓	○	○	○	○	○	◉	●	●	◓	●	◉	●	◓
5. Flexible route selection model	○	○	○	○	○	○	○	○	○	○	○	◉	●	◍	○	●	●	●
6. Driver behavior model	○	○	○	◓	◓	○	○	○	○	○	◍	◉	◍	○	○	◉	◓	●
7. Detailed incident model	○	◓	○	●	●	◓	○	○	○	○	●	●	●	○	◓	◉	?	◓
8. Infra.-to-veh. comm. limitations model	○	○	○	◍	◍	○	○	○	○	○	○	●	◉	○	○	◉	◍	◉
9. Inexpensive computer platform	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	◓	◍	◉
10. Standard input formats and editing interface	●	●	○	○	●	?	◓	◓	◓	◓	◓	?	◉	●	●	◉	?	●
11. Source code access	●	?	●	●	●	?	?	?	?	●	●	●	◉	◉	●	●	◓	◉
Strategic-Level Model Requirements																		
12. Integrated networks	○	○	○	◍	◍	○	○	○	○	◓	◍	●	●	●	●	●	●	●
13. Networks of extensive scope	○	○	◓	◉	◉	○	○	○	○	◓	◍	◓	●	●	○	◓	◍	●
14. Data latency model	○	○	○	○	○	○	○	○	○	○	○	●	●	○	○	●	●	●
15. Outputs suitable for benefits evaluation	◓	◓	◓	◓	◓	○	◓	◓	◓	◓	◓	●	◉	◍	●	◉	●	◓
16. Flexible traffic management strategy model	○	○	○	◍	◍	○	○	○	○	○	●	●	●	◓	○	●	●	◓
17. Dynamic origin-destination flow model	○	○	○	◍	◍	○	○	○	○	○	◍	○	●	●	○	○	?	●
Tactical-Level Model Requirements																		
18. Outputs suitable for determining comm. loads	○	○	◓	●	●	○	○	○	○	○	●	●	◓	◓	◓	●	◓	◓
19. Detailed surface street intersection model	●	○	○	◓	◓	○	●	●	●	◓	●	●	◍	○	◓	●	◍	○
20. Detailed freeway links and ramp model	●	●	●	●	●	●	●	○	○	○	○	●	◍	○	●	●	●	○
21. Vehicle-vehicle interaction model	○	○	○	●	●	○	○	○	○	○	●	●	○	○	○	●	◍	○
22. Surveillance model	○	○	○	●	●	○	○	○	○	○	●	●	○	○	○	◓	○	○

Figure 3-2. Model Survey Results

models that meet many of the requirements are being evaluated in more detail so that we may understand what model modifications will need to be made to meet the architecture modeling requirements defined from table 3-1. The following sections will briefly discuss how well each of the models meets our set of requirements. When a model only partially meets a requirement, some discussion is provided about why that rating was assigned. For those models that do not seem to support enough of our requirements, there is only a brief description of the model and an explanation for why this model will not be considered further.

Highway Capacity Software (HCS): HCS is a macroscopic, empirically based software package that implements the 1985 Highway Capacity Manual (HCM). HCS is not a dynamic model, and it does not evaluate the network system as a whole; it evaluates only roadway segments. Further, HCS could not be easily modified to meet our evaluation needs. For these reasons, we will not consider HCS further for this task.

FREQ: FREQ is a macroscopic, analytically based model that performs simulation and optimization of traffic flow and was developed by the University of California at Berkeley. It evaluates unidirectional freeway operations resulting from lane additions, blockages, and various ramp configurations and ramp metering schemes. FREQ does not model surface streets or intersections, and it can simulate only one simplified parallel alternative route. Because of FREQ’s shortcomings, it would not be useful for the architecture evaluations and will not be considered further for use in this task

FREFLO: FREFLO is a dynamic, macroscopic, analytically based simulation model that represents traffic in terms of aggregate measures on each section of a freeway. It evaluates incidents and entrance ramp operations and freeway-to-freeway connections. It can simulate entire freeway networks in both directions. FREFLO provides the following measures of effectiveness: average vehicle speed, vehicle stops, vehicle-miles of travel, average queue length, and fuel consumption. While FREFLO meets many of the requirements for architecture evaluation, it requires a mainframe computer to run and it is limited to freeway segments, so it will not be considered further for this task.

INTRAS: INTRAS (INtegrated TRaffic Simulation) is a microscopic analytically based simulation and optimization model that can provide detailed analysis of freeway sections and the surrounding street network It models individual vehicle movements, car following, and lane changing. INTRAS simulates entire freeway networks including frontage roads and urban arterial streets. INTRAS has the feature of being able to collect data at specific points in the network through simulated detectors. It can be used to evaluate incident detection algorithms, real-time ramp metering strategies, traffic operations implications of design strategies, and weaving sections. It can also optimize freeway operations, producing an entrance-ramp metering scheme.

INTRAS meets many of our defined requirements for evaluation, but because of the recent more user-friendly version called FRESIM that is being introduced into the TRAF family of models, INTRAS will not be considered further for use in this study.

FRESIM: FRESIM, which is currently under development, is an enhanced, user-friendly version of INTRAS and a component program of the TRAF system developed by the Federal Highway Administration. Enhancements include improved geometric representation and operational capabilities, the ability to simulate more complex freeway geometries, and an improved representation of traffic behavior.

FRESIM has not been released yet, except as a beta-test version, but it is based on INTRAS, which is a mature model. FRESIM fully meets all but one of the tactical-level model requirements, could meet most of the strategic-level requirements with some major modifications, and it meets many of the general requirements as well. For these reasons, FRESIM was selected as a contender for possible use in evaluating the proposed architectures. Specifically, it would be used for evaluating microscopic-level interactions at freeway intersections.

For requirement 1, Models Generalized Network Topologies, while FRESIM does model freeways, it cannot model grid networks such as a typical surface street network.

Requirement 4, Multiple Vehicle Classes, is only partially met because FRESIM does not have an HOV modeling capability.

Requirement 6, Driver Behavior Model, is partially met because the information provided can only be tested on a static basis.

Requirement 8, Infrastructure-to-Vehicle Communication Limitations Model, could be met by changing FRESIM to a dynamic model and having the simulated message signs change dynamically.

