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A Comparison of Traffic Models: Part 1, Framework

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ABSTRACT

This report defines a framework for comparing dynamic traffic models. It emphasizes four dimensions: functionality, traffic dynamics, route choice dynamics, and overall network performance. The first dimension compares the models through a check-list of model functions. Regarding the last three comparison dimensions, a total of five networks and twelve scenarios are defined. These test scenarios are designed to accentuate model properties and differences. Also included in this report are a list of performance measures for comparison purposes, and a discussion of the interpretation of results.

Keywords: **Traffic Models Comparison, Traffic Simulation, Dynamic Traffic Assignment**

EXECUTIVE SUMMARY

This report is part of a series of three that covers the scope of study for MOU 148--Traffic Models Comparison and Origin-Destination Sensitivities. Part I, reported herein, provides the background information regarding the development of traffic models, and defines in detail the comparison framework and test scenarios. Parts II and III, to be finished, will provide the comparison results among the four models selected for this study and the impact of perturbations to origin-destination data, respectively.

This report first provides an overview of the philosophy of dynamic route choice model development, highlights the different approaches, and reviews the four models selected for this study--INTEGRATION, DYNASMART, DINOSAUR, and METS. This background information helps delimit appropriate expectations and limitations of these models.

We then developed a comparison framework that encompasses four dimensions: functionality, traffic dynamics, route choice dynamics, and overall network performance. For comparison purposes, a check-list of model functions, detailed definitions of the test networks and scenarios for each of the comparisons, the criteria or measures to be produced, and a discussion of the interpretation of results were provided. This comparison framework is designed to be generic so that it permits a comparison among other traffic models.

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1. INTRODUCTION

Ever since the proposal of Intelligent Transportation Systems (ITS) as potential tools for mitigating this country's transportation problems, Advanced Transportation Management and Information Systems (ATMIS) have always been considered as crucial elements. It is expected that, by using advanced computing, processing, and communication technologies, ATMIS will be instrumental in relieving both recurrent and non-recurrent congestion.

The crux of ATMIS relies on its ability to generate, analyze, simulate, and select reactive or proactive traffic management strategies. These abilities are predicated on the development of dynamic traffic models (DTM). Such models may be developed for planning purposes--analyzing what-if scenarios, supporting cost-effective studies by modeling the impacts of installing new facilities fine-tuning signal control strategies, evaluating and eventually implementing route guidance strategies, etc. Unfortunately, it is generally accepted that existing DTMs lag behind the sophistication of technological and hardware capabilities (Mahmassani and Chang, 1992). There is no existing model that can fully support the uses and needs of ATMIS. Realizing this gap, the Federal Highway Administration (FHWA) has developed a five-year program plan to strengthen existing and develop new DTMs (Santiago, 1993).

Perhaps observing the same need, the California Department of Transportation (Caltrans) in the past few years has provided partial support for the development of a number of DTMs, including DYNASMART (University of California, Irvine), METS (Cal Poly, San Luis Obispo), DINOSAUR (PATH Program), and WATSIM (University of California, Berkeley). All of these models are still being actively refined. Nevertheless, it is important to ascertain what they have accomplished so far and highlight future improvements. The objective of this report is to review these DTMs and set up an appropriate framework and suitable scenarios for their comparison. The focus here is not to assess "which is a better model per se", but rather, to shed light on "the context where they may be applicable", and to point out their current limitations, so that future development efforts can be directed. Due to time and resource constraints, we did not finish a complete evaluation of all the four DTMs[1]; only DYNASMART and DINOSAUR, and partially METS were included. Due to its prevalence in the general DTM community and role in assessing the Smart Corridor project in Southern California, we also included INTEGRATION in this comparison.

These four DTMs--DYNASMART, DINOSAUR, METS, INTEGRATION--were motivated by similar purposes. All of them attempt to replicate or represent traffic flows in a network. All of them focus on incorporating route choice decisions or behavior in their modelign approaches. None of them specializes in signal optimization, transportation demand analysis, mode and departure time decisions, although these parameters are used as exogenous input. Finally, all of them are developed as off-line evaluation tools. For convenience, we classify them as Dynamic Route Choice Traffic Models (DRCTM). In general, in addition to the four models studied here, DTMs belong to this group include INTRAS, THOREAU, FREQ, DYMOD, NETSIM, CORQ, etc. (See, for example, Gardes and May, 1990). This scope helps establish a meaningful and fair comparison framework. As described in more detail in Section 2, the comparison framework examines these four aspects: functional, traffic dynamics, route choice dynamics, and overall network performance. Although in this study the four models are compared through this framework, the framework and scenarios are designed to be generic enough for comparing other DRCTMs too.

This report is part of a series of three that covers the scope of study for MOU 148--Traffic Models Comparison and OD Sensitivities. Part I, reported herein, provides background information regarding the development of traffic models, and defines in detail the comparison framework and test scenarios. Parts II and III, to be finished, will provide the comparison results among the four models selected for this study and the impact of perturbation to OD data, respectively.

The rest of this Part I report is organized as follows. Section 2 discusses general approaches for developing DRCTMs, and the history of each of the four models chosen for this study. Section

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[1] The revised version of NETSIM was not yet operational at the time of our assessment.

3 delineates the comparison framework together with the detailed comparison scenarios. Finally, Section 4 provides some summary remarks.

2. DYNAMIC ROUTE CHOICE TRAFFIC MODEL DEVELOPMENT

Before we embark on comparing the models, it is necessary to establish some understanding of the philosophy behind dynamic route choice model development, so as to form appropriate expectations. In this section, we provide an overview of DRCTM development, and then a discussion of each of the four models studied in this project.

In general, there are two well-accepted approaches for DRCTM development: simulation-based and analytical-based. The first approach emphasizes the ability to model vehicular flows microscopically. The crux of this approach involves a simulation engine to model vehicle movements. Two types of input are necessary to drive the simulation engine. The first type is microscopic vehicle movement characterizations, such as vehicle lane-changing and lane-following rules, and queue formation and dissipation. The second is route choice and / or turning movements. Most simulation-based models would explicitly address the modeling of queues. On the other hand, lane-changing and lane-following behavior are largely an open research topic due to the lack of good data.

For the second input type, earlier generations of simulation models generally use a set of intersection turning percentages to direct vehicle flows. This may be appropriate if one is interested in analyzing intersection signal performance alone. However, if the objective is to analyze route guidance performance, the notion of “route” must be explicitly represented. To rectify this shortcoming, most simulation-based models have added a “path-processor” to derive vehicle routes for each origin-destination pair. For example, recently, Caltrans has sponsored a project to add this capability to NETSIM. These path-processors mostly adopt simple concepts of route derivations, such as shortest time path or K-shortest time paths. More advanced approaches use these path processors in combination with a concept of “bounded rationality"* to model dynamic route switching (Chang and Mahmassani, 1988). Whether the notions of shortest time path and bounded rationality are good characterizations of route choice behavior are open to discussion and debate. It is sufficient here to highlight that route choice characterization is one of the crucial elements for defining simulation-based models.

We also note two points generic to all simulation-based models. The first is that simulation-based models are essentially descriptive, not prescriptive tools. They portray the results of certain traffic management strategies, but do not prescribe what traffic management strategies ought to be. The second is their lack of solution properties. Simulation-based models produce one realization per run out of a large space of probable realizations. By carefully ensuring that the system has been "warmed up" before collecting statistics, and by obtaining results from multiple runs with different random seed numbers, and so forth, meaningful results can still be obtained at an aggregate link or network level in terms of averages and standard deviations. (However, it is too often the case that people run the simulation once and generalize the results as representative of the network.) This lack of solution properties means that one has to be extremely carefully in generalizing results, because results learned from one case may not be transferable to other cases. It also implies that bounding analyses are not possible with simulation; one cannot tell whether the system has achieved optimality.

DRCTM may also be developed based on an analytical approach, which is a relatively new research area. The solutions thus obtained have well-defined and understood properties. If the solution is obtained under an user-equilibrium condition, then the system is in equilibrium. If the solution is defined for an system optimal condition in which the objective is to minimize system travel time, then the system has a minimal travel time. Because the solution can be obtained in an "operator-defined" manner, the model can be used for both prescriptive or descriptive purposes. In the context of route guidance, this approach can be used to model the cases where the route plan is calculated either in the vehicle or at a centralized location, while the simulation-based approach can only model the first or "in-vehicle" case. The disadvantage of this approach is that it requires the development of new theories and fast solution

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[2] That drivers will switch routes only when the difference between the new and current paths is greater than a certain user-defined threshold.

algorithms. Some examples of these models include DINOSAUR by (Ran, Lo, and Boyce, 1996) and DYMOD by (Janson, 1991). The other shortcoming is that since these models are formulated based on mathematical programs, adding vehicle dynamics such as queuing and lane-changing behavior is very difficult. For this reason, analytical-based DRCTM are all macroscopic[3].

These two approaches--simulation and analytical based--have their strengths and weaknesses. They may be useful and appropriate for different purposes of the analysis. In this study, we intend to illustrate and highlight these differences, so that users of these models can interpret model results in a more appropriate way. In the following, we provide some brief background for each of the models selected for this study.

2.1 INTEGRATION

The development of INTEGRATION began in 1984, as a result of the doctoral thesis of Van Aerde at the University of Waterloo in Canada. INTEGRATION was first developed as a research tool to analyze the operations of an integrated network, particularly traffic routing between freeways and surface streets during recurrent and non-recurrent congestion. The first version was completed in 1988. INTEGRATION contributed toward integrating the simulation of freeways and surface streets in a single platform; traffic models in the 70's and 80's treated these two types of simulations separately, despite their close interactions.

INTEGRATION became commercially available in 1992 and since then, it has been updated continuously, with more features added. The most recent version (Version 1.5x3D, released in

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[3] Based on the level of detail in vehicle representation, DTM may be classified as macroscopic, microscopic and mesoscopic. Macroscopic models consider the average traffic stream characteristics (flow, speed, density) or vehicle packets. In contrast, microscopic models consider the characteristics of each individual vehicle (location, speed, acceleration, etc.) and its interactions with other vehicles in the traffic stream. Mesoscopic models utilize aggregate traffic flow characteristics to derive macroscopic characteristics, while still tracking individual vehicles.

February 1995) permits the user to define the routing characteristics of up to seven types of driver information systems. The routing characteristics are defined by these parameters: routing strategy, source and quality of traffic information, and link access permissions. Together with a parameter to define the information update frequency, INTEGRATION is arguably one of the most comprehensive models to simulate Advanced Transportation Information Systems (ATIS) (Gardes and May, 1990).

INTEGRATION is a time-based simulation model. Vehicles are modeled as individual entities with self-assignment capabilities. Vehicle movements are simulated by combining results from macroscopic speed-density-flow relationships as well as explicit queuing delays, while microscopic lane-changing and -following characteristics are not modeled[4]. Therefore, the model is often classified as mesoscopic-between macroscopic and microscopic. This design speeds up the code substantially. Route choice is primarily based on the concept of shortest path for individual vehicles. Multiple path equilibrium assignment is only available for the static case, which may not be appropriate for dynamic traffic simulation.

In addition to ATIS parameters and network representation, input to the model include dynamic origin-destination (OD) demands, signal timing plans[5], and incident. INTEGRATION generates statistics on link flows and queues, total network travel times, etc. It also provides on-screen animation of vehicle movements as the simulation proceeds.

