Title

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Abstract

This working paper is the second part of a series comparing dynamic traffic flow models. It documents the results of comparison based on the framework defined in Part 1. The traffic models selected for comparison are DINOSAUR, DYNASMART, INTEGRATION, and METS. The areas of comparison comprise four categories: functionality, traffic dynamics, route choice mechanism, and network performance. The first category was compared with a check-list of functions. A total of thirteen test scenarios were constructed to compare models for the last three categories.

Keywords: Traffic Flow Model, Traffic Simulation, Dynamic Traffic Assignment, Route Choice.

Executive Summary

This working paper is the second part of a series that covers the scope of study for MOU148 — Traffic Model Comparison and Origin-Destination Sensitivities. The purpose of the study is to examine the performance of both analytical and simulation traffic flow models in modeling the dynamic behavior of traffic flows on transportation networks and to assess the state-of-the-art of model development in this area. A detailed comparison framework was defined in Part 1. This part provides the results of comparison.

As advised by Caltrans, the models selected for comparison in this study include DINOSAUR, DYNASMART, INTEGRATION, and METS. Whereas the first model is an analytical model, the last three are all mesoscopic simulation models. The report starts with discussing the status of the models selected for comparison and the comparison approach. The areas for comparison include functionality, traffic dynamics, route choice mechanism, and overall network performance. The rest of the report contains the results for comparison. For the functionality comparison, a check-list of functions were prepared for all four models. For traffic dynamics, route choice, and network performance comparison, thirteen test scenarios were constructed to compare the selected models. The scenarios cover various traffic conditions (recurrent and non-recurrent congestion), roadway geometries (merge and diverge junctions), and network characteristics (one-to-one and many-to-many networks). The focus of comparison is on the macroscopic behavior of traffic flow models, for this level of aggregation is most relevant to applications that involve dynamic route choice traffic flow models.

The results of this working paper may shed light for future model development. For model developers, the test scenarios constructed for this study can be used for model verification. For model users, the test results may help them identify the areas where cautions should be exercised in interpreting the output from models.

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1 Introduction

Traffic flow models have been widely used both in transportation planning and traffic operation analysis, ranging from the design of freeway facilities to the development of traffic signal plans or control strategies. Conventionally, many of these areas were studied with static steady state traffic flow models. These static models are known to be inadequate in describing many phenomena akin to the dynamic nature of the transportation system such as congestion behavior. Realizing their deficiencies and confronting with the need to model new traffic management strategies and devices introduced as part of ATMIS (Advanced Transportation Management and Information Systems), a number of dynamic traffic flow models such as INTRAS, TRAF, THOREAU, INTEGRATION, DYNASMART, METS, DYMOD, DINOSAUR have been developed. These models are intended to provide a platform for studying the dynamic performance of traffic networks with real-time information under both recurrent and non-recurrent traffic conditions.

Many of the existing models were developed based on either simulation approaches (e.g. INTEGRATION, TRAF, etc.) or analytical approaches (e.g. DYMOD, DINOSAUR). Simulation-based models have the capabilities to model vehicular flows either microscopically or macroscopically. Detailed behavioral characteristics and network attributes can be modeled with relative ease. The major weakness of this type of model is that there is no guarantee that its solutions would reach or approximate some desired states, e.g., user-equilibrium or system optimal, often used as assumptions for route choice. The analytical models, on the other hand, were developed to predict route travel times and traffic flows under a user-defined condition. It is hoped that if the solution is obtained under a user-equilibrium condition, the traffic flow pattern in the system should then be in a user-equilibrium state. Models developed to date are mostly formulated as mathematical programming, optimal control, or variational inequality problems. The major weakness of this approach is that the behavior of the model can easily be complicated by its mathematical details. Consequently, features essential to a transportation network are often buried in the mathematical limitations.

The purpose of the study is to examine the performance of both analytical and simulation traffic flow models in modeling the dynamic behavior of traffic flows on transportation networks and to acquire a general assessment of the current status of model development in this area. This report is the second part of a series of reports for traffic flow model comparison. The detailed comparison framework was set up and discussed in Part I (Lo, et al, 1996). This part provides the outcome of the comparison. As pointed out in Part I, the focus here is not to assess "which is a better model per se", but rather, to show how different models perform under the same scenarios. This may shed light for future model development. For model users, a good understanding of the behavior of a model would provide a better sense of the validity of the model output. For model developers, the outcome discussed in this study can also be used for model verification.