Requirement 12, Integrated Networks, is partially met now in that FRESIM can simulate most prevailing freeway geometries but it only has a limited model of the surface street interface with the freeway system. It could be met in full if the major modification of adding the surface street representation was made.

For requirement 13, Networks of Extensive Scope, FRESIM is limited because of memory limitations of the PC. FRESIM, when running on a PC with 4 megabytes of memory, can model 3,000 vehicles, 250 detectors, and 200 links. Maximum size can be expanded by modifying array dimensions.

Requirement 15, Output Suitable for Benefits Evaluation, was given a partial, because the model cannot provide trip times by vehicle type or by level of equipage. Information on the time in queue is also not provided.

Requirement 16, Flexible Traffic Management Strategy Model is currently not met because traffic management strategies can only be tested on a static basis, but if the major modification of changing the model to a dynamic one were made, this requirement could be met.

Requirement 17, Dynamic Origin-Destination Model, could also be met with this major modification.

For requirement 19, Detailed Surface Street Intersection Model, we assigned a partial because FRESIM can model only signalized intersections with fixed signal times.

QUEWZ: Is a macroscopic, analytically based simulation that evaluates road user costs and queue lengths associated with freeway work zone lane closures. The model identifies work schedules so as to avoid queues exceeding a user-specified length. QUEWZ does not meet enough requirements to be considered further for use in this task.

PASSER II: Is a macroscopic model that can optimize timing for isolated signalized intersections and for a series of signalized intersections. Analysis procedures are similar to those of the 1985 HCM. It provides an on-screen graphical representation of traffic operations with a visual display of individual vehicle movements and MOE values. Since PASSER II can evaluate only a small system of intersections, it is not really applicable to this task, and it will not be considered further.

PASSER III: Is a macroscopic optimization model that analyzes pre-timed or traffic-responsive fixed sequence signalized diamond interchanges. Since PASSER III can evaluate only diamond interchange signal systems, it is not really applicable to this task, and it will not be considered further.

TEXAS: TEXAS is a microscopic computer simulation that performs detailed evaluations of the operational effects of various traffic demands, types of traffic control, and/or geometric configurations at isolated intersections. It can evaluate existing or proposed intersection designs and assess the effects upon traffic operations of changes in roadway geometry, driver and vehicle characteristics, flow conditions, intersection control, lane control, and signal timing plans. Since TEXAS can evaluate only an isolated intersection or diamond interchange signal systems, it is not really applicable to this task, and it will not be considered further.

TRANSYT-7F: Is a macroscopic traffic signal timing optimization program that evaluates existing or other predetermined timing plans and optimizes new timing plans that minimize stops, delays, fuel consumption, or cost. It includes a Data Input Manager (DIM) program and a Platoon Progression Diagram (PPD) Since TRANSYT-7F is not a dynamic model, it is not applicable to this task and it will not be considered further.

NETSIM: NETwork SIMulation Model (NETSIM) is a microscopic simulation program that provides a detailed evaluation of proposed operational improvements in a signalized network. It can evaluate the effects of changes such as those from converting a two-way street to a one-way, adding lanes or turn pockets, moving the location of a bus stop, or installing a new signal. NETSIM was selected as a contender for possible use in evaluating the proposed architectures. Specifically, it would be used for evaluating microscopic-level interactions on surface streets.

Requirement 3, Individual Vehicle Modeling and Routing, is only partially met because NETSIM models only vehicle routing for buses.

Requirement 5, Flexible Route Selection Model, could be met with the major modifications to the source code. The FHWA currently has plans for this modification. This modification will also help in meeting requirement 6, a Driver Behavior Model; however, the planned modified version from the FHWA will not be available for three years.

Requirement 10, Standard Input Formats and Editing Interface is only partially met because the GUI is not as user-friendly as desired.

Requirement 12, Integrated Networks, is not met but the current planned major modification of joining of FRESIM with NETSIM to form CORSIM will help meet this requirement.

For requirement 13, Networks of Extensive Scope, NETSIM is currently limited to 500 links, 250 nodes, 1,000 vehicles, 100 actuated controllers, and 500 detectors when running on a PC with 2 megabytes of memory.

Requirement 15, Outputs Suitable for Benefits Evaluation, is given a partial because the model cannot provide trip times by vehicle type or by level of equipage.

Requirement 17, Dynamic Origin-Destination Model, would be able to be met with the major modification of changing the model to a dynamic model and having the simulated information change dynamically.

INTEGRATION: Integration is a traffic simulation model that was developed by Queens University, Canada that analyzes the operation of integrated freeway/arterial networks, real-time traffic control, and route guidance systems. INTEGRATION models vehicles at the individual vehicle level, and models each intersection explicitly. At the network level, INTEGRATION models the effects of incidents, dynamic O-D flow rates and link-to-link interactions. Since INTEGRATION meets most of our general and strategic-level model requirements, and could meet most of the tactical-level requirements with some major modifications to the source code, it will be considered for further use in this task.

Requirement 6, Driver Behavior Model, is met partially, because while INTEGRATION approximates differences in driving styles through different platoon dispersion rates, all drivers are 100 percent compliant. With the major modification of adding a driver behavioral model, this requirement would be met.

Requirement 8, Infrastructure-to-Vehicle Communication Limitation Model, is partially met because INTEGRATION does model broadcasts at beacons (selected nodes) but to be fully met, the minor modification of adding a “quality of transmission” would have to be made.

Requirement 10, Standard Input Formats and Editing Interface, could be met with the minor modification of adding a graphical users interface for editing.

Requirement 11, Source Code Access, was assigned this rating because while the source code is privately owned, we feel that some type of licensing agreement could probably be made for its use in this task. It should be noted that all modifications will require access to the source code.

Requirement 15, Outputs Suitable for Benefits Evaluation, could be met with the minor modification of adding a compliance/noncompliance model.

Requirement 19, Detailed Surface Street Intersection Model is only partially met because INTEGRATION does not currently model intersections in enough detail specifying, among other things, unprotected movements and gap acceptance.

Requirement 20, Detailed Freeway Links and Ramp Model, is only partially met and could be met with the addition of merging to the model.

Requirement 22, Surveillance Model, is only partially met because no sensors are modeled. With the major modification of adding a sensor model, it could be fully met.