There are a number of articles written about INTEGRATION, including Van Aerde (1992, 1994). Interestingly, there is also a critic by Yagar (1993). These articles provide a more comprehensive overview of the model.

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[4] The most recent version (which was not tested here) can model microscopic properties such as lane changing and vehicle following logic. See Van Aerde (1996).

[5] The later versions can generate signal timing plans: Webster and Cobbe algorithm for Isolated intersections, and a corridor optimization scheme for coordinated intersections.

2.2 DYNASMART

DYNASMART (DYnamic Network Assignment Simulation Model for Advanced Road Telematics) was officially named in 1992. An earlier version of the code was part of Jayakrishnan's doctoral thesis with Mahmassani at the University of Texas, Austin (1988-1991). Most of the current version of DYNASMART was developed later on (1990-1992) by Mahmassani, Hu, and others at the University of Texas, Austin, through FHWA support, and Jayakrishnan, subsequently at University of California, Irvine, through Caltrans support. DYNASMART was developed for research purposes and has never been commercially available.

DYNASMART is a simulation-based model specifically developed for studying the effectiveness of alternative information-supplying strategies, traffic control measures and route assignment rules at the network level. It does not attempt to find optimal configurations of ATMIS; it only simulates the effectiveness of a given configuration.

DYNASMART uses a link-node configuration to represent networks and simulates traffic through a time-based approach. Although macroscopic flow models are used, vehicle movements are captured individually, making DYNASMART mesoscopic in scope. There are seven types of driver (behavior) classes differing by vehicle type, network restrictions and information availability. DYNASMART models driver response to ATIS information with boundedly-rational behavior rules. It has extensive path processing capabilities such as the determination of time-dependent k-shortest paths. Recently, Jayakrishnan has added a front-end processor to facilitate data input as well as a post-processor for displaying results.

Developers of DYNASMART have also linked the model with a set of network assignment modules to simulate user-optimal or user-equilibrium patterns. However, in the version that we received from University of California, Irvine, such capabilities were absent, and many of the parameters were hard-coded. Because of this, it should be noted that this partial version of DYNASMART prevented us from testing the model for the entire set of scenarios.

There are a number of articles written about DYNASMART, including publications from University of Texas, Austin's Center for Transportation Research (1994), and Mahmassani et al. (1992, 1993), Hu and Mahmassani (1995), and Jayakrishnan et al (1994).

2.3 DINOSAUR

DINOSAUR (Dynamic Information Network Optimizer for System and User Requirements) is a macroscopic dynamic traffic network model based on analytical approaches. A prototype of DINOSAUR was first developed as part of Ran's Ph.D. Thesis at University of Illinois, in 1993. Part of DINOSAUR development effort has also been sponsored by Caltrans through PATH, especially toward its testing, revision and enhancement. The model continues to be updated with added ATMIS modeling capabilities, such as multiple user classes, congestion pricing, signal control, etc.

DINOSAUR was developed for and continues to be used for research purposes. Its guiding vision was to be used to provide dynamic user-optimal or dynamic user-equilibrium route travel times and traffic flows. While DINOSAUR is macroscopic in scope, it also models some more detailed traffic network characteristics, such as delay functions for signalized arterials.

DINOSAUR models driver choice with three traveler classes: those following pre-specified, externally-generated routes, those with partial or imperfect information (unguided) and those with information (guided). This consideration of information in driver choice, along with DINOSAUR's ability to generate equilibrated route travel times under both recurrent and nonrecurrent congestion, give it strong potential to be applied in future ATMIS systems.

DINOSAUR uses approaches based on variational inequality, optimal control and non-linear programming for its formulation and solution methods. The solution approach uses an iterative procedure to find the dynamic user-optimal state for the network traffic through the creation of an time-space expanded network. The iterations will stop when user-specified convergence criteria are met.

DINOSAUR provides an analytical framework for studying the integration or interaction between route guidance and signal control, or network performance with departure time and mode choice models. Mathematically, these interactions can be formulated with relative ease. The greatest drawback lies in its computational requirements. Coupling these functions in the modeling framework may require formidable effort in arriving at solutions. Speeding up the code will continue to be an aspect that requires substantial research. References for DINOSAUR can be found in Ran (1993), Ran and Boyce (1994), and Ran, Lo and Boyce (1996).

2.4 METS

METS (Mesoscopic Event-based Traffic Simulator) was developed with Caltrans support under the direction of Hockaday and Sullivan at California Polytechnic State University at San Luis Obispo in 1994. It is a simulation-based model that is mesoscopic is scope; individual vehicles are tracked through the network with their following distances determined by macroscopic traffic characteristics.

METS uses “linked sections,” rather than a traditional links and nodes, to represent networks. The simulated road system is divided into sections of road with uniform traffic characteristics and no branches or merges. Branches (divergence) and merges occur only at the beginning and end of links. This approach eliminates the need to store information on intermediate nodes as required by the link-node approach. In addition, each section may have a certain cost associated with it such as to reflect congestion pricing or toll roads. Information related to “nodes,” such as arterial intersections or control methods, can be stored in an “intersection file.”

The overriding design objective behind METS appears to keep the program small, flexible and to allow user interaction. While METS can handle 1024 origins and 1024 destinations, each origin and destination can be further broken up into “neighborhoods” to and from which the traffic flow can be randomly generated or directed to. With this compromise method, over 10,000 origin neighborhoods and 10,000 destination neighborhoods can be handled, effectively resulting in an O/D matrix with 100,000,000 entries.

METS also incorporates randomness into its calculations of route choice. METS records an individual destination for each vehicle as well as turn-ratio probabilities for each divergence. Turning movements for each vehicle are microscopically determined by a Monte Carlo choice of a down stream link. METS allows a different path choice for each type, static or dynamic. Static types rely on turning ratios provided and updated by the user, while dynamic types rely on METS to update their turning movements based on the current status of the network.

METS has no predefined driver classes (behavior type); these must be defined by the user by specifying whether it is static or dynamic, the percent of time this type will obey the route choice instructions, how it evaluates the cost of traveling each section, turning ratios (if the type is static) and whether the TMC can assert control over that vehicle. A typical METS run has 10+ behavior types.

METS is event-driven to allow for faster execution and more flexible design. Each event points to its own event-handling function. There are events to advance vehicles from link to link, to introduce new vehicles at origin points and to update shortest-path values as the simulation progresses. These events are held in a standard priority queue in order of their time-stamp. This queue is implemented as a balanced heap to speed up simulation execution.

METS can also be executed in controlled, time-based "steps," with the smallest being 0.1 of a second. No user interaction is allowed to take place during the execution of steps, but between them, the user can collect data, change parameters, introduce incidents, or save the current state as a "snapshot" from which to start future executions. The references for METS include Hockaday and Sullivan (1994) and Staley, Sullivan and Wormley (undated).

2.5 Summary

INTEGRATION, DYNASMART, and METS may be classified as mesoscopic traffic simulation models, though they may have different granularity of traffic flow representation. INTEGRATION and DYNASMART both use a time-based simulation approach and a traditional node-link approach to represent a network. They also have a number of route derivation rules and can model a number of vehicle classes. In both cases, the notion of “route” is explicitly captured and modeled. METS, on the other hand, is different from INTEGRATION and DYNASMART in a number of ways. First, it is an event-based simulation model. Second, METS uses the concept of link alone; node is not explicitly modeled. Both of these designs are intended to speed up the code, and save memory requirements. More importantly, METS relies on turning percentages at intersections to direct vehicle flows. The notion of “route”, though may be used to derive the turning percentages, is not simulated directly. It is not possible to track or enforce the routes to be followed by individual vehicles. Depending on the purpose of the simulation, this design may prove to be an important deficiency for modeling ATIS scenarios. For modeling other functions **such** as signal control, it may be an efficient design, however. It is sufficient to highlight that there is potentially a tradeoff consideration here.

DINOSAUR is developed from a totally different approach. It is based on analytical approaches, which intrinsically cannot model traffic characteristics microscopically. However, it has other nice properties as mentioned earlier. The important point to determine is whether the output from these different models are comparable at coarser levels of aggregation. In other words, will results from these models agree with each other at an overall network level, link level, or queue level? Will they identify the same “hot” spots at about the same time?

3. MODEL COMPARISON FRAMEWORK

We propose a framework for comparing dynamic route choice traffic models (DRCTMs) in this section. This comparison framework is intended to be generic so that it can be applied for other DRCTMs comparison. Three dimensions are highlighted in this framework: functionality comparison, traffic dynamics comparison, route choice comparison, and finally overall network performance Comparison.

Functionality comparison addresses the features and ways of modeling as claimed by the model developers. Note however that since most DRCTMs are undergoing constant upgrades, features claimed may not necessarily imply their availability at the present moment. Sometimes, a check may simply mean that the model framework permits such development in the future. As such, by no means should this comparison be used as a rigorous approach to assess a model. This comparison, however, may provide a quick overview of what each model is intended to include. The detail of this comparison is discussed in Section 3.1.

Traffic dynamics comparison focuses on whether the model can accurately represent vehicle flows at an aggregate level. Speed-flow-density relationships at a link level are to be compared, while microscopic behavior such as Lane-changing and vehicle-following will not be included. To achieve this goal, a few simple networks are constructed. They are simple enough that detailed tracking of vehicle flows are possible. This in turn permits an easier understanding of the results. Section 3.1.1 provides a more detailed discussion of this comparison.

The third comparison examines how the model determines route choices. Does it use user-optimal or system-optimal criteria, shortest path concepts, or others. Since route choice is critical in deriving the underlying traffic flows in a network, one should have a good understanding of this component before examining the results. Section 3.3 provides a detailed description of this comparison.

Finally, the fourth comparison pertains to overall network performance. Ultimately, we want to see if the models are comparable among themselves when applied to a realistic network. Will the randomness effect due to larger network size and more origin-destination flows even out the discrepancies highlighted in the traffic dynamics and route choice comparisons? Here we have to select a network that balances this effect of size with the tractability of results, We then define a comparison scheme that is according to the need and intention of using the models. Detail is discussed in Section 3.4.

3.1 Functionality Comparison

We set up the comparison of functionality features by five aspects, as addressed in each of the following subsections. This comparison is intended to classify the capabilities of the models as claimed in modeling traffic system functions. These functionality aspects include the modeling of: network representation, traffic dynamics, multiple vehicle classes, ATIS modeling capabilities, and ATMS modeling capabilities. A way to compare different DRCTMs is to examine how they perform or model these functions.

3.1.1 Network Representation

An urban roadway network consists of both freeway and surface street systems. A DRCTM should have the ability to model both systems. In the theory of network flows, a network is usually represented as a collection of links and nodes. Each node represents a point in the network. Each link represents the connection between two nodes. In representing an urban roadway network, a node can be a physical point connecting two links ,such as an intersection, or can be a centroid representing the location of traffic inflow (or outflow), commonly known as origin (or destination). Traffic control attributes such as signals are often associated with a node. Given the importance of signal ***control,*** the detail of which will be further discussed in Section 3.1.5.