The rest of the report is organized into seven sections. The following section discusses the status of the models selected for this comparison. Section 3 describes the comparison approach and the four major areas considered in this study. Section 4 outlines the functionality features of the selected models. Sections 5, 6, and 7 discuss the outcome of the comparison in these three areas: traffic dynamics, route choice mechanism, and overall network performance. Also included in these sections are the scenario description, input data requirement, and output results. Finally, the summary findings are given in Section 8.

2 Status of the Models Selected for Comparison

Advised by Caltrans, the models selected for comparison in this study include DINOSAUR, DYNASMART, INTEGRATION, and METS. The development of METS (Cal Poly, San Luis Obispo), DYNASMART (University of California at Irvine), and DINOSAUR (PATH program) were either fully or partially supported by Caltrans. INTEGRATION was chosen for its role in a number of research projects performed in California and funded by Caltrans.

Of the four models considered for our comparison study, DYNASMART, INTEGRATIONS, and METS can be classified as mesoscopic traffic simulation models, which track vehicles individually but advance them based on macroscopic flow models. DINOSAUR was developed from an analytical approach based on variational inequality. A review of their features, development philosophy, and modeling logic can be found in PART I of the report (Lo, et al, 1996).

2.1 DINOSAUR

DINOSAUR (Dynamic Information Network Optimizer for System and User Requirements) was first developed in 1993. Further testing, revision, and enhancement were performed in 1994. It is the only analytical model selected for our comparison study. To save computational time, we ran a simplied version of DINOSAUR hard-coded for a single vehicle class, which is sufficient for the purposes of this study. DINOSAUR runs on a UNIX platform.

2.2 DYNASMART

The prototype program of DYNASMART (DYnamic Network Assignment Simulation Model for Advanced Road Telematics) was initially developed in the late eighties and officially named in 1992. It is specifically developed for studying the effectiveness of alternative information-supplying strategies, traffic control measures and route assignment rules at the network level. The version available to us is the most current one, developed between 1990 and 1992. The executable code is named DYNA, running on a UNIX environment. As will be noted in Section 5, the version of DYNASMART available to us via Caltrans contains only the simulation part; many features regarding the optimization components to derive the system optimal and user equilibrium solutions are not included.

2.3 INTEGRATION

INTEGRATION's development effort was started in 1984, initially as a research tool to analyze the operations of an integrated network with freeways, arterials, and surface streets. It became commercially available in 1992. The version of INTEGRATION available to this study is identical to the one used for the FHWA's Systems Architecture program (version V1.5x3D). It was further modified in August, 1995, after an error was identified in the course of this evaluation study. The comparison results, to be reported herein, are all based on the modified version as of August, 1995.

2.4 METS

METS (Mesoscopic Event-based Traffic Simulator) was developed under the direction of Hockaday and Sullivan at California Polytechnic State University at San Luis Obispo in **1994.** Due to substantial administrative and other delays in acquiring the results and that we did not have direct access to the executable program — results were obtained by rounds of exchanging input and output files with the developer, only partial results are reported here.

3 Comparison Approach

In this section, we discussed the aspects considered for model comparison, the design philosophy behind the test scenarios, the flow-density relationship that characterizes the roadway geometry, the time-space relationship that determines the expanded time-space network lattice, and the forms of output for comparison.

3.1 Areas for Comparison Study

In this study, we emphasize on the key areas that would determine the overall behavior or performance of a model. This comparison framework starts with a comparison of the functionality features as claimed by the model developers. It should be noted that for various reasons, not all the features claimed are actually available. Moreover, some of the claimed outputs require other external post-processors for their derivations. In addition to this functionality comparison, we set up scenarios to evaluate the models according to these three areas: traffic dynamics, route choice mechanism, and overall network performance. These are the key areas relevant to dynamic route choice traffic models (DRCTMs). We chose to do so for reasons discussed below.