CONTRAM: CONTRAM is a traffic assignment model developed by the Transportation and Road Research Laboratory (TRL) in the UK. It models time-varying traffic demands on roadway networks that are restrained by limited capacity and transient overload, and predicts the variation through time of the resulting routes, queues, and delays. CONTRAM can be used to predict the effects of signal timings and coordination, fuel consumption, and numbers of stops. It can be used for designing urban-area traffic management schemes.

CONTRAM fully meets some of the general model requirements and strategic-level model requirements. Additionally, it is the driver of two projects under development, one by the TRL called ROGUS and another called RG CONTRAM that is being developed by the University of Southampton. While CONTRAM would not be considered for use alone, since it is really just an assignment model, it may play an important role in that ROGUS and RG CONTRAM were developed from, and use CONTRAM.

Requirement 3, Individual Vehicle Routing and Modeling, could be met with major modifications. Currently CONTRAM loads traffic onto the network in packets that consist of one to 20 vehicles of the same type that are assigned at the same time to an origin destination pair.

Requirement 4, Multiple Vehicle Classes, is partially met because CONTRAM allows for the modeling of fixed-route vehicles in conjunction with vehicles assigned according to dynamic equilibrium. CONTRAM is not specifically built to handle route guidance evaluation, i.e., the background model is equivalent to most intelligent vehicle routing strategies.

Requirement 5, Flexible Route Selection Model, would also require major modifications. CONTRAM currently assigns traffic to the network based on a modified version of Dijkstra’s algorithm. CONTRAM presently does not have the ability to model dynamic route guidance techniques except through the modeling of fixed route plans originally implemented for bus routing. Vehicles take routes based on a multi-path dynamic assignment model between origins and destinations. Since CONTRAM is only an assignment model, it would require major modifications to allow for the routing of different vehicles based on different levels of equipage as their is currently no vehicle routing in the model.

Requirement 11, Source Code Access, was assigned the rating of a minor modification because while the source code is not owned by the FHWA, we feel that some type of agreement could probably be made with the TRL for its use in this task. It should be noted that all modifications will require access to the source code.

Requirement 15, Outputs Suitable for Benefits Evaluation, could be met with the major modification of modeling individual vehicles, as the statistics on the effects of management schemes are already provided at a more aggregate level.

Requirement 16, Flexible Traffic Management Strategy Model, is partially met since CONTRAM has a signal control/coordination model and it can be used for designing urban area traffic management schemes, but it does not support the modeling of actuated signals.

Requirement 18, Outputs Suitable for Determining Communication Loads, is partially met because information on queues and delays are provided as outputs to the model.

CORFLO: CORFLO is a component model of the TRAF simulation system developed by the FHWA to model corridors at a macroscopic level. It can be used to analyze integrated urban networks or corridors and has traffic assignment capabilities. The traffic assignment is based on a variation of the Frank-Wolf decomposition algorithm. It is made up of the three macroscopic submodels of FREFLO, NETFLO 1, and NETFLO 2 that all share a common traffic assignment model. FREFLO is a macroscopic freeway simulation model. NETFLO 1 is an event-based surface street network simulation model. NETFLO 2 is a macroscopic platoon based surface street network simulation model. These three models can be run independently or applied to a specific sub-network that is a partition of a larger network. CORFLO explicitly handles automobiles, trucks, buses, and carpools on freeways and surface streets. It produces reports with a wide range of measures of effectiveness on a movement-specific and link-specific basis, aggregated over each sub-network and over the global network.

Requirement 2, Mature Model Using Proven Dynamic Methodology, is assigned a partial because CORFLO is a relatively new model in that while some of its components are more mature, the CORFLO model was just released this past fall.

Requirement 7, Detailed Incident Model is assigned a partial because the FREFLO component represents an incident through a specified reduction in the number of lanes and a constraint on the flow rate past the incident. There is no capability for modeling incidents at the shoulder.

Requirement 18, Outputs Suitable for Use in Determining Communication Loads, is assigned a partial because the model does not have a surveillance capability and there is no capability of collecting statistics by vehicle class.

Requirement 19, Detailed Surface Street Intersection Model, is assigned a partial because CORFLO does not model intersections in detail. Vehicles are moved intermittently, so no car-following logic is employed.

THOREAU: THOREAU (Traffic and Highway Objectives for REsearch, Analysis, and Understanding) is a microscopic simulation model that was developed by The MITRE Corporation for the purpose of modeling the effects of ATIS and ATMS on traffic operations.

THOREAU partially or fully meets all requirements, except for requirement 17, Dynamic Origin-Destination Flow Model. Eleven of the requirements are fully met, and it is felt that six more of them could be fully met with some minor modifications to the source code. Furthermore, THOREAU is written in MODSIM, an object-oriented simulation language that makes for easy modification to the model since a modification will require changing a small set of objects. While THOREAU is a relatively young model, we feel that it should be considered for use in this task because it does address so many of our defined model requirements.

Requirement 2, Mature Model Using Proven Dynamic Methodology, is assigned a partial because THOREAU is a relatively new model in that its development began only two and a half years ago, and few studies have been done using the model.

Requirement 4, Multiple Vehicle Classes, could be met with the minor modification of adding performance characteristics for trucks and buses to the model.

Requirement 6, Driver Behavioral Model, could be met with the minor modification of adding a compliance/noncompliance model since it already models four driving styles.

Requirement 7, Detailed Incident Model, is partially met because there is no explicit modeling of shoulder incidents, estimated to be a minor modification.

Requirement 8, Infrastructure-to-Vehicle Communications Limitations Model, could be met with the minor modification of adding the capability of simulating dead areas of a radio-based system, and a partially equipped beacon-based system. There is no current modeling of an intelligent vehicle not being able to update his route; that is, all vehicles designated as intelligent receive regular updates.

Requirement 9, Inexpensive Computer Platform, is assigned a partial because THOREAU runs on a SUN workstation that is somewhat expensive.

Requirement 10, Standard Input Formats and Editing Interface, is partially met and could be fully met with the minor modification of adding an interactive graphic network editing system.

Requirement 13, Networks of Extensive Scope, is assigned a partial because THOREAU is limited in that it cannot model big networks at a reasonable speed. At present, THOREAU can tractably model several thousand vehicles on networks containing hundreds of links on a SUN workstation.