Generally, a link is defined on a roadway segment with homogeneous characteristics. Physical link characteristics include length, saturation flow, free-flow speed, jam density, and number of lanes. Sometimes, to enable the modeling of ATMIS, besides these characteristics, the attributes of detectorization and lane usage (such as HOV or toll facility) are also specified at the link level. In summary, the recommended, all DRCTMs should have a way of representing these attributes:

1. Node Characteristics
    a) Designation
        i) Intersection
        ii) Origin and destination
        iii) Incident location

        iv) CMS locations

    b) Control attributes

        i) Signal control

        ii) Turning movement allowance/restriction

    c) Physical attributes

        i) Intersection capacity or saturated flow

        ii) Level or kind of detectorization

2. Link Characteristics

    a) Control attributes

        i) Lane usage (e.g., HOV, Bus lane, etc.)

    b) Physical attributes

        i) Length

        ii) Saturation flow

        iii) Free-flow speed

        iv) Jam density

        v) Number of lanes

        vi) Level and kind of detectorization

There are variations in the association of attributes with the node and link characteristics. The above list only provides a general approach for DRCTMs. For example, some models associate incident location at the link level rather than at the node level. And there are different approaches for the association of detector placement; some at the node, others at the link level.

3.1.2 Traffic Dynamics

Traffic dynamics can be loosely defined as the evolution of traffic flow over time given a set of OD demand and determined route choices. Depending on the purpose of the DRCTM, one may wish to model traffic dynamics microscopically or macroscopically. A microscopic DRCTM models the movements of each individual vehicle, including lane-changing and car-following maneuvers, through a set of rules relating vehicle headway and movement patterns. Given the nature of this approach, generally these models require intensive computation, and simulation is the only possible approach.

On the contrary, a macroscopic DRCTM models traffic flow through the collective or aggregate movements of vehicle streams. A macroscopic approach typically uses these three variables: speed (V), flow (F), and density (K), and the fundamental relationship: F=V*K. By assuming a certain relation between two of the variables, the entire relationship between these three variables is fully specified. Some well-known examples include the Greenshield function, and subsequently the BPR (Bureau of Public Research) function. Given its analytical representation of traffic flow, this approach is used in analytical DRCTMs.

As compared to the microscopic approach, the macroscopic approach offers much faster computational time in deriving link performance measures. On the other hand, the microscopic approach provides details that may be important for traffic dynamics modeling. Naturally, it would be advantageous to combine these two approaches and exploit their distinctively advantage. This results in the mesoscopic approach. In this approach, vehicle link travel time is typically represented by two components: link travel time determined by a macroscopic relationship, and intersection or node delay determined by simulating queues microscopically. Other mesoscopic approaches are developed for trading off the requirements for accuracy and computational effort. For example, instead of simulating and developing vehicle headway microscopically and in each time instant, the headway can be pre-determined and packaged in a standard length as derived from a macroscopic relationship. This "standardized" headway is subsequently used in simulation to speed up computation.

In the following, a list of features for capturing traffic dynamics modeling is provided. By checking this list against a model, the granularity of its ability to capture traffic dynamics can be illustrated.

1. Model type
    a) microscopic
    b) mesoscopic
    c) macroscopic
2. Detailed features captured
    a) Lane changing
    b) Car following

c) Acceleration/Deceleration patterns
d) Separate turning movements
e) Platoon progression
f) Merging
g) Weaving
h) Queue dynamics (on one link)
i) Queue spillback (on multiple links)

The detailed features listed in item 2. are not independent. Ideally a detailed modeling of lane-changing and car-following should encapsulate features such as merging and weaving automatically, while models that capture merging and weaving through a macroscopic approach may not have lane-changing and car-following features. So features 2 a) and 2 b) imply features 2 e), f), g), h), but not vice versa.

3.1.3 Multiple vehicle classes

To adequately model the transportation network, one must acknowledge the fact that there are different vehicle classes operating simultaneously, and that they interact with one another. To the extent that they are relevant and without adding unduly complexity, three major classification schemes can be defined: physical characteristics, driver maneuvering behavior, and travel choice behavior. Each scheme may be further subdivided according to the purpose of the analysis.

The first category differentiates that bus, truck, auto, and HOV have different access permissions to facilities, and different operational characteristics (such as requiring frequent stops). Some macroscopic models assign numeric (usually greater than 1) auto-equivalency to trucks and buses to represent their greater impedance on traffic flow. Microscopic models sometimes assign different parameters to the car-following and lane-changing rules for trucks and buses, or sometimes define a set of different rules for them.

The second category delineates driver maneuvering characteristics, as represented by the different lane-changing and car-following rules. An example is that an “aggressive” driver may execute these rules at much tighter headway or gap than for an “average” driver. This category is primarily applicable for microscopic approaches.

The last category is also the most complicated, which is grouped into the general heading of travel choice behavior. Encapsulated in this category include destination choice, departure time choice, route choice, and mode choice. Each of these choices can be expressed as a relation to its decision inducement. Some examples of the inducements may include the availability of traffic information, travel costs (the impact of congestion pricing may thus be formulated), trip value, and early and late arrival penalty, etc. As one can see easily, there is a host of factors that affects trip making and choices for mode, route and departure time. As a broad framework, all travel choices are important for consideration. Regarding the focus of this study, however, since most existing DRCTMs assume given mode and departure time choices, we emphasize route choice alone (knowing well that it is only part of the choice set).

Under route choice characteristics, one can further develop four subcategories to categorize multiple classes of vehicles: (i) levels of traffic information availability, (ii) toll amount, (iii) driver’s reaction to information and preferences, and (iv) system control. Traffic information availability can be classified by the time dimension: instantaneous, or predictive; by instructional types: descriptive (of what are the traffic conditions), or prescriptive (of how the travelers ought to respond); and finally, by different accuracy levels. It also includes the case where traffic information is not provided or available. Toll may be used as an input to route, mode, and departure time models. One can also set different tolls to different vehicle classes. Items (i) and (ii) may be connected with ATMIS strategies to model their impacts. Item (iii) includes drivers’ reactions and preferences to these strategies, which contains factors such as compliance to routing instructions, performance differences or “bounded rationality” to trigger route switches, the intention to follow user-equilibrium (UE) or user optimal (UO) route choices, and various biases for or against freeway and arterial. Finally, the fourth category is reserved for routing strategies that achieve a system optimal solution. Although this last strategy seems unlikely for day-to-day operations, situations such as emergency evacuation may warrant an system control approach. So we reserve this as the fourth category for modeling considerations.

Other than approaches that explicitly model route choice, as driven primarily by the need to model route guidance impacts, some existing models use an implicit way of modeling route choice, such as using turning percentages at an intersection to direct traffic flow. Note that this implicit approach cannot tag vehicles by their routes taken. There are also approaches that use a cruder way of modeling route choice--assigning same OD demand onto the same route, commonly known as "all-or-nothing". Strictly speaking, this can be considered as a degenerate case in which the entire system contains only one vehicle class (in terms of route choice) and that vehicles share the same travel time by traveling on the same route. For classification purposes, we put the above two approaches, which are based on convenient modeling constructs rather than explicit route choice behavior, under the category of miscellaneous.

In summary, modeling for multiple vehicle classes may include these features:

1. Physical characteristics
    a) Auto
    b) Truck
    c) Bus
    d) High occupancy vehicle (HOV)
2. Driver maneuvering Behavior
    a) Aggressive, average, slow, etc.
3. Travel choice modeling
    a) Mode Choice (out of scope of this study)
    b) Departure time Choice (out of scope of this study)
    c) Route choice
        i) Traffic information availability for various vehicle classes
            a) time scale: pre-trip, instantaneous, predictive information
            b) instructional types: descriptive, prescriptive
            c) information accuracy
        ii) Preferential toll for different vehicle classes
            a) dynamic/static tolling scheme (see Lo and Hickman, 1996)
        iii) Traveler's response and preferences
            a) % compliance to routing instruction

    - b) Bounded rationality
    - c) Bias for/against: freeway/arterial
    - d) User-equilibrium (UE) or user-optimal (UO) choices
    - e) Time elasticity
  - iv) System-Control
    - a) System optimal assignment
  - v) Miscellaneous
    - a) Turning percentages at intersections
    - b) All-or-nothing assignment

3.1.4 ATIS Modeling Capabilities

Advanced Transportation Information Systems attempt to improve traffic flow through providing traffic information to travelers, so that they may be able to make informed travel decisions. Generally speaking, information dissemination may be used to alter or influence travel choices including destination, mode, departure time, and route, as discussed in Section 3.1.3. To be consistent with the theme of this study, the focus here is mainly on information dissemination for influencing route choice.

Section 3.1.3 already described the attributes of traffic information that may be used to alter or influence route choice, including time scale: instantaneous or predictive; instructional type: descriptive or prescriptive; and accuracy level. In practice, the approach for delivering the information often has important implications for cost-effective considerations. In terms of traffic modeling, however, the delivery approach is entirely transparent. Therefore, the modeling of CMS and HAR is similar in traffic models; both approaches may be modeled as delivering instantaneous descriptive incident information.

Generally, modeling the provision of instantaneous information is simpler than predictive information. Without extensive analytical methods, simulation-based models often need to iterate the entire simulation run a number of times, and use traffic information collected from earlier runs to feed into later ones to mimic the presence of "predictive" information.

Analytical models, due to its analytical nature, can often incorporate the generation and hence usage of predictive traffic information directly in their formulations.

In a similar manner, modeling descriptive information is simpler than prescriptive information. Descriptive traffic information merely represents a collection of network traffic conditions, which may subsequently be fed into the route choice component for selecting route choices according to travelers' response or preferences (Section 3.1.3). Simulation-based models can handle descriptive information quite well. Prescriptive information is often related to assigning vehicle routes to achieve some sort of system objective, such as arriving at a system optimal condition. For this purpose, only analytical-based models can derive prescriptive strategies since it is always linked to some kind of optimization to drive at an optimal solution.

One additional component of ATIS strategies that is of importance is the frequency of updating traffic information. This parameter may have important consequences in directing or diverting traffic especially for vehicles with in-vehicle route guidance devices. Therefore, we capture this as the last important aspect for modeling ATIS strategies.

In summary, the features for modeling ATIS strategies include:

1. Traffic information
    a) Time scale
        i) Instantaneous information
        ii) Predictive information
    b) Instructional types
        i) Descriptive
        ii) Prescriptive
    c) Information accuracy
2. Information updating frequency
    a) Time scale: daily, hourly, every 15 minutes, etc.

3.1.5 ATMS Modeling Strategies

Traffic management functions that are important to be captured in a modeling framework include: signal control, freeway ramp metering, incident management, and road pricing. There are many different ways of deriving signal control approaches. However, most DRCTMs do not perform signal optimization functions other than simple ones such as the Webster-Cobbe algorithm. Instead, DRCTMs often use timing plans developed by external specialized signal optimization models. The question is whether DRCTMs have sufficient built-in linkages to use different signal control approaches. These features may include: fixed time control, different phases, ramp metering, actuated signal control, coordinated signal control. The last item refers to a broad spectrum of coordination approaches such as between ramp meters and arterial signals, or between neighboring signals.