At the network level, traffic dynamics and route choice are the two most fundamental components for a model to transfer vehicles from origins to destinations. The former governs vehicle movements within and between roadway segments whereas the latter determines a series of linked road segments or **a** "route" leading to a vehicle's desired destination based on some prespecified conditions (e.g. user-equilibrium, system optimal, etc.). The quality of a dynamic flow model, no matter how many features it claims to possess, depends heavily on these two fundamental modeling components.

In model applications, the overall network performance characterization is perhaps the one used most frequently. Total delay or average travel time is often cited in practice to justify the design of a system (e.g. traffic signal plans, travel information systems) or implementation of traffic control strategies. Therefore, a comparison of how network performance is characterized is also included in our study.

3.2 Scenario Development

For the three areas considered for evaluation, we have established scenarios to capture the fundamental characteristics of traffic flow modeling. For this purpose, small and simple networks are preferable to large and complicated ones. Results from small networks are less likely to be tainted by noise, which often arises in large networks due to vehicle interactions. They can be checked against common sense and predictions from existing theories. Moreover, the scenarios are designed to be sufficiently general so that the outcome could allow inferences easily be made to networks with different configurations.

In the following, we discuss the assumptions for the model input and the form in which the results are presented.

3.2.1 Input Assumption: Flow-Density Relationship

The flow-density relationship used here is of triangular shape as shown in Figure 1 which can be calibrated with three parameters: the free flow speed, v_f, the maximum flow, q_{max}, and the jam density, k_j. The mathematical expression of this triangular flow-density relationship is:

$$q = \begin{cases} v_f k & \text{if } k \leq \frac{q_{max}}{v_f} \\ \frac{q_{max} v_f}{k_j v_f - q_{max}}(k_j - k) & \text{if } \frac{q_{max}}{v_f} \leq k \leq k_j \end{cases}$$

This form of flow-density relationship implies that the speed remains the same as long as traffic is uncongested. It has been used by a number of researchers (Hall, *et al.* 1986, Newell, 1994, Daganzo, 1995) and supported by empirical evidence (Lin and Ahanotu, 1995) for certain scenarios. Using this simple flow-density relationship, the progression of

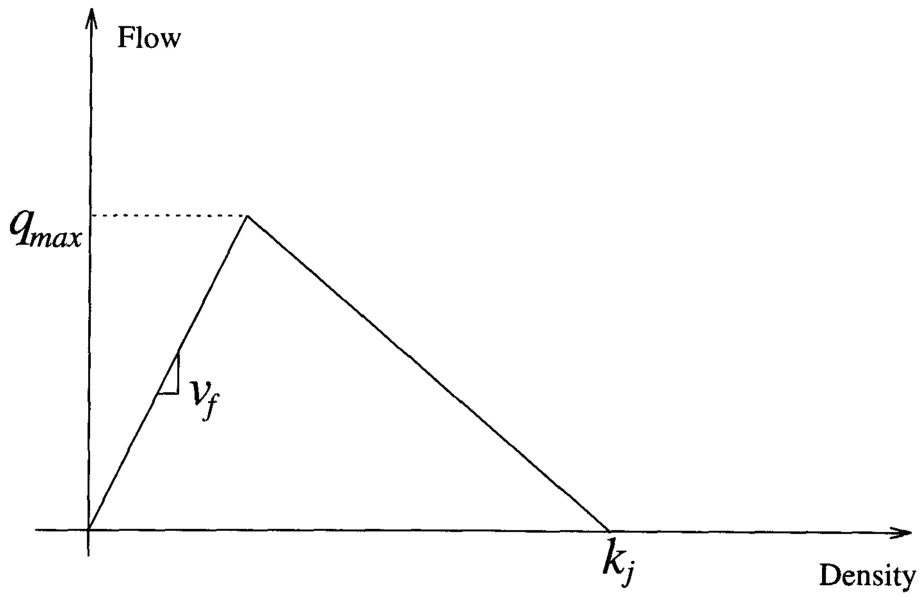


Figure 1: Assumed flow-density relationship

traffic flow can be conveniently calculated by hand. The outcome from the model can thus be easily checked with the theoretical results, which would allow us to obtain a qualitative and quantitative assessment of the model performance.