Requirement 15, Outputs Suitable for Benefits Evaluation, is partially met because THOREAU provides many of the required outputs but there is currently no data on compliance/noncompliance, and it could be fully met with the minor modification of adding a compliance/noncompliance model.

Requirement 22, Surveillance Model, is assigned a partial rating because while THOREAU models sensors at intersections, it currently can model only loop detectors.

DYNASMART: DYNASMART is a mesoscopic simulation model that was developed by the University of Texas to model commuter route choice and behavior. It uses a micro-level model iteratively to identify a set of stable routings. It fully meets many of our defined requirements from both the General and Strategic Level Requirements Sections. In addition, DYNASMART could meet most of the Tactical Level Requirements with some major modifications to the source code. While DYNASMART meets many of our requirements, it runs on a Cray supercomputer. It has recently been altered to run on a workstation; however, it runs at very slow speeds. It would not be reasonable to expect the contractors to be able to access a Cray for use in this task DYNASMART would have to be used on a CRAY for strategic-level models and it is not user-friendly or flexible enough to be considered a viable tactical-level model. Finally, the workstation version of DYNASMART is so new that it cannot be considered as a mature model. We will not consider DYNASMART further for use in this task.

ROGUS/RG CONTRAM: ROGUS, a suite of models based around the CONTRAM traffic model, was developed to simulate Dynamic Route Guidance Systems. It is useful for studying the detailed effects of route guidance on networks of up to about 500 links operating under nonrecurring or recurring congestion. ROGUS was developed by the Transportation and Road Research Laboratory (TRL) in the United Kingdom. RG CONTRAM has similar aims and objectives as the ROGUS model, and was developed by the University of Southamptom in response to certain deficiencies that they saw with the ROGUS model. These models were selected as contenders for possible use in evaluating the proposed architectures. Specifically, one of the two could be used for evaluating microscopic-level interactions on surface streets.

Requirement 2, Mature Model Using Proven Dynamic Methodology, is assigned a partial that would require major modifications to be fully met because ROGUS is still under development. While the CONTRAM component is very mature, the ROGUS suite of models is still new with varying reports on its performance. The TRL has informed MITRE that ROGUS is at least a year away from “releasable” maturity. RG CONTRAM is also a very new model.

Requirement 4, Multiple Vehicle Classes, is assigned a partial because the differences between each of the vehicle classes are not explicitly modeled. Further we are not sure if this modeling approach has been proven yet.

Requirement 7, Detailed Incident Model, is assigned a partial because ROGUS represents an incident as a reduction in capacity. There is no capability for explicitly modeling incidents at the shoulder.

Requirement 8, Infrastructure-to-Vehicle Communication Limitations Model, is assigned a partial because error rates are not modeled.

Requirement 9, Inexpensive Computer Platform, is assigned a partial because ROGUS runs on a VAX workstation that is somewhat expensive.

Requirement 11, Source Code Access, was assigned this rating because while the source code is privately owned, we feel that some type of agreement could probably be made for its use in this task. It should be noted that all modifications will require access to the source code.

Requirement 15, Outputs Suitable for Benefits Evaluation, is assigned the same rating as in CONTRAM because we could not get any further information on how ROGUS may address this requirement differently.

Requirement 16, Flexible Traffic Management Strategy Model, is assigned the same rating as in CONTRAM because we could not get any further information on how ROGUS may address this requirement differently.

Requirement 18, Outputs Suitable for Determining Communication Loads, is partially met because information on queues and delays is provided as outputs to the model.

CORSIM: CORSIM (CORridor SIMulation Model) is a microscopic simulation under development by the FHWA for the analysis of integrated freeway and arterial corridors. It will combine all of the functionalities of the FRESIM and NETSIM simulations, together with a new capability to model dynamic route guidance assignments. Although CORSIM meets most of the general and tactical requirements, the software will not be released for beta-testing until sometime in 1994. Given this availability schedule, CORSIM cannot be considered for the first modeling phase.

Requirement 2, Mature Model Using Proven Dynamic Methodology, is assigned a partial because the model is still under development. FRESIM and NETSIM, the two component parts of the CORSIM model, are mature models with wide application. CORSIM receives a partial rating only because of its state of development, not because of methodology.

Requirement 5, Flexible Route Selection Model, is assigned a partial because unequipped vehicles will still follow paths determined by probabilistic splits at nodes. CORSIM could be modified to accept externally generated paths for unequipped vehicles without major modification.

Requirement 6, Driver Behavior Model, is assigned a partial because there is no compliance model. This is considered a minor modification.

Requirement 13, Networks of Extensive Scope, is assigned a partial because CORSIM is not designed to be a strategic-level model. While it is true that array sixes may be expanded to run a network of virtually any size, the model will run too slowly for large-scale analysis.

3.4 CALIBRATION OF SIMULATION TOOLS

Any benefit analysis in the 5-year, 10-year, or 20-year scales must be compared against some baseline measures that represent the “state of the system” before the introduction of an IVHS infrastructure. The traffic model(s) identified and used in architecture evaluation should be calibrated using 100 percent background (nonequipped) traffic. The model should be able to reproduce current observed point-to-point travel times, average and maximum link loadings, and other congestion measures when the baseline data is used as input.

Modeling the background (unequipped} traffic realistically then becomes an important and nontrivial task. In many discrete-event traffic simulations, each background vehicle is modeled as an individual entity that can receive route guidance information from the model in a manner similar to equipped vehicles, but according to some other primarily static and nonresponsive set of selected paths. Within the simulation community, there is much debate on how these paths can be identified or approximated. Some use a free-flow shortest path algorithm, while others choose paths generated from a static equilibrium assignment model.

No consensus exists on the "best method" of modeling background vehicles. In general, however, the methods considered to be the most accurate and current state of the art are dynamic, multi-path assignments. A multi-path assignment allows for the vehicles with identical origins and destinations to be split between several paths. A dynamic assignment allows vehicles with identical origins and destinations to be assigned different paths depending on their time of departure at the origin.

Another approach is to model background traffic in packets; that is, groupings of two or more vehicles. This reduces the amount of computation required in the modeling of large networks, but packets still must be routed according to path choices identified as if they were individual vehicles.