There are two perspectives for modeling incident management: descriptive versus prescriptive. The first perspective provides answers to what-if scenarios. For example, what is the impact on traffic if a certain incident happens on a certain location at a certain time with a certain severity? Three attributes are needed for this modeling: incident location, incident occurrence time and duration, and incident severity in terms of capacity reduction. Results from this modeling activity may help understand the impact of incidents. The second perspective looks at how to formulate strategies to reduce the impact of incident. Some examples include re-directing traffic through prescriptive ways by using results obtained from traffic assignment, or modify signal control plans. The first item has been discussed in Section 3.1.4. The second item requires the DRCTMs to have built-in ability to modify the timing plans responding to traffic conditions.

Finally, one may also consider road pricing as a traffic management strategy. This aspect has not yet been captured in any substantial way in DRCTMs. None of the operational models we know of have this capability. To model road pricing, one needs to capture the time-cost elasticity of a traveler's route choice (see Section 3.1.3), and incorporate this route choice function in the simulation/assignment procedure.

In summary, these are the features that DRCTMs may have for ATMS modeling:

1. Signal control
    a) Fixed time control
    b) Phasing
    c) Ramp metering
    d) Actuated signal control
    e) Optimized signal coordination
2. Incident Management
    a) Descriptive
        i) Incident location
        ii) Start and end time of incidents
        iii) % capacity reduction
    b) Prescriptive
        i) Real-time re-routing
        ii) Real-time adjustable signal control
3. Road pricing

Sections 3.1.1 - 3.1.5 depict five important aspects of modeling features that DRCTMs may contain. They organize the capabilities of DRCTMs for comparison purposes. This framework is intended for encompassing a broad range of DRCTMs. As such, it is realized that some DRCTMs integrate the modeling of ATIS and ATMS strategies. Therefore, separating them into different categories may introduce some discontinuities in presenting ATM/IS strategies. Table 1 summarizes the features that can be used for comparing DRCTMs.

Table 1 Features for comparing DRCTMs

MODEL FEATURES	MODEL 1	MODEL 2
A. NETWORK REPRESENTATION		
1. Node Characteristics		
a) Designation		
i) Intersection		
ii) Origin and destination		
iii) Changeable Messge Sign locations		
b) Control attributes		
i) Signal control		
ii) Turning movement allowance/restriction		
c) Physical attributes		
i) Intersection capacity or saturated flow		
ii) Level or kind of detectorization		

2. Link Characteristics		
a) Control attributes		
i) Lane usage (e.g., HOV, Bus lane, etc.)		
b) Physical attributes		
i) Length		
ii) Saturation flow		
iii) Free-flow speed		
iv) Jam density		
v) Number of lanes		
vi) Level and kind of detectorization		
c) Incident Location		
B. TRAFFIC DYNAMICS REPRESENTATION		
1. Model type		
a) microscopic		
b) mesoscopic		
c) macroscopic		
2. Detailed features captured		
a) Lane changing		
b) Car following		
c) Acceleration/Deceleration patterns		
d) Separate turning movements		
e) Platoon progression		
f) Merging		
g) Weaving		
h) Queue dynamics (on one link)		
i) Queue spillback (on multiple links)		
C. MULTIPLE VEHICLE CLASSES REPRESENTATION		
1. Physical characteristics		
a) Auto		
b) Truck		
c) Bus		
d) High occupancy vehicle (HOV)		
2. Driver maneuvering Behavior		
a) Aggressive, average, slow, etc.		
3. Travel choice modeling		
a) Mode Choice (out of scope of this study)		
b) Departure time Choice (out of scope of this study)		
c) Route choice		
i) Traffic information availability for various vehicle classes		
a) time scale: pre-trip, instantaneous, predictive information		
b) instructional types: descriptive, prescriptive		
c) information accuracy		
ii) Preferential toll for different vehicle classes		
a) dynamic/static tolling scheme		
iii) Traveler's response and preferences		
a) % compliance to routing instruction		
b) Bounded rationality		
c) Bias for/against: freeway/arterial		
d) User-equilibrium (UE) or user-optimal (UO) choices		
e) Time-cost elasticity		
iv) System-Control		
a) System optimal assignment		
v) Miscellaneous		
a) Turning percentages at intersections		
b) All-or-nothing assignment		
c) Multiple path assignment		
D. ATIS STRATEGIES		
1. Traffic information		
a) Time scale		
i) Instantaneous information		

ii) Predictive information		
b) Instructional types		
i) Descriptive		
ii) Prescriptive		
c) Information accuracy		
2. Information updating frequency		
a) Time scale: daily, hourly, every 15 minutes, etc.		
E. ATMS STRATEGIES		
1. Signal control		
a) Fixed time control		
b) Phasing		
c) Ramp metering		
d) Actuated signal control		
e) Optimized signal coordination		
2. Incident Management		
a) Descriptive		
i) Incident location		
ii) Start and end time of incidents		
iii) % capacity reduction		
b) Prescriptive		
i) Real-time re-routing		
ii) Real-time adjustable signal control		
3. Road pricing		

3.2 Traffic Dynamics Comparison

Traffic flow characteristics can be represented in three levels -- macroscopic, mesoscopic, and microscopic. At the microscopic level, traffic is modeled by treating each vehicle as a single entity. This level of representation is important in modeling detailed vehicle dynamics such as car-following, lane-changing, or weaving behavior. At the macroscopic level, on the other hand, traffic is modeled as a stream of flow. Gross performance measures such as link speed and travel time are the ultimate objectives of this level of representation. Without capturing detailed vehicle dynamics, macroscopic models relate vehicle volume or density measures directly to link speed or travel time. The Greenshields or BPR functions are examples of this class. Mesoscopic approaches are a middle ground between macroscopic and microscopic models. They use macroscopic models to derive the travel time of the "flow" part of vehicle travel, and microscopic representation to "move" individual vehicles consistent with the "flow" part travel times, queueing conditions, and origin-destination requirements. They can capture the properties of continuity (e.g. smooth traffic) and discontinuity (e.g. shocks) in traffic flow.

The representation of traffic dynamics has a significant impact on dynamic traffic assignment models. In static traffic assignment models, traffic dynamics is irrelevant since both the OD demand and link flow are constant, and time is not explicitly modeled. In dynamic traffic assignment, however, traffic dynamics directly affects link travel times, and hence the resulting route choices. The key to reflecting traffic dynamics in analytical or simulation DRCTMs is on how well they capture the forward propagation of vehicle flows and the backward propagation of stoppage waves, because both are directly related to modeling travel times. This section discusses the methodology for evaluating the performance of the models in this regard.

3.2.1 Speed-Flow-Density Relationships

Most DRCTMs allow a user to vary the parameters for modeling traffic dynamics. Depending on the approach, these parameters may include free-flow speed, speed at capacity, capacity, jam density, or the coefficients associated with the BPR or Greenshields types of functions.

Van Aerde and Rakha (1995) showed that for different types of links, such as freeway, tunnel, and arterial, the coefficients of these terms, and hence the resultant speed-flow-density relationships may be different. It is, therefore, impossible to contend a set of parameter values for all conditions. For comparison purposes, we set the parameters as:

1. Jam density = 210 vehicle per mile
2. Free-flow speed = speed at capacity = 60 miles per hour
3. Capacity = 1800 vehicles per hour.

It is advantageous to employ this simplest possible speed-flow-density relationships as shown in Figure 1 and Figure 2. By fixing those defined points, many functional shapes are still possible. In recent years, a triangular form has been adopted by a number of researchers (e.g., Hall et al. 1986, Newell, 1994, Daganzo, 1995) to represent the flow-density relationship. Under this representation, the free-flow speed and the speed at capacity are the same as long as traffic is uncongested. The speed-flow curve corresponding to this flow-density curve is uniform on its upper envelope and decreases steadily on its lower envelope or the congested regime, as illustrated in Figure 2. However, since different models may adopt different predefined functional forms in the congested regime, the detailed traffic dynamics resulting from each model may still be quite different.

In particular, the triangular flow-density relationship does not apply to models using the BPR types of functions. Under these models, travel cost is a strict increasing function of flow or the number of vehicles on a link. The speed for traffic near capacity can be significantly different from the speed for light traffic, even though under both situations traffic might be free-flow.

Due to differences in specifying the underlying theories of traffic flow, it is anticipated that different models will produce different traffic patterns. In any case, it is the objective of this study to find out how different they are.

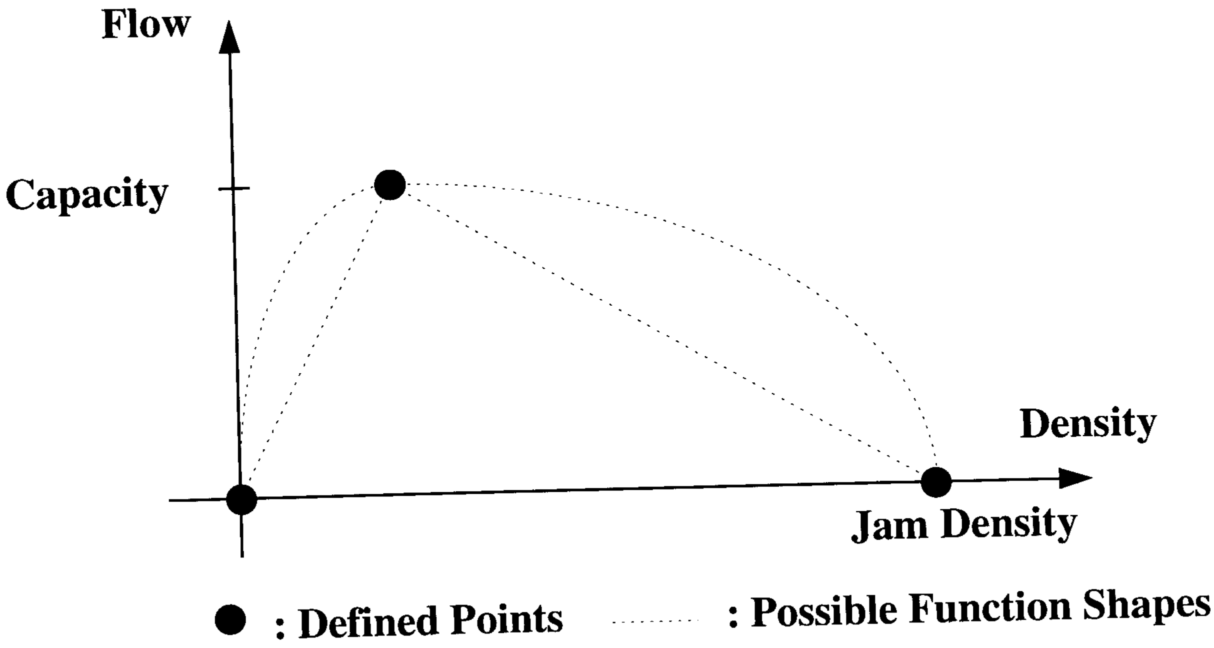

Figure 1 Flow-density relationship used for comparison.