3.2.2 Input Assumption: Time-Space Relationship

All the models included in our comparison study use link-node representation for a network. By selecting the units of time and link length appropriately, we can ensure that for free flow traffic it takes a single time unit for a vehicle to traverse a link. For example, if the discrete time interval is chosen to be 6 seconds and free flow speed 60 miles per hour, then the above property can be ensured by choosing the length of a link to be 0.1 miles. This requirement would make the results generated from a model simple for inspection.

3.2.3 Presentation of Output for Model Comparison

The outcome of our study will be presented with link occupancy, showing the number of vehicles on a link, or in some cases, with link vehicle density in which the number of vehicles is normalized by the length of the link. Since link travel time and velocity have

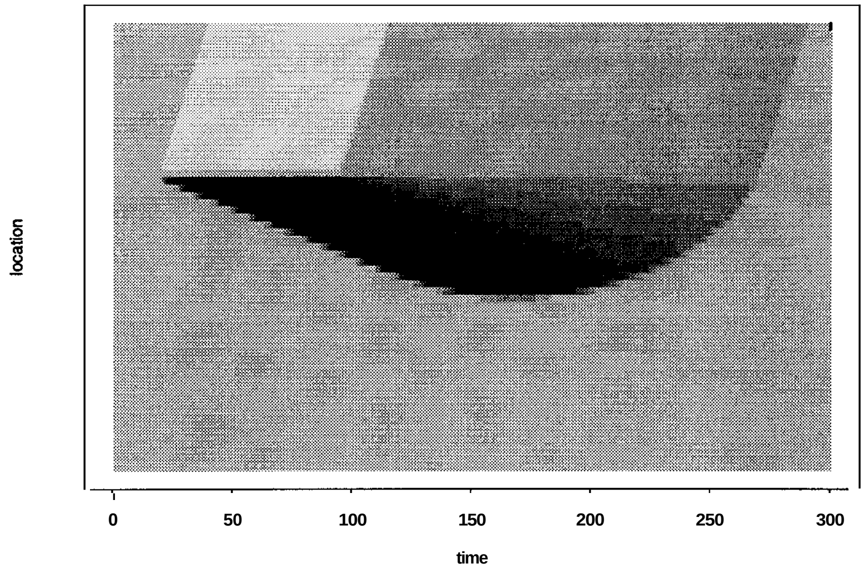


Figure **2:** Occupancy intensity plot

an one-to-one relationship, many important measures of performance such as velocity and link travel time can be derived from link occupancy. Moreover, link occupancy expressed as the number of vehicles on a link is less biased than other measures such as link travel time; the latter often requires other formula for their derivation.

For traffic dynamics comparison, we present our results in occupancy over time and space-time diagrams as shown in Figure **2.** In this example, the diagram represents a lane-blockage incident happening during the period of 25-100. The shading intensity corresponds to the traffic occupancy level. **As** customary, traffic flow propagates in the direction of vertical axis, whereas the horizontal axis is for time. The plot reveals clearly the path of queuing propagation and dissipation over time and space. One can visualize the discontinuity in traffic, i.e., the shock wave and acceleration wave corresponding to queue formation and dissipation due to incidents or bottlenecks. It should be noted that the scale of the shades is specific for each plot. Thus, it is inappropriate to make quantitative comparison across different plots based on the shading intensity.

For route choice and overall network performance comparison, we present our results in occupancy over time plot on a link-by-link basis, since the emphasis for this comparison is no longer on the propagation of queues. However, one can still examine the spatial effect of queues because the link occupancy plot is made for every link.

Due to the differences in modeling approach, it is expected that the model output should exhibit some levels of differences among the models even for the same input data. Without a set of field measurements to form a solid reference, qualitative as opposed to quantitative comparison is more meaningful. However, we do provide some quantitative results corresponding to the shading intensity plot, such as the queue length, the time congestion is fully relieved, and so on.

4 Functionality Comparison

According to the comparison structure defined in Part I of this report series, Table 1 summarizes the features of the models selected for this study. Table 1's legend is as follows: "X" denotes the availability of the feature listed in column one, "N/A" for "Not Available" and "?" for "Cannot Tell" based on the documentation provided. One should note that the checks are based on our interpretation of the model's available documentation. In cases where there are discrepancies between our understanding of the model and the features claimed in the documentation, we follow the latter to fill in Table 1. Therefore, the table may not be perfectly accurate and should not be considered as such. Nevertheless, given that the four models are still being refined, Table 1 provides some ideas about where they are heading or what they are attempting to achieve. The following four subsections describe the features of each of the selected models.