Finally, in some simplified models, background traffic is modeled as a single entity, reducing capacity on each link. This method is simple and requires much less computer power to implement, but can neither evaluate dynamic route guidance effects, nor model the effects of signalization control.

Current background assignment models include ASSIGN, which supports the INTEGRATION simulation package, and CONTRAM-5, which works as a part of the ROGUS suite of models. An independent assignment model may also be developed.

For architecture evaluation, the critical aspect is that background traffic shall be modeled consistently across the set of models selected and across architectures, rather than the accuracy of the background model alone.

SECTION 4

COMMUNICATION MODELING FOR ARCHITECTURE EVALUATION

This section describes the requirements for the communication model within the architecture evaluation effort.

4.1 FUNCTIONAL REQUIREMENTS

Given the expected diversity in the proposed system architectures, there will be a corresponding diversity in the communication system requirements. This implies that a flexible set of modeling and simulation tools will be required to evaluate a broad range of communications architectures. These tools will be used to evaluate the efficiency of topologies, protocols, and links. We have identified specific communication model requirements necessary for effective communication architecture modeling and evaluation. These are summarized in table 4- 1.

The following describes the 11 communication model requirements. Each requirement is stated and justified.

1. Generalized Network Topologies

   Requirement: The communication system model shall be capable of modeling various geometric configurations corresponding to communication networks.

   Justification: The evaluation will include many communication system scenarios with diverse topologies. In order to accurately predict the performance and effectiveness, the model must be flexible enough to accommodate this diversity.

2. Heterogeneous Networks

   Requirement The communication system model shall be capable of simulating communication architectures incorporating multiple topologies.

   Justification It is probable that a message may traverse multiple networks between the source and destination. In order to measure the source-to-destination performance in terms of throughput, delay, and error rate, the model must be capable of handling multiple topologies.

3. Flexible Node Functions and Structures

   Requirement: The model shall be capable of simulating a wide variety of node structures. It should allow flexibility in specifying message queues, message processors, message generators, and type of transceiver.

Table 4-l. Communications Modeling Requirements for Architecture Evaluation

1. Generalized Network Topologies
2. Heterogeneous Networks
3. flexible Node Functions and Structures
4. Standard Protocols
5. Non-Standard Protocols
6. Various Communication Media
7. Mobile Nodes (Vehicles)

a. Integrated Link-Network Simulation Capability

9. Well Designed User Interface
10. Strong Post Processing Capability
11. Generates Outputs Consistent With Traffic Model Input Parameters

Justification: The allocation of the processing requirements to the nodes will be architecture-dependent. In order to capture the performance and effectiveness of each node, a model must be flexible and adaptable to varying processing requirements.

4. Standard Protocols

Requirement: The model shall be capable of simulating standard communication protocols covering the lower four levels of the OSI model. This implies that an extensive protocol library should be available to the user. Examples of standard protocols to be included am: HDLC, TCP/IP, X.25, PDDI, IEEE 800.X.

Justification: It is reasonable to assume that many proposed architectures will incorporate standard protocols. In order to minimize the effort required to model complex networks, standard protocol functions should be available.

5. Nonstandard Protocols

Requirement The user shall have the flexibility to build and simulate custom communication protocols. Ideally, this should be accomplished using a building block approach, rather than writing code.

Justification It is likely that new IVHS-specific protocols will be proposed, particularly for the infrastructure-vehicle mobile communications link. In order to provide an accurate assessment of the effectiveness of nonstandard protocols, a convenient method to model them must be incorporated.

6. Various Communication Media

   Requirement: When modeling links, the user shall be able to choose the transmission medium. The package should allow the user to accurately model the effects (e.g., noise, attenuation) of various links such as: fiber-optic, coaxial cable, twisted pair wire, satellite, and Radio Frequency (RF) technologies.

   Justification: A key difference between architectures will be the technologies they employ to connect nodes. In order to provide a true measure of the end-to-end system performance, the model must capture the link characteristics and must do so for diverse link types.

7. Mobile Nodes (Vehicles)

   Requirement: The model shall be capable of modeling mobile nodes (vehicles). The link characteristics between a fixed and mobile node must be modeled dynamically. Parameters such as vehicle speed and acceleration shall be variable. The model shall account for degradation in a mobile communications environment.

   Justification: Inherent to all IVHS architectures will be infrastructure-to-vehicle communications. In order to fully characterize the end-to-end performance of this type of network, the degradation characteristics of a land mobile communications must be modeled.

8. Integrated Link-Network Simulation Capability

   Reauirement: The overall simulation shall take into consideration the dynamic effects of the links concurrently with the performance of the networking protocols and processing algorithms. This is especially important for mobile RF links where propagation effects are dynamic.

   Justification: A key factor in measuring the performance of the communications architecture will be to characterize the end-to-end network. In order to accomplish this the model must dynamically account for the effectiveness of all the links especially the RF links to vehicles.

9. Well Designed User Interface

   Requirement The user interface should be designed to minimize the amount of code the user must generate to implement a model. Ideally the interface should be graphic with a block-diagram editing approach.

   Justification: The evaluation process will require modeling a wide variety of communication protocols, nodes, and links. A well designed user interface will decrease the level of effort and the overall cost associated with simulation.

10. Strong Post-Processing Capability

    Requirement: The simulation package should incorporate extensive post-processing capability. This should include statistical analysis as well as animation.

Justification An extensive set of analysis tools will be required to evaluate varying communication architectures. Animation in the simulation will accelerate the debugging process and model development.

11. Generates Outputs Consistent with Traffic Model Input Parameters

Requirement: The model shall have adequate post-processing analysis capability to determine the effectiveness of the communications network. The output required to interface with the traffic model must include measures of message delay times, message error rate, and missed message information.

Justification: The communications and vehicle traffic analysis will be accomplished independently. However, the results of the communications analysis will be used as parameters in the traffic model.

4.2 COMMUNICATIONS MODEL SURVEY

There are many modeling and simulation tools available that can model communication links and likewise there are many packages that model networks and protocols. These can be divided into three categories: general-purpose simulation languages, communication-oriented simulation languages, and communication simulators. General-purpose simulation languages such as MODSIM II, SIMAN, and SIMSCRIPT II.5 are the most flexible. However, they would require extensive programming to adapt to communications applications. Communications-oriented simulation languages such as OPNET and BONES are also flexible and incorporate built-in features that make it easier for users to develop communications models. They require a moderate amount of programming. Communication simulators such as COMNET, LANNET NETWORK, and LANSIM have very limited flexibility but are much simpler to use.