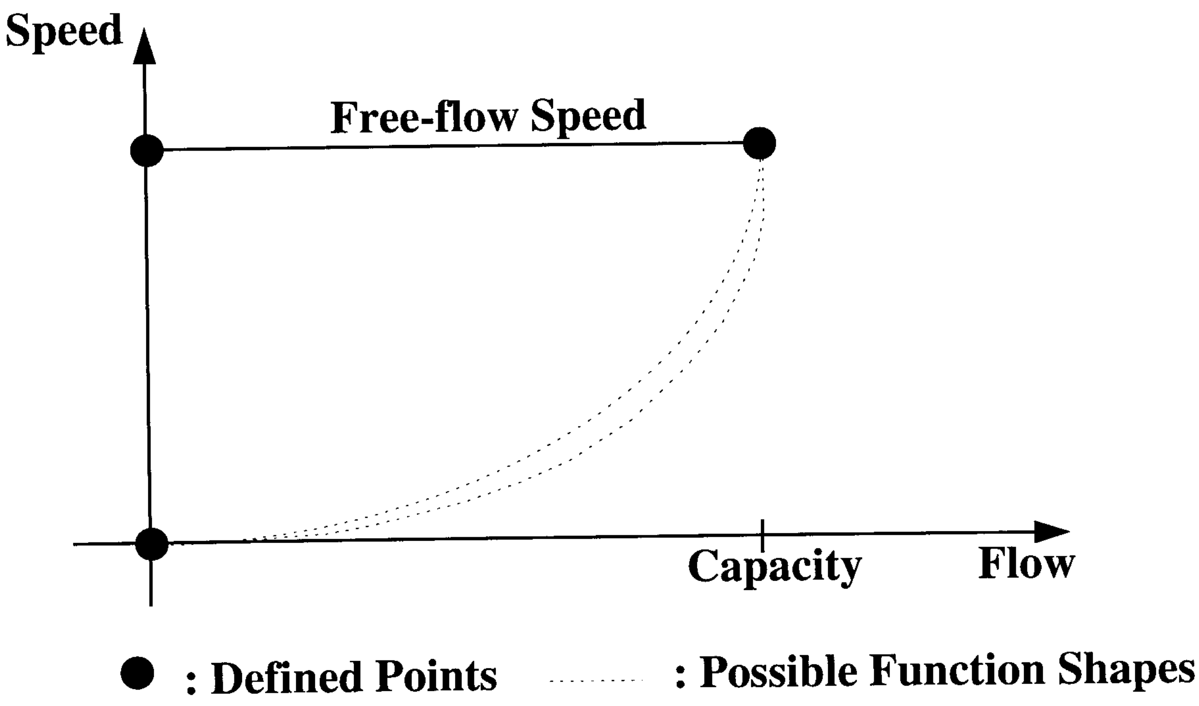

Figure 2 Speed-flow relationships used for comparison

3.2.2 Test Networks

Several test networks are set up to evaluate the traffic dynamics characteristics of DRCTMs, in particular, the formation, propagation, and dissipation of queues. They are constructed in a way such that the results generated from any specific model can be easily checked against common sense and the prediction from the existing traffic flow theories. In this spirit, small and simple networks are preferable. These networks, however, must be realistic and representative in the sense that they are building blocks for large complicated networks. They should also have the capability in demonstrating the effects of the time-varying demand, bottlenecks, and incidents on traffic congestion.

3.2.2.1 Network Topology

There are three network settings adopted in our evaluation: (A) a network with a single origin and a single destination, (B) a network with a single origin and two destinations, and (C) a network with two origins and a single destination, as shown in Figure 3 through Figure 5.

Each network consists of links and nodes. Links carry the physical length and nodes serve only for the purpose of connectivity. The length of the link and the free-flow speed are defined such that a single discrete time step is needed for vehicles to traverse each link. This would enable one to trace easily the vehicle movement from link to link and compare results across different models and with the prediction from the existing traffic flow theory.

The network with a single origin and a single destination can be viewed as a simple linear network. Even in such a simple linear network, both the effect of fixed bottlenecks (e.g. lane drops) and time-varying bottlenecks (e.g. lane closure due to incidents for some period of time) on traffic flows can be studied.

The network with a single origin and two destinations contains a single diverge junction can be viewed as a representation for off-ramp areas or interchanges in a large scale network. Likewise, the network with two origins and a single destination has a single merge junction can be viewed as a representation for on-ramp areas or interchanges in a large scale network. The effects of vehicle interactions are to be studied in these areas. It is crucial for any traffic assignment models to model traffic in these building blocks properly before modeling traffic in a large scale network.

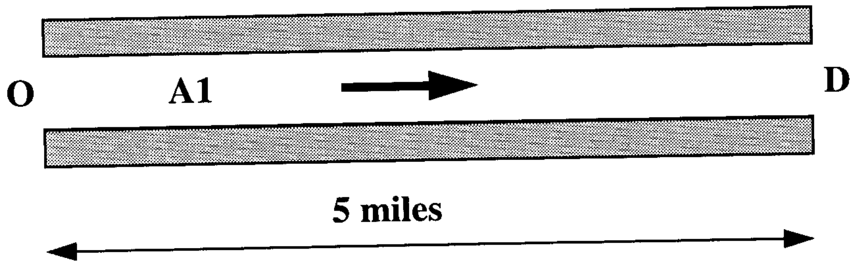

Figure 3 The linear network A

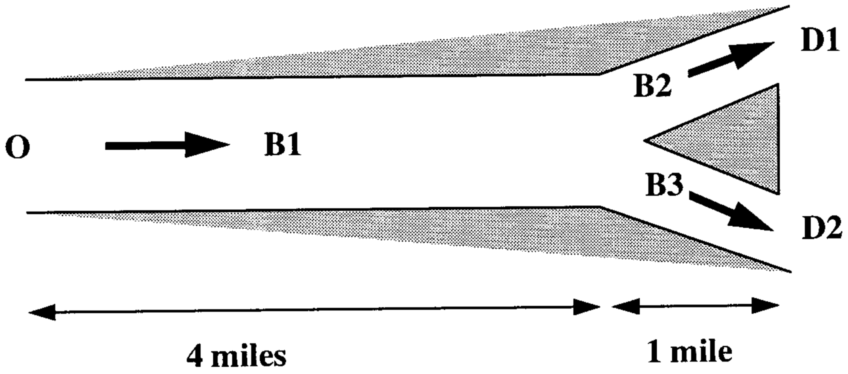

Figure 4 The diverge network B

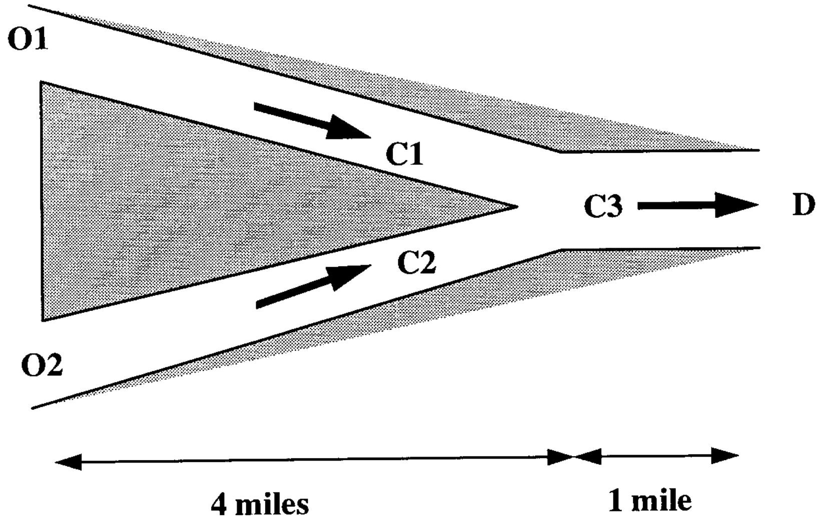

Figure 5 The merge network C

Each of the branches shown in Figure 3 through Figure 5 is modeled to comprise of links of 0.1 mile long. Hence, there are 50 links running between each origin-destination pair. Unless otherwise specified, the link characteristics are shown in Table 2.

Table 2 Link characteristics in each network

Links in Branch	No. of Lanes	Free Flow speed (mph)	Speed at Capacity (mph)	Capacity (vph)	Jam Density (vpm)
A1	1	60	60	1800	210
B1	1	60	60	3600	420
B2	1	60	60	1800	210
B3	1	60	60	1800	210
C1	1	60	60	1800	210

C2	1	60	60	1800	210
C3	1	60	60	3600	420

3.2.2.2 *Test Scenarios*

Two test scenarios are considered for evaluating traffic dynamics, one for recurrent congestion and the other for non-recurrent congestion for each of the network settings (linear, merge, and diverge). In order to compare traffic phenomena across different models, only the minimum common inputs are required for each model and functions unique to any specific models are disabled. For each scenario, there are four pieces of input data: roadway geometry as depicted in the previous section, travel demands, simulation runtime parameters, and incident or bottleneck characteristics.

Traffic demands are defined as the departure rate of vehicles from each origin to each destination. Simulation runtime parameters are defined as the length of a discrete time step and the total time for each complete simulation run. Incident characteristics describes the start time, duration, magnitude, and the location of incidents. Finally, bottleneck characteristics delineates the bottleneck's location and length, and its associated capacity reduction. Table 3 and Table 4, respectively, summarize the input parameters for the non-recurrent and recurrent scenarios. These parameter values are chosen to accentuate the output of different DRCTMs.

For the linear network, two types of travel demands are considered: constant travel demands and time-varying travel demands. For time-varying travel demands, the total time duration is divided into three periods that cover the transition between the light and the heavy traffic. For the networks with junctions (merge and diverge cases), symmetric and asymmetric travel demands are considered. This would allow one to observe vehicle interactions, induced by vehicles competing with each other (e.g. the ratio of the vehicles coming from different branches in a merge junction), at the junction area. Also covered are two types of capacity restrictions: dynamic, as represented by an incident, and static, as represented by a bottleneck.

Table 3 Scenario description of the non-recurrent cases

Scenario	Network	Runtime parameters	Traffic Demand	Incident
1	Linear A	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	O-D: 1200 vph for 30 min.	Start time: 5.5 min. Location: 1 mile from D Severity: 100% blockage Duration: 6 min.
2	Diverge B	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	O-D1: 1200 vph for 30 min. O-D2: 900 vph for 30 min.	Start time: 5.5 min. Location: 0.5 mile from D1 Severity: 100% blockage Duration: 9 min.
3	Merge C	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	O1-D: 1200 vph for 30 min. O2-D: 900 vph for 30 min.	Start time: 5.5 min. Location: 0.5 mile from D Severity: 100% blockage Duration: 9 min.

Table 4 Scenario description of the recurrent cases

Scenario	Network	Runtime parameters	Traffic Demand		Bottleneck
4	Linear A	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	Time (sec.)	Departure rate	Location: 0.5 mile from D Length: 0.2 mile (2 links) Capacity: 900 vph Jam Density: 105 vpm
			0-300	600 vph	
			301-600	1800 vph	
			601-1800	600 vph	
5	Diverge B	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	O-D1:		Location: 0.5 mile from D1 Length: 0.2 mile (2 links) Capacity: 900 vph Jam Density: 105 vpm
			Time (sec.)	Departure rate	
			0-300	600 vph	
			301-600	1800 vph	
			601-1800	600 vph	
			O-D2:		
			Time (sec.)	Departure rate	
			0-300	600 vph	
			301-600	1200 vph	
			601-1800	600 vph	
6	Merge C	Time step: 6 sec. Total time: 30 min. or until traffic is cleared	O1-D:		Location: 0.5 mile from D Length: 0.2 mile (2 links) Capacity: 1800 vph Jam Density: 210 vpm
			Time (sec.)	Departure rate	
			0-300	600 vph	
			301-600	1800 vph	
			601-1800	600 vph	
			O2-D:		
			Time (sec.)	Departure rate	
			0-300	600 vph	
			301-600	1200 vph	
			601-1800	600 vph	

3.2.3 Comparison Criteria

3.2.3.1 *Space-Time Relationship*

On a large scale network, the presence of queues directly changes the route choice behavior of drivers which in turn changes the traffic distribution. The temporal and spatial effect of a time-dependent queue also affects the effectiveness of the real-time travel information on trip times. Therefore, one of the major tasks in model comparison for traffic dynamics is to evaluate how queues are represented in various models.