4.1 DINOSAUR

According to its developers, DINOSAUR has these distinctive features:

- macroscopic representation of network traffic flow;
- multi-class representation of traveler behavior and characteristics;
- descriptive route choice criteria: DUO (dynamic user optimal);
- guaranteed solution properties: existence, necessity and sufficiency;

MODEL FEATURES	DINOSAUR	DYNASMART V. J1	INTEGRATION V1.5x3D	METS Nov. '94
A. NETWORK REPRESENTATION				
1. Node Characteristics				
a) Designation				
i) Intersection	X	X	X	X
ii) Origin and destination	X	X	X	N/A
iii) Incident location	X	N/A	X	X
iv) CMS locations	N/A	X	X	X
b) Control attributes				
i) Signal control	X	X	X	X
ii) Turning movement allowance/restriction	X	X	X	X
c) Physical attributes				
i) Intersection capacity or saturated flow	N/A	N/A	N/A	N/A
ii) Level or kind of detectorization	N/A	N/A	N/A	N/A
2. Link Characteristics				
a) Control attributes				
i) Lane usage (e.g., HOV, Bus lane, etc.)	N/A	X	X	X
b) Physical attributes				
i) Length	X	X	X	X
ii) Saturation flow	X	X	X	X
iii) Free-flow speed	X	X	X	X
iv) Jam density	X	X	X	X
v) Number of lanes	X	X	X	X
vi) Level and kind of detectorization	N/A	X	X	N/A
B. TRAFFIC DYNAMICS REPRESENTATION				
1. Model type				
a) microscopic	N/A	N/A	N/A	N/A
b) mesoscopic	N/A	X	X	X
c) macroscopic	X	N/A	N/A	N/A
2. Detailed features captured				
a) Lane changing	N/A	N/A	N/A	X
b) Car following	N/A	N/A	N/A	N/A
c) Acceleration/Deceleration patterns	N/A	N/A	N/A	N/A
d) Separate turning movements	N/A	X	?	N/A
e) Platoon progression	N/A	N/A	X	N/A
f) Merging	N/A	N/A	N/A	N/A
g) Weaving	N/A	N/A	N/A	N/A
h) Queue dynamics (on one link)	X	X	X	X
i) Queue spillback (on multiple links)	N/A	X	X	X
C. MULTIPLE VEHICLE CLASSES REPRESENTATION				
1. Physical characteristics				
a) Auto	X	X	X	X
b) Truck	N/A	X	N/A	N/A
c) Bus	N/A	X	N/A	N/A
d) High occupancy vehicle (HOV)	N/A	X	X	N/A
2. Driver maneuvering Behavior				
a) Aggressive, average, slow, etc.	N/A	N/A	N/A	N/A
3. Travel choice modeling				
a) Mode Choice (out of scope of this study)	N/A	N/A	N/A	N/A
b) Departure time Choice (out of scope of this study)	N/A	N/A	N/A	N/A
c) Route choice				