Given these three categories, general-purpose simulators are judged to be too cumbersome to develop models for varying communications architectures and therefore are not recommended. Communication simulators are restrictive in their flexibility to meet the varying requirements; therefore, they are not recommended. Communication simulation languages offer the flexibility to model a wide variety of communication systems. Two commercially available tools have been identified that completely or nearly completely fulfill the requirements outlined above. A summary of their key features is given below.

OPNET/B: This software package provides a framework for constructing simulations of communications networks and distributed systems. It is distributed by MIL 3, Inc. The simulation model is developed hierarchically, encompassing the following domains:

- Network domain (graphical input)
- Node domain (graphical input)
- Process domain (graphical/‘C’ programming)
- Link domain (graphical)

The simulation kernel has more than 200 primitives for communications system modeling, and supports heterogeneous network topologies including Radio, Point-to-Point, and Bus Links. OPNET/B also provides a modular framework for radio link models, which should be sufficient to model any RF link OPNET/B models mobile nodes, and node modeling also includes functional modules with user-variable parameters.

Process modeling allows for the inclusion of standard and user-defined protocols. OPNET/B offers a library of standard protocols and functions as well. The simulation has a graphical user interface and supports the construction of additional modules in the 'C' programming language. OPNET/B includes a post-processor to analyze simulation results, including animation. The package is supported on a number of platforms, including Sun-3, Sun-4, HP 9000 series, DEC stations, and Silicon Graphics (IRIS).

BONES: This software package is a product of COMDISCO Systems Inc. BONES provides a block-oriented graphical environment with automatic type and consistency checking, using hierarchical data flow diagrams with hierarchical data structures as methodology (unlimited levels). A library of more than 300 primitives for communications systems modeling are also included. BONES models heterogeneous networks, and includes an extensive library of standard protocols, such as: X.25, trunk radio, and mobile/cellular. Within BONES, user-defined data structures allow great flexibility in network modeling, and the graphical user interface allows for the development of simulation models using block diagrams. The user may specify link parameters such as transmission rate and delay error rate. Additional modules may be constructed in the 'C' programming language. BONES includes a post-processor to analyze simulation results, including animation. The package is supported on a number of platforms, including Sun-3, Sun-4 (SPARC), and DEC (2100/3100).

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

This section concludes the document with a set of recommendations for both traffic and communication modeling for architecture evaluation.

The first recommendation is that two traffic models be used, one for strategic analyses and another for tactical analyses, rather than relying on a single traffic simulation. A detailed discussion of leading traffic model candidates is presented for tactical analysis. Next, a discussion is presented of leading traffic model candidates for strategic analysis. For both tactical and strategic analysis, pros and cons for each candidate are described. Two traffic models are recommended, followed by a discussion of source code access and the coordination of strategic and tactical analyses.

For the communication simulation, two models are recommended for consideration by the contractor teams. Either of these models or another model may be selected by the contractor teams for communication modeling, subject to governmental approval. A recommendation is also made for the model to be used for independent verification and validation efforts.

5.1 TRAFFIC MODEL RECOMMENDATIONS

The first key recommendation for traffic modeling is that the strategic and tactical modeling be done separately using a set of models designed specifically for each level of analysis rather than relying on a single model. No single model fully or partially fulfills all the requirements for architecture evaluation. In the next five years, advanced simulations may become available that satisfy both strategic- and tactical-level requirements. However, given the short time frame of this project, the evaluation must be completed with the best currently available tools requiring only limited source code changes. The use of two models will require the contractor teams to develop expertise with more than one model; however, this disadvantage is outweighed by the accuracy in modeling gamed by such an approach. Several models can be made to work effectively in concert if careful thought is given to their coordination.

51.1 Tactical Analysis: Candidates and Recommendation

For tactical analysis, the leading candidates for usage in architecture evaluation are either a combination of the FRESIM/NETSIM simulations from the FHWA-developed TRAF family or the MITRE-developed THOREAU model. Each of the leading candidates are discussed in light of the modeling requirements, with pros and cons listed for each.

5.1.1.1 Candidate: NETSIM and FRESIM

NETSIM and FRESIM provide the most detailed vehicle-vehicle interaction model currently available in a microscopic traffic simulation. FRESIM is the micro-level simulation for freeway road segments, NETSIM for surface street networks. It is recommended that these two models be considered together, since tactical-level analysis may occur on either surface streets, freeways, or a small integrated network. Both models or their precursors are well-known within the modeling community. NETSIM also includes a detailed surveillance model.

Together, the two models partially or fully meet all the tactical and general modeling requirements. NETSIM and FRESIM were first developed before the advent of IVHS technology, and do not currently support a wide range of architecture-related modeling applications. Of the seven partially fulfilled requirements, the most serious deficiency is the difficulty with implementing and measuring the effects of dynamic route guidance with NETSIM and FRESIM.

Although NETSIM and FRESIM both model vehicles on an individual level, specific routes cannot be passed to vehicles traveling on the network and then changed during the run of the simulation. Typical vehicles in NETSIM and FRESIM are generated at sources and make random turns at intermediate nodes, so one cannot guarantee that a particular vehicle will reach a predetermined destination, nor enforce the traversal of a particular route between source and sink nodes. NETSIM and FRESIM do allow for fixed-route vehicles (originally intended for bus modeling), but these routes cannot be changed during a single run of the simulations. Dynamic route guidance could be modeled by declaring all equipped vehicles to be fixed-route bus analogs and the dynamic effects captured through a series of additional simulation runs; however, this would be cumbersome.

The random-traverse assignment module within NETSIM and FRESIM also complicates the modeling of background vehicles. In order to accept a multi-path assignment on a network larger than a single intersection, every vehicle on the network would have to be modeled using the fixed-route option. This attribute makes the implementation of externally generated assignment difficult to implement.