The spatial and temporal effect of the queue in the network exhibits in several conditions. Under the bottleneck situation, one may examine whether the queue is formed inside or upstream of a bottleneck, how fast the queue propagates, and the density, flow, speed associated with the queue.

Significant differences between the point queue model and the spatial queue model would become evident under a situation when queues back up from a diverge branch to the junction. For the point queue model, the effect will not be shown at the junction since no spillover is modeled. With a spatial model, however, the spillover will block the traffic going to the other branch. For the spatial queue model, it is worthwhile to take one step further to examine how this spillover would affect the vehicle composition at the junction area when a queue is formed at one of the diverge branches by tracking the rate of exiting flows to each branch under congestion.

One may also want to examine how queues dissipate. For a model that considers both the temporal and spatial effects of a queue, there are two distinctive features in queue dissipation under recurrent and non-recurrent congestion. In the bottleneck situation, queues can only be reduced by a reduction in traffic demands. As a result, queues should dissipate starting from the upstream end and in the direction of the traffic flow. In the incident situation, queues dissipate, when the incident is cleared, starting from the downstream end and in the direction opposite to the traffic flow. Again, the point queue models would not make this distinction. Though seemingly subtle, this distinction could well influence the route choice dynamics and thus further affects the network performance.

The space-time diagram as illustrated in Figure 6 is a convenient tool to depict the formation and dissipation of a queue. The figure uses different shades to represent vehicle occupancies on each link, that capture not only the level of congestion but also a detailed profile of the backward and forward moving waves. This tool provides a graphical means for comparing results, especially on queuing spillback and impact.

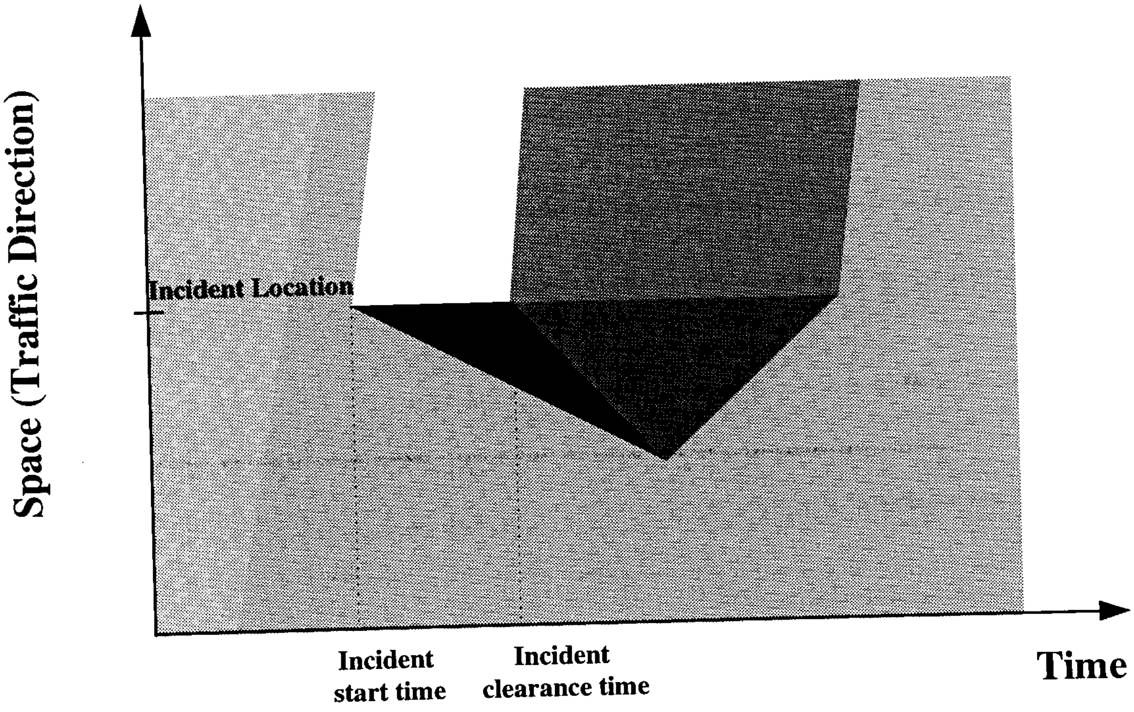

Figure 6 A space-time diagram showing the impact of an incident on a linear network

3.2.3.2 *Time-dependent Link Travel Time*

For most models, the ultimate variable used in deriving routes or traffic assignment are time-dependent link travel times. This comparison investigates whether simpler macroscopic link performance functions, which do not capture queuing impact explicitly, will perform similarly to microscopic models. For this comparison, travel-time versus time graphs can be used, with an example shown in Figure 7. By overlaying results from different models on the same graph, one can see if similar peak travel times and their occurrence time are predicted similarly.

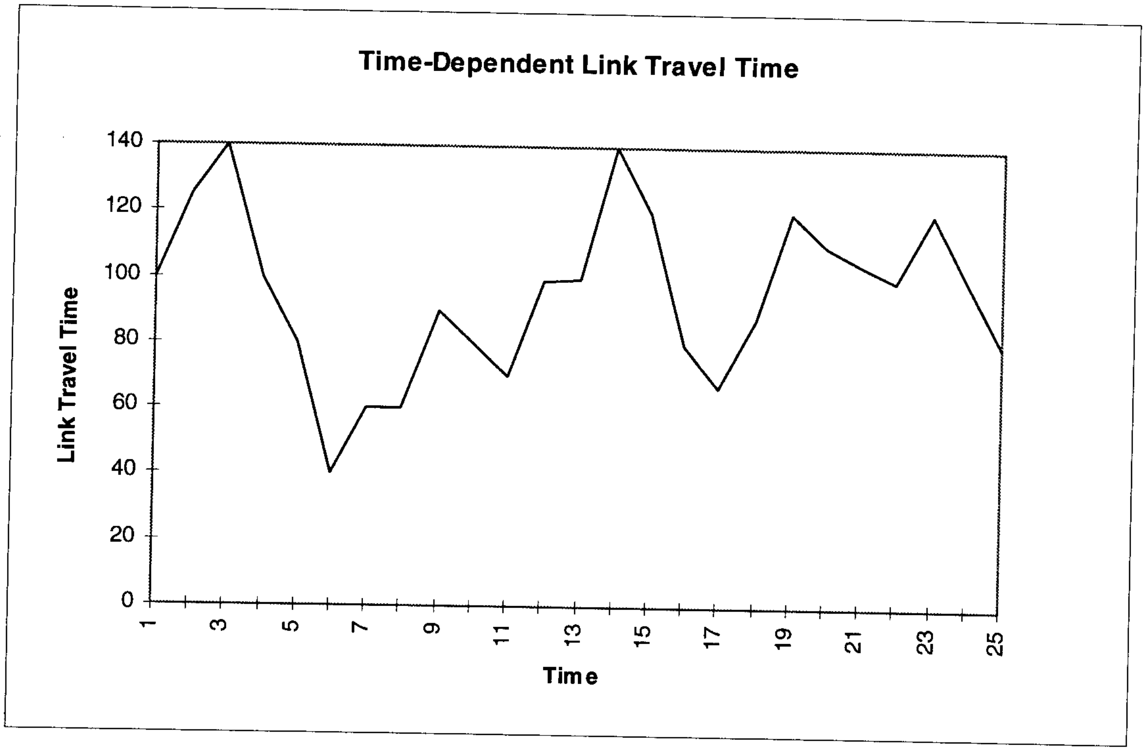

Figure 7 Time-dependent link travel time

3.3 Route Choice Comparison

In addition to simulating vehicle flows on each link as described in Section 3.2, deriving route choices or directing traffic flow according to the flow's origin-destination is of utmost importance. Models such as METS, NETSIM and its variations avoided the modeling of "route" by introducing turning percentages at each intersection. This modeling approach is a convenient device; however, it cannot preserve the intended or stated origin-destination flows of the network, and cannot model the impact of route guidance since the notion of "route" is not captured.

DRCTMs employ a variety of methods to simulate the route choice of a vehicle. At the most basic level, vehicles can be divided into two types: those following fixed routes and those following dynamic routes. In the former type, a DRCTM prespecifies a set of fixed routes for each origin-destination pair, perhaps based on the shortest distance criterion, regardless of the prevailing traffic conditions. The latter type is modeled to follow a route that either (i) minimizes its individual criteria such as travel time or distance traveled based on the network conditions, or (ii) minimizes the overall system delay. Case (i) in the literature is often called the Dynamic User-Optimal condition (DUO), and case (ii) the Dynamic System Optimal (DSO) condition.

While the definition of DSO is easy to define--the selected criterion is minimized for the entire system for the entire modeling horizon, the definitions of DUO are not. Generally the DUO conditions are defined by extending the Wardrop's principle (1952) of static user equilibrium, which requires that the cost of a used route between a given origin-destination pair equals the minimum route cost, and that no unused route has a lower cost. To extend Wardrop's static condition to a dynamic one, researchers have generally differentiated between two types of DUO conditions--instantaneous and actual. Instantaneous DUO can be defined as: For each origin-destination pair at each decision node at each instant of time, the instantaneous travel times for all routes that are being used equal the minimal instantaneous route travel time (Ran and Boyce, 1994). Actual DUO can be defined as: For each origin-destination pair at each instant of time, the actual travel times experienced by travelers departing at the same time are equal and minimal. (Ran and Boyce, 1994). The difference between Instantaneous DUO and Actual DUO lies in whether a route is selected based on instantaneous or prevailing travel times at each instant (which may be different from the actual travel time that a vehicle shall experience), or to-be-experienced actual travel times. The Instantaneous DUO condition can be achieved if one has a perfect knowledge of the current status of the network at each instant of time, while the achievement of the Actual DUO condition requires a perfect knowledge of the future states of the network as well.

In applications, the DUO condition is appealing because it seems to describe a common behavior of travelers--minimizing their individual travel criteria, while the DSO condition defines the upper bound performance of traffic system management. Many DRCTMs adhere themselves to these definitions and try to produce traffic patterns that are consistent with them.

There are other route choice approaches proposed by previous research. Simulation-based DRCTMs commonly assign vehicles to the shortest-time route at each defined time interval based on the prevailing traffic conditions as the simulation time proceeds. In this approach, the resultant traffic patterns and route choices may be affected by the order of assigning the O-D pairs. This property may render this approach different from the Instantaneous DUO condition defined earlier, in which the order of assigning the traffic is unimportant. Other models proposed the use of not only the shortest path but k-shortest paths for vehicle route assignments. There is also the notion of "Bounded Rationality" proposed and implemented in some models. This notion uses a threshold of route travel time differences to activate a route change.