Table 1: Features for comparing DRCTMs

MODEL FEATURES	DINOSAUR	DYNASMART V. J1	INTEGRATION V1.5x3D	METS Nov. '94
i) Traffic information availability for various vehicle classes				
a) time scale: pre-trip, instantaneous, predictive information	X	X	X	X
b) instructional types: descriptive, prescriptive	X	X	X	X
c) information accuracy	X	N/A	X	N/A
ii) Preferential toll for different vehicle classes				
a) dynamic/static tolling scheme	N/A	N/A	N/A	X
iii) Traveler's response and preferences				
a) % compliance to routing instruction	N/A	N/A	N/A	X
b) Bounded rationality	N/A	X	N/A	N/A
c) Bias for/against: freeway/arterial	X	N/A	X	X
d) User-equilibrium (UE) or user-optimal (UO) choices	X	N/A	X	N/A
e) Time elasticity	N/A	X	N/A	?
iv) System-Control				
a) System optimal assignment	N/A	N/A	N/A	N/A
v) Miscellaneous				
a) Turning percentages at intersections	N/A	N/A	N/A	X
b) All-or-nothing assignment	X	X	X	N/A
c) multiple path assignment	X	X	X	N/A
D. ATIS STRATEGIES				
1. Traffic information				
a) Time scale				
i) Instantaneous information	X	X	X	X
ii) Predictive information	X	N/A	X	N/A
b) Instructional types				
i) Descriptive	X	X	X	X
ii) Prescriptive	X	X	X	X
c) Information accuracy	X	N/A	X	N/A
2. Information updating frequency				
a) Time scale: daily, hourly, every 15 minutes, etc.	N/A	X	X	N/A
E. ATMS STRATEGIES				
1. Signal control				
a) Fixed time control	X	X	X	X
b) Phasing	N/A	X	X	N/A
c) Ramp metering	N/A	X	X	N/A
d) Actuated signal control	N/A	X	N/A	N/A
e) Optimized signal coordination	N/A	N/A	X	N/A
2. Incident Management				
a) Descriptive				
i) Incident location	X	X	X	X
ii) Start and end time of incidents	X	X	X	X
iii) % capacity reduction	X	X	X	X
b) Prescriptive				
i) Real-time re-routing	X	X	X	X
ii) Real-time adjustable signal control	N/A	X	X	N/A
3. Road pricing	N/A	N/A	N/A	X

Table 1: Features for comparing DRCTMs (continued)

- uniqueness for variational inequality models and optimal control models;
- convergent computational algorithms.

DINOSAUR takes a different approach to modeling traffic; it relies entirely on an analytical approach. Traffic flow relationships are modeled macroscopically. DINOSAUR derives the resultant traffic patterns based on these inputs: dynamic O-D matrices, network geometry and control data, and incident data from surveillance systems. The objective of DINOSAUR is to minimize each traveler's travel time or travel disutility. Since it is developed as a mathematical program, its developers claimed that achieving the DSO (dynamic system optimal) objective can be done relatively easily.

DINOSAUR is formulated as a variational inequality, and is solved by a combination of the relaxation technique, the Frank-Wolfe technique, and the Method of Successive Averages. If the convergence criteria are met, the model generates link flows, link travel times, route flows and route travel times.

DINOSAUR uses a directed graph with nodes and directed links to represent a transportation network with multiple origins and destinations. A node can represent either an origin or a destination, or simply an intersection. The model considers a fixed time period $[0, T]$, where T is a time sufficient for all persons to complete their trips.

DINOSAUR uses a set of constraints to model traffic flow. These constraints capture the physical characteristics of traffic flow by requiring conditions on flow conservation for links and nodes, flow propagation, first-in-first-out (FIFO) and oversaturation. These constraints are written for each O-D pair, each route and each traveler class, respectively.

DINOSAUR uses a modified Greenshields formula to determine link travel times for freeway links. This travel time function has a monotonic relationship with traffic density. DINOSAUR also has a link travel time function for signalized arterial links, consisting of three components: **1)** cruise time over the uncongested portion of a link; **2)** uniform delay due to signal control; and **3)** overflow delay. The cruise time is determined by using the appropriate cruise speed on the roadway type. The uniform delay is calculated by using the first term of Webster's formula. And the overflow delay is calculated by using a revised Akcelik's formula when time step is relatively long. The developers also developed a formula to estimate queuing delay by estimating the physical queue length through a moving queue concept. Furthermore, the link travel time function for arterial is specified by turning movement to account for higher delays associated with left-turns.

DINOSAUR can model multiple user classes in the transportation network, such as vehicles with route guidance devices and those without. At present, DINOSAUR can model three classes of vehicles: those who follow a set of fixed routes, those with imperfect information, and those with perfect information. The first class follows a set of pre-determined routes, mostly based on static historical information. The second class of vehicles is emulated by a stochastic loading approach, in which perceived travel times are simulated by adding travel time perturbations derived from specific distributions to the actual travel times. These perceived travel times are then used to determine the route selection of travelers. The third class is often referred to as the guided vehicles, which follows the DUO routes. The developers claimed that DINOSAUR is capable of including other classes of vehicles that follow other route choice objectives by altering the objective functions.