Dynamic route guidance will be modeled explicitly in future versions of NETSIM, but these versions are not expected to be fully developed any earlier than 1994, which is too late for the architecture evaluation effort CORSIM, a new simulation combining NETSIM and FRESIM logic, is also under development. A version of CORSIM that includes the dynamic route guidance capability would be most likely meet all or nearly all of the modeling requirements. However, in conversations with the development team, it appears certain that the delivery date for this model cannot be accelerated to accommodate the architecture evaluation effort time table.

Finally, the model is so detailed that it may require extensive run times for congested, multi-intersection networks. While source code access is not a problem, the code is extensive, written in FORTRAN, and difficult to modify for programmers unfamiliar with its structure. Any modification to the code would probably best be done by the current development team.

Pros and cons of employing FRESIM and NETSIM for tactical analysis for architecture evaluation are listed in table 5-1.

5.1.1.2 candidate: THOREAU

THOREAU is a newer model developed from its inception to model specific IVHS concepts. It has a flexible route guidance and traffic management modules that can accept externally generated control strategies. THOREAU may model multiple classes of equipped vehicles simultaneously, and has the ability to model multi-path assignment techniques. THOREAU is also written in a compact, high-level language (MODSIM) with an object-oriented approach that makes modifications to the code less difficult.

THOREAU partially or fully meets all the tactical and general modeling requirements for architecture evaluation. Many of the requirements that are not fully met could be met with modifications to the source code. Many are minor changes; however, some modifications are more extensive. For example, THOREAU does not have a sophisticated surveillance model and a nontrivial effort would be required to fully develop this capability. Source code is available for THOREAU.

The most serious obstacle for THOREAU is that it is a relatively new model. While the micro-level simulation logic has been validated, THOREAU is not yet a “product” with a wide user base and extensive application. For this reason, it is recommended that the architecture evaluation effort consider THOREAU using only the validated micro-level logic, and not the still experimental mixed strategic-/tactical-level logic. This recommendation restricts the consideration of THOREAU to tactical analyses.

Pros and cons for THOREAU in tactical analysis for architecture evaluation are listed in table 5-2.

Table 5-l. Tactical Analysis: Pros and Cons for FRESIM and NETSIM

Pros:	• Detailed vehicle-vehicle interaction model
	• Surveillance model
	• Both models (or precursors) enjoy wide usage
Cons:	• Cumbersome dynamic route guidance modeling
	• Background model implicit, nonmodular
	• Requires long run times for congested, multi-intersection networks
	• Extensive code makes modification difficult
	• Contractor teams must learn and use two models for tactical analysis

Table 5-2. Tactical Analysis: Pros and Cons for THOREAU

Pros:	• **Only currently available simulation offering**
	• Flexible, modular route guidance and traffic management models
	• May model muttiple classes of equipped vehicles **simultaneously**
	• Modular, multi-path background traffic modeling
	• Compact high-level language and object-oriented design
Cons:	• New model without wide usage
	• Requires workstation for tractable run times on congested networks

5.1.1.3 Recommendation: THOREAU

The THOREAU model using the validated micro-level logic is recommended for tactical-level analysis. THOREAU fully or partially meets all general and tactical requirements. Some modifications are required to fully meet all the modeling requirements. Although THOREAU is a relatively new model, it is recommended that this drawback is outweighed by the flexibility it offers in tactical analysis.

NETSIM and FRESIM, while detailed microscopic traffic models, have not yet been fully developed as IVHS models. The current versions of these models do not meet critical architecture modeling requirements, including the modeling of dynamic route guidance.

While in the future these models may meet all the identified requirements, these modifications are not expected to be completed in time for inclusion in the architecture effort.

5.1.2 Strategic Analysis: Candidates and Recommendation

For strategic analysis, the leading candidates for usage in architecture evaluation are ROGUS, INTEGRATION, and CORFLO. Each of the leading candidates are discussed in light of the modeling requirements, **with** pros and cons listed for each.

5.1.2.1 Candidate: ROGUS/RG CONTRAM

ROGUS is a suite of models designed around the CONTRAM-5 simulation-assignment model. ROGUS tractably handles networks of extensive scope on a workstation, and models multiple classes of equipped vehicles. ROGUS allows the analyst to model the effects of differing levels and quality of information being passed to vehicles. ROGUS also explicitly models architecture differences vis-a-vis vehicle-infrastructure communication media. Originally designed for the modeling of beacon-based systems, ROGUS may also model broadcast-based systems through a “dense-beacon” approach. Since ROGUS contains CONTRAM-5 as a submodel, background traffic may be calibrated and modeled using dynamic multi-path assignment generated from an induced user-equilibrium based on perceived travel time.

ROGUS fully or partially meets all the strategic and general model requirements for architecture evaluation. Modifications will still have to be made to both model parameter and source code to fully meet all requirements. If source code may be obtained, the modification process may involve changing model modules written either in FORTRAN and ADA. In addition, while transportation engineers in North America may have heard of CONTRAM, both it and ROGUS are not well known or widely used. Finally, ROGUS is still under development and testing in the UK by TRL. No release date has been set for ROGUS, and one is not expected in 1993. ROGUS’ only current computer platform is a VAX Station.

A similar route guidance assignment model, RG CONTRAM, has been developed by the University of Southampton, and is also currently undergoing testing. ROGUS and RG CONTRAM are very similar in the functional model requirements that they address and in their stages of development. Depending on the availability of source code and on the model documentation for each of these models, one of the two may prove to be a superior model for our purposes.

Pros and cons for ROGUS in strategic analysis for architecture evaluation are listed in table 5-3.

Table 5-3. Strategic Analysis: Pros and Cons for ROGUS/RG CONTRAM

Pros:	• Provides sophisticated background model in CONTRAM-5 module • Models multiple classes of equipped vehicles • Models networks of extensive scope • Models architecture differences in vehicle-infrastructure communication
Cons:	• Modifications require knowledge of both FORTRAN and ADA • Still under development • Little exposure/user base in North America

5.1.2.2 Candidate: INTEGRATION

INTEGRATION is a strategic-level simulation for large integrated networks that provides several choices for route guidance, including a single class of vehicles that may be routed externally. INTEGRATION models vehicles at an individual level, and allows the analyst to highlight differences between architecture infrastructure-vehicle communication (beacon vs. broadcast).