Many of these route choice proposals have behavioral appeals. Which model is more correct or appropriate, or whose resultant traffic patterns can describe reality better is up for debate and is largely an open research topic. In any case, it is not the intention of this report to conduct this assessment. We, however, devise a simple network to delineate which route choice approach is implemented in the DRCTM, and what is the major difference in the resultant traffic patterns. These results may then assist users in deciding whether the model satisfies their particular modeling needs.

3.3.1 Test Network

The purpose of this section is to focus on the route-choice capabilities of each traffic simulation/assignment model. Many models allow a user to select different information provision strategies and random numbers. It is not the intention of this study to assess whether these parameters can produce better results. As such, the scenarios are designed to remove the information restraint and randomness as much as possible. To make the tests simple and the results from different models comparable, the test scenarios exhibit the following characteristics:

- Route selection is entirely based on real-time link travel times, which are updated every second or as often as allowed in the model[6].
- The travel time information is correct, with no error in collection or transmission.
- The traffic stream consists of one class of vehicles. All vehicles have identical flow characteristics and follow the assigned paths.
- Random factors (such as the platoon dispersion factor and pulsing) are disabled.

These simulation runs provide a framework to test the models. In addition, the results of these runs can also be used as a "benchmark" to compare runs that relax the above assumptions.

3.3.1.1 *Network Topology*

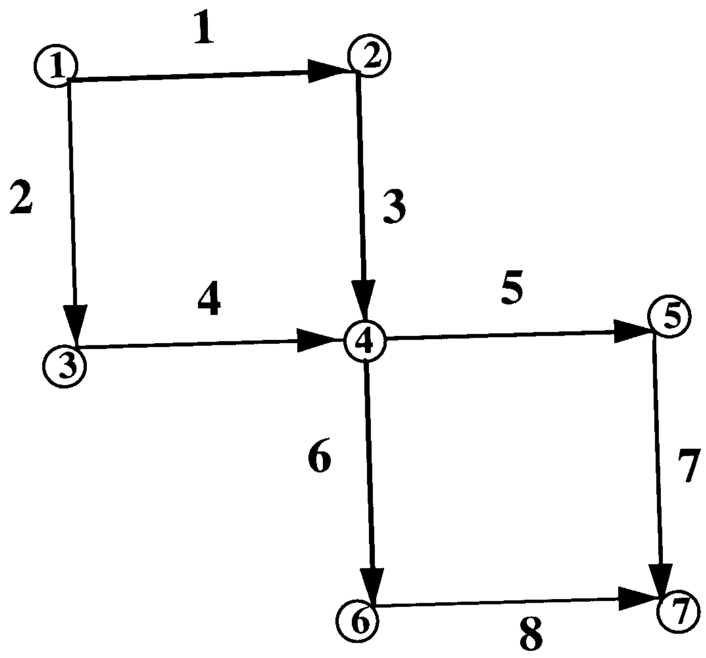

Figure 8 The test network for route choice comparison

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[6] The version of DYNASMART we tested has a hard-coded information update frequency of 2 minutes.

Figure 8 shows the topology of the test network. Node 1 is the origin and node 7 the destination. As one can see, the routes connecting node 1 to node 7 are symmetrical and consist of two similar loops. Vehicles can follow any one of four different paths between them. The link characteristics are shown in Table 5. Each link is identical in this regard: unidirectional, one lane wide, and 0.5 miles (0.8 km) long.

Table 5 Link characteristics in the test network for route choice comparisons

Link	No. of Lanes	Length (mile)	Free Flow speed (mph)	Speed at Capacity (mph)	Capacity (vph)	Jam Density (vpm)
1	1	0.5	60	60	1800	210
2	1	0.5	60	60	1800	210
3	1	0.5	60	60	1800	210
4	1	0.5	60	60	1800	210
5	1	0.5	60	60	*	210
6	1	0.5	60	60	*	210
7	1	0.5	60	60	*	210
8	1	0.5	60	60	*	210

Note: * refers to Table 6 in section 3.3.1.2.

3.3.1.2 *Test Scenarios*

For each test scenario, a constant demand of 1800 vph is introduced at the origin for one hour and then the network is allowed to clear. The traffic stream consists of one class of vehicles, all of whom use the same strategy and information in their route choice selection, as delineated in section 3.3.1. And there is no fixed route traffic.

The scenarios are constructed by varying the link capacities of the lower loop to form different bottlenecks. The objective of the scenarios is to test whether the models can adjust their route choice assignments to balance traffic flows. The link capacities for each scenario are shown in Table 6. The first pair (scenarios 7 & 8) focuses on the location of link capacity reduction on links 5 & 6, while the second pair (scenarios 9 & 10) focuses on links 7 & 8. Even with these reduced capacities, the total capacity downstream of node 4 is not less than the OD load of 1800 vehicles per hour (vph).

Table 6 Scenario parameters for route choice comparisons

Scenario	Runtime parameters	Traffic Demand	Link Capacities
7	Time slice: 30 sec. Sim. horizon: 2 hr. or until vehicles clear the network	Node 1 to node 7: 1800 vph for 1 hour	Link 5: 1200 vph Link 6: 600 vph Link 7: 1800 vph Link 8: 1800 vph
8	Time slice: 30 sec. Sim. horizon: 2 hr. or until vehicles clear the network	Node 1 to node 7: 1800 vph for 1 hour	Link 5: 600 vph Link 6: 1200 vph Link 7: 1800 vph Link 8: 1800 vph
9	Time slice: 30 sec. Sim. horizon: 2 hr. or until vehicles clear the network	Node 1 to node 7: 1800 vph for 1 hour	Link 5: 1800 vph Link 6: 1800 vph Link 7: 1200 vph Link 8: 600 vph
10	Time slice: 30 sec. Sim. horizon: 2 hr. or until vehicles clear the network	Node 1 to node 7: 1800 vph for 1 hour	Link 5: 1800 vph Link 6: 1800 vph Link 7: 600 vph Link 8: 1200 vph

The scenarios are set up to answer three questions, as explained in detail in the following paragraphs: How close is the model in replicating the DUO or DSO objectives? Does the model incorporate queuing in its route assignment procedure? Does the model has intrinsic biases that a user should be aware of?

By defining the speed at capacity equal to the free flow speed, and the total downstream (of node 4) capacities of the bottleneck links (i.e., links 5 and 6 in scenarios 7 and 8, and links 7 and 8 in scenarios 9 and 10) equal to the OD load, one would not expect any queue build up if the assignment is based on either the DUO or DSO approach. The expected result for an DSO and DUO assignment ought to be the same, and that the travel times of all paths equal to 2 minutes (=2 miles/60 mph) and the total system travel time ought to be 3600 minutes (=1800 vph * 1 hour * 2 minutes). An DUO or DSO assignment should also divide the traffic flows according to the proportion of the capacities of the bottleneck links. For example, 2/3 of the traffic should choose link 5 and 1/3 on link 6 in scenario 7. Deviations from these expected results are then an indicator of how close the models can achieve the DUO and DSO objectives. Alternatively, to verify the objective of DUO, one can check the travel times of all the used paths and see if they are equal.

By comparing the results between scenarios 7 and 9, and between scenarios 8 and 10, one can assess whether the locations of the bottlenecks and queuing characteristics will affect a model's route assignment. In scenarios 7 and 8, there is no room for queues to form after the decision node 4, while there is for scenarios 9 and 10. If queuing impacts[7] are not considered in the assignment procedure, scenarios 7 and 9 should have identical results because the two branches of the lower loop have the same "route" capacity. The same holds for scenarios 8 and 10.

In the course of developing these scenarios, we found[8] that some traffic models, for convenience or other reasons, have a bias to assign vehicles to the link with the lowest label (or number) among downstream contender links that have identical travel times. This may lead to misleading results since (i) link labels are given arbitrarily, and (ii) the results hence produced are unrealistic—the assignment will fill up the lower-labeled link near to its capacity while ignoring the available capacities of the other contender links. To reveal this potential pitfall, scenarios 7 and 8 are constructed by flipping the capacities between links 5 and 6. Similarly, scenarios 9 and 10 are constructed by exchanging the capacities between links 7 and 8. By verifying whether the resultant assignments are accordingly exchanged, as indicated in the results between scenarios 7 and 8, and between scenarios 9 and 10, one can check if the model has such a bias.

3.3.2 Comparison Criteria

Four criteria are used to expose a model's performance with respect to the three questions raised in section 3.3.1.2: route travel time, link travel time, and link volume, all expressed as a function of simulation time, and overall system travel time and speed.

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[7] Here we mean the explicit modeling of queue formation and dissipation, not through a point-queue or BPR types of functions to capture congestion)

[8] See Part II of this series for detail.

3.3.2.1 *Time-dependent Route Travel Time*

Time-dependent route travel time is defined as actual travel time to finish a route given a fixed departure time. Travel times of the four routes linking node 1 to node 7 are plotted over the demand's departure time. A sample plot is shown in Figure 9. A perfect DUO assignment will produce equal travel times for all four routes—i.e., four overlapping lines in this type of plot.

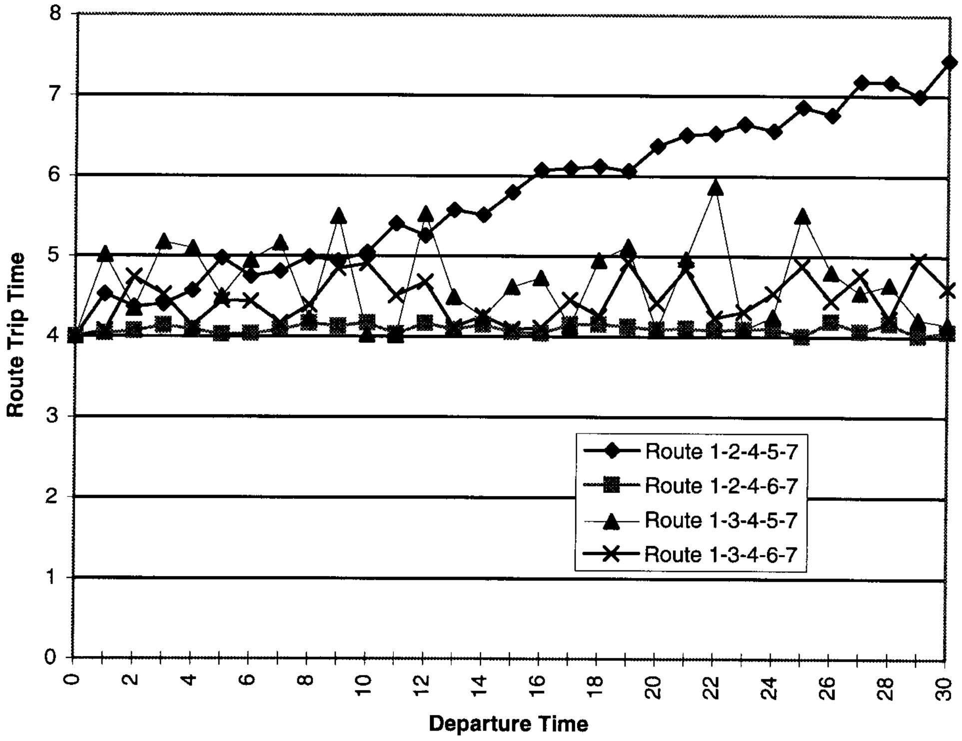

Figure 9 A sample route travel time versus derparture time graph

3.3.2.2 *Time-dependent Link Travel time*

Link travel times versus time plots provide more detailed information to understand the assignment procedure of a model. Plots as illustrated in Figure 7 will be useful for this purpose. They allow one to identify when and under what conditions will the assignment or route choice procedure switch routes. Information collected at the link level can further illustrate whether a model has a certain bias toward a certain type of link, as discussed in section 3.3.1.2.