DINOSAUR currently has limited capability of modeling signal control. Only pretimed control is incorporated in the current version. DINOSAUR has built-in capability to model incidents. DINOSAUR creates a dummy node at the location where an incident occurs, so that traffic performance before and after the dummy node can be modeled separately. The start time of an incident can be modeled as random in DINOSAUR. However, the incident's duration and severity are treated as deterministic once the incident is pronounced. For simplicity, a uniform capacity reduction is assumed for the incident period. The developers claimed that a more gradual recovery curve could be added so that the capacity representation under incidents would be more accurate. Multiple incidents at different locations and different time instants are modeled by a multi-period assignment procedure. Rerouting assignment is performed whenever an incident occurs.

4.2 DYNASMART

The DYNASMART we received through Caltrans, DYNASMART v. J1, is is a module out of a bigger framework for modeling ATMIS. It is basically a simulation model. Many features claimed by the model developers, such as the optimization module to derive the user-equilibrium or system-optimal solutions, are not available to us as of the time of this study. So the comparison results reported here pertain only to the simulation part.

DYNASMART uses a node to designate a junction of links. When a node is designated as an origin (destination), there is a dummy link upstream (downstream) of the node to introduce (remove) vehicles into (from) the network. DYNASMART can simulate different types of controls at a node to allocate appropriate right-of-ways to vehicles. DYNASMART is also capable of modeling left-turn movements at unsignalized intersections or without protected turning signals. The process first calculates the maximum flow rate for left-turn and then adjusts the saturation flow rates for straight and right-turn approaches according to the 1985 Highway Capacity Manual. DYNASMART then follows the determined outflow-inflow constraints to transfer vehicles from one link to another. The left-turn capacity values were adopted from Lin et al. (1984) and Lee et al. (1983) using the TEXAS model.

A link represents a homogeneous roadway segment, as characterized by its physical attributes shown in Table 1. In addition, a link can be designated for different usage, such as HOV, bus, or general traffic. However, allocating multiple designations to the same link is not possible. Lastly, DYNASMART models CMS, detectorization, as well as incidents at the link level.

DYNASMART uses established macroscopic traffic flow models and relationships to model vehicle flows through a network. However, whereas macroscopic simulation models do not keep track of individual vehicles, DYNASMART moves vehicles individually or in packets, thereby keeping a record of the locations and itineraries of individual particles. By doing so it is able to capture the dynamics of queue on one link and the spillback of queue on multiple links. Although it keeps track of movements of individual vehicles, DYNASMART does not model microscopic features such as lane changing, car following, acceleration/deceleration patterns, merging, and weaving. Therefore, DYNASMART is classified as a "mesoscopic" model.

DYNASMART models traffic dynamics using a two-step process: link movement and node transfer. The density of each link at the beginning of a time step is used to calculate the prevailing speed for that particular link. The speed-density relationship currently used is a modified version (Chang et al., 1985) of the well known Greenshields' equation. DYNASMART also uses a specified minimum speed at jam density to guarantee a non-zero speed for all links at all times. The relationship used is:

$$v = v_0 + (v_f - v_0)(1 - k/k_j)^{\alpha},$$

where

$v_0 =$ a user-specified minimum (jam) speed,

$v_f =$ free-flow speed of the highway segment,

$k_j =$ density at the jam speed, and

$\alpha =$ a user-specified parameter.

All vehicles on a link are moved at the same prevailing link speed. The exact movement of a vehicle, however, is determined by its current location, the prevailing link speed, and the "flow" space on the link (defined as the link's length minus the queue length, if any). If a vehicle's expected movement under the prevailing link speed is greater than the link's "flow" space, then the vehicle will join the end of the queue. If there is no queue, the vehicle will move to the end of the link and wait for the node transfer module to determine its time to exit the link.

The node transfer module performs the link-to-link vehicle transfers. For nodes with control, this node transfer module allocates the appropriate right-of-ways according to the intersection control strategy, based on the approach volumes at each simulation time step as well as the volume entering and exiting the network. Queues are modeled to form on the upstream links of the intersection when the total inflows are greater than the total outflow capacities.

DYNASMART allows for different classes of vehicles with different information availability, behavioral responses, performance characteristics, and link access restrictions. Different