INTEGRATION fully or partially meets all the strategic and general modeling requirements for architecture evaluation. Modifications to the model will be most likely be necessary, so source code access is required. INTEGRATION itself does not include an equilibrium traffic assignment module for background vehicles. A background assignment module for INTEGRATION has been developed, but is not yet widely used or validated. Even with the addition of the assignment module, INTEGRATION does not have the ability to model multipath assignment without modification to the source code.

Pros and cons for INTEGRATION in strategic analysis for architecture evaluation are listed in table 5-4.

Table 5-4. Strategic Analysis: Pros and Cons for INTEGRATION

Pros:	• Provides extensive route guidance capabilities • Models vehicles at an individual level • Highlights differences between architecture communication media
Cons:	• Background model not in wide use • Cannot perform multi-path assignment as-is

5.1.2.3 Candidate: CORFLO

CORFLO is a set of macroscopic traffic simulation models. The components of CORFLO enjoy wide usage and run on inexpensive computers. CORFLO fully or partially meets all the strategic and general modeling requirements for architecture evaluation. Modifications to the component models will be necessary to fully meet all the requirements. CORFLO retains the random network traversal feature common to TRAF family members FRESIM and NETSIM, hampering its ability to model dynamic route guidance.

Pros and cons for CORFLO in strategic analysis for architecture evaluation are listed in table 5-5.

Table 5-5. Strategic Analysis: Pros and Cons for CORFLO

Pros:	• Addresses many general requirements • Runs on a inexpensive computer • Component models are well-established
cons:	• Not built for dynamic route guidance modeling • Background model implicit, nonmodular

5.1.2.4 Recommendation: INTEGRATION

Given INTEGRATION's ability to model dynamic route guidance and its relatively mature state of development, the recommendation for strategic-level modeling is for INTEGRATION, provided a suitable source code license can be arranged. INTEGRATION allows for flexible route guidance modeling under both beacon and broadcast communication media. INTEGRATION has a number of current users, including the University of Michigan and the University of California-Berkeley. INTEGRATION was also used as a part of the TravTek operational test in Orlando.

INTEGRATION will require some modification to meet all the requirements for architecture evaluation. Most significantly, INTEGRATION should be modified to accept multi-path assignments for background traffic modeling. A separate entity, either the INTEGRATION-specific ASSIGN module, CONTRAM-5, or a dynamic, multi-path assignment model developed in-house (by MITRE), should be included with a revised version of INTEGRATION. Since THOREAU can accept general multi-path assignments, a consistent background model can be used in both strategic- and tactical-level analyses.

The ROGUS, or the RG CONTRAM suites of models, hold a great deal of promise because of their ability to model and generate multi-path assignment for background and equipped vehicles. However, neither are mature models yet. Currently, ROGUS is not considered validated and is used only as a research model by TRL. TRL has informed MITRE that ROGUS is at least a year away from a state at which it could be considered "releasable." Given the lack of exposure of ROGUS in North America and the modifications that would still have to be made to it, ROGUS is considered to be too early in its development to be included in the architecture evaluation project. RG CONTRAM is in a similar state of development as ROGUS.

The use of CORFLO is not recommended because of the difficulties in performing analysis of dynamic route guidance.

ROGUS and INTEGRATION are both good IVHS models, but at different stages of development. Since ROGUS is not currently available as a mature model, the recommendation for strategic-level modeling is for INTEGRATION. The simulation lacks a proven background assignment model, but acceptable background modeling can still be accommodated with modifications to the source code.

5.2 COMMUNICATION MODEL RECOMMENDATIONS

Both OPNET/B and BONES are very powerful packages. Either of them would be effective tools for evaluating communications architectures.

Each package uses a hierarchical modeling methodology that differs in the implementation of protocols and processes. BONES uses a data structure approach where packets are constructed and processed using a graphical block diagram editor. OPNET/B uses a graphical state diagram editor that generates "C" programming structures. Processes are then implemented by writing "C" code. The result is that OPNET/B will require more low-level programming, but will be more flexible.

Another important difference is in the ability to model RF links. OPNET/B employs a transceiver pipeline module that is an analytical model of the communications channel. BONES offers an optional module that incorporates an analytical model for satellite communication links. However, this model is not ascomprehensive as OPNET/B's analytical link model. The vendor of OPNET/B is working on a land mobile channel model and may meet this requirement at a later date.

Mobile networks will be modeled as a part of the architecture evaluation effort. OPNET/B has a built-in capability to model these nodes, whereas BONES has demonstrated that it is capable of modeling such nodes but does not incorporate this feature as a standard function.

The OPNET/B package also incorporates a feature for graphically entering a nonstandard statistical distribution function. This may be effective for modeling the demand curves generated by the traffic model.

OPNET/B incorporates a graphical utility for entering arbitrary antenna patterns for transmit and receive antennas. This utility will be useful for implementing and determining coverage zones. There is no comparable utility incorporated in BONES.

While contractor teams may use any communication model for their analyses, both OPNET/B and BONES are recommended. For the independent validation and verification efforts, the recommendation is for OPNET/B because the versatility offered in modeling mobile communication networks.

5.3 CONCLUSIONS

For the architecture evaluation effort, a scenario-based modeling approach is recommended using a set of traffic models and a communication model.

Traffic modeling will take place on both a large-scale strategic level and a smaller-scale tactical level. For tactical analyses, the THOREAU micro-logic simulation is recommended. For strategic analyses, the INTEGRATION simulation is recommended, provided licensing arrangements can be made. Contractor teams will be required to use the recommended models for their benefits analysis.

For communications modeling, the contractor teams may select any model as a basis for their analysis, subject to governmental approval. Of the commercially available models, either

OPNET/B or BONES is recommended for this task. OPNET/B is recommended for use in the independent verification and validation process, to be conducted by MITRE.

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GLOSSARY

ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
CONTRAM	Continuous Traffic Assignment Model
CORSIM	CORridor SIMulation Model
COTS	Commercial Off-the-Shelf Software
CVO	Commercial Vehicle Operations
FHWA	Federal Highway Administration
HCS	Highway Capacity Software
INTRAS	INtegrated TRaffic Simulation
IV&V	Independent Validation and Verification
IVHS	Intelligent Vehicle Highway Systems
THOREAU	Traffic and Highway Objectives for REsearch, Analysis, and Understanding
TMC	Traffic Management Center
TRL	Transportation and Road Research Laboratory

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