3.3.2.3 *Time-dependent Link Volume*

Link volume versus time plots are proposed as the last criterion for discerning route choice performance of a model. These plots allow one to determine from the traffic state the route choice split at the critical junction—node 4 of the test network, and facilitate an understanding of how and whether queuing impacts are incorporated in the assignment or route choice procedure.

3.3.2.4 *Average Network Travel Time and Speed*

Average network travel time is defined as the total system travel time divided by the total number of simulated vehicles per simulation duration. Average network speed is defined as the total travel distance divided by the total system travel time per simulation duration. These two measures provide gross estimates of a network's congestion level. They can also be used as indicators to examine whether or how close a model can achieve the objective of DSO, and the impact of different traffic management strategies.

3.4 Overall Network Comparison

The objective of this last comparison is to illustrate whether the models will produce similar traffic results to support different traffic management functions. Despite differences in the models' underlying approaches and levels of traffic representation, the key question is whether and at what level of aggregation will the traffic output be comparable. Regardless of the approach taken, are the outputs of the different models similar enough to support planning types of activities, or more detailed operations types of functions?

Ideally, the results of the models should be compared against a set of actual measurements on a real network. Due to resource limitations of this project, this is not feasible. Instead, we set up the scenarios to facilitate the comparison of results across the models. This comparison is still meaningful. If all models produce similar results, then model selection becomes an easier task. One just needs to consider the cost of implementing a model, in terms of data input and computational requirements. On the contrary, if the models produce very different results, one must be careful in interpreting the results. A good understanding of the behavior of a model could help users identify the validity of the ouput from the model.

3.4.1 Test Network

In general, there is no restriction on the types of networks to be selected for this comparison. For the purpose of our study, since some models have restrictions on the network size and number of vehicles generated, we cannot select a large network. For convenience, we use the network depicted in the INTEGRATION user manual (Van Aerde, 1992), referred to as QNET.

3.4.1.1 Network Topology

Figure 10 shows the topology of QNET. The origins include nodes 1, 4, 5, 6, 7, and the destinations nodes 2 and 3. One can think of QNET as a typical network for a central business district. There are two parallel routes linking the origins with the destinations. The network used for this section is a modified version of the test network included in INTEGRATION v1.5. This test network, dubbed QNET by the manual, is based on a corridor section of the local road network in Kingston, Ontario, Canada. For our purposes, signals at the intersections have been removed and the network has been changed to only permit flow in one direction, except for the short connectors roads between the two main routes. There are 19 nodes, connected by 25 links. These links are mostly homogenous, sharing the same V-K curve (flat), jam density, per lane capacity as used before (e.g. Table 2 and Table 5, and section 3.2.1) and only differ by the number of lanes and length per link. The upper route linking nodes 1 and 2 simulates an arterial section and has only one lane along its length, as do the aforementioned connector roads. The rest of the network is made up of 2 lane links. Table 7 summaries the link features.

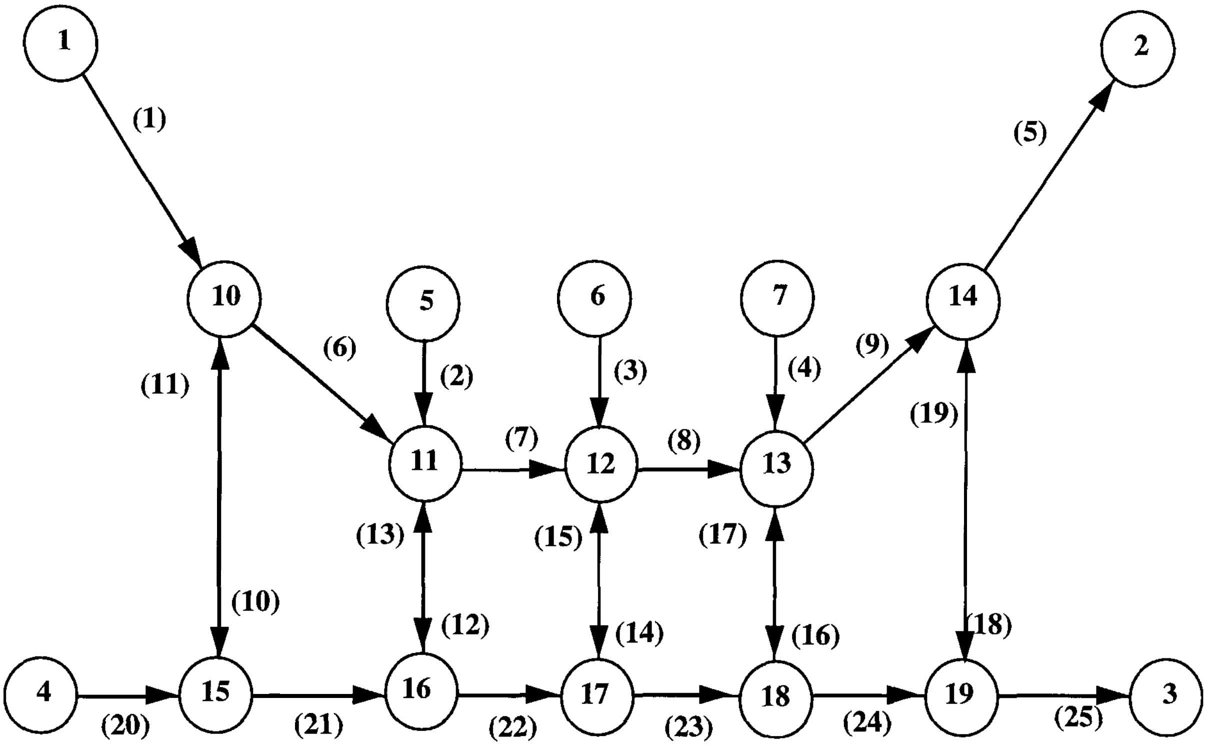

Figure 10 The network topology of QNET (not drawn to scale).

Table 7 Link Characteristics of QNET.

Link No.	Length (mi)	No. of Lanes	Free Flow speed (mph)	Speed at Capacity (mph)	Capacity (vph per lane)	Jam Density (vpm per lane)
1	0.884	2	60	60	1800	210
2	0.625	2	60	60	1800	210
3	0.625	2	60	60	1800	210
4	0.625	2	60	60	1800	210
5	0.884	2	60	60	1800	210
6	1.400	1	60	60	1800	210
7	1.250	1	60	60	1800	210
8	1.250	1	60	60	1800	210
9	1.400	1	60	60	1800	210
10	0.938	2	60	60	1800	210
13	0.938	2	60	60	1800	210
12	0.500	1	60	60	1800	210

Link No.	Length (mi)	No. of Lanes	Free Flow speed (mph)	Speed at Capacity (mph)	Capacity (vph per lane)	Jam Density (vpm per lane)
13	0.500	1	60	60	1800	210
14	0.500	1	60	60	1800	210
15	0.500	1	60	60	1800	210
16	0.500	1	60	60	1800	210
17	0.500	1	60	60	1800	210
18	0.938	2	60	60	1800	210
19	0.938	2	60	60	1800	210
20	0.625	2	60	60	1800	210
21	1.250	2	60	60	1800	210
22	1.250	2	60	60	1800	210
23	1.250	2	60	60	1800	210
24	1.250	2	60	60	1800	210
25	0.625	2	60	60	1800	210

3.4.1.2 *Test Scenarios*

Two scenarios are tested, representing two different traffic demand levels: unsaturated and saturated conditions. The purpose is to determine if a larger network size, and more O-D pairs would even out the discrepancies among the traffic models. In each of the two scenarios (Scenario 11 and 12), the network is loaded for twenty 30-second time intervals (or a total of 600 seconds) according to the OD demand rates depicted in Table 8 and Table 9. In both scenarios, traffic is allowed to clear.

Table 8 OD demand rates (vph) for Scenario 11: the unsaturated case

Destination nodes	Origin nodes				
	1	4	5	6	7
2	450	450	450	450	450
3	450	450	450	450	450

Table 9 OD demand rates (vph) for Scenario 12: the saturated case

Destination nodes	Origin nodes				
	1	4	5	6	7
2	1020	450	450	450	450
3	1020	450	450	450	450

3.4.2 Comparison Criteria

For comparison purposes, we examine the outputs according to three categories: (i) overall network travel time and speed; (ii) time-dependent route travel time; and (iii) time-dependent link travel time and occupancy. The first category is relevant to planning activities that examines overall network performance. It is the highest level of results aggregation for our comparison. The second category is important for route guidance activities in which getting accurate route travel time estimates is critical. The third category is intended to illustrate whether the results are suitable for traffic operations such as signal control, in which identifying the correct “hot” spots at the right time is crucial. This is also the lowest level of results aggregation for the purpose of this study.

3.4.2.1 Average Network Travel Time and Speed

Average network travel time is defined as the total system travel time divided by the total number of simulated vehicles per simulation duration. Average network speed is defined as the total travel distance divided by the total system travel time per simulation duration. These two measures provide gross estimates of a network’s congestion level. They can also be used as indicators to examine whether or how close a model can achieve the objective of DSO, and the impact of different traffic management strategies.

3.4.2.2 Time-dependent Route Travel Time

The definition of time-dependent route travel time is the same as the discussion in section 3.3.2.1. Most models do not provide this measure directly. Composing this measure for a big network based on piece-meal model outputs is a tedious task. Sometimes this is not even possible. To the extent that this measure can be derived, it provides a good indicator for the performance of the routes, which is particularly relevant to assessing the impact and performance of route guidance.

3.4.2.3 Time-dependent Link Travel Time and Density

Time-dependent link travel time and density are used as the last criteria for comparing model outputs. These two measures are directly related to traffic operations such as signal control. Most models produce these two measures directly. Plots of these two measures versus time can be a valuable tool for judging whether the results of the models are consistent at a link level.

4. SUMMARY REMARKS

This report is part of a series of three that covers the scope of study for MOU 148--Traffic Models Comparison and OD Sensitivities. Part I, reported herein, provides the background information regarding the development of traffic models, and defines in detail the comparison framework and test scenarios. Parts II and III, to be finished, will provide the comparison results among the four models selected for this study and the impact of perturbation to OD data, respectively.

This report first provided an overview of the philosophy of dynamic route choice model development, highlighted the different approaches, and reviewed the four models selected for this study--INTEGRATION, DYNASMART, DINOSAUR, and METS. This background information helps delimit appropriate expectations and limitations of these models.

We then developed a comparison framework that encompasses four dimensions: functionality, traffic dynamics, route choice dynamics, and overall network performance. For comparison purposes, a check-list of model functions, detailed definitions of the test networks and scenarios for each of the comparisons, the criteria or measures to be produced, and a brief discussion of the interpretation of results were provided. This comparison framework is generic enough to be used for comparing other traffic models.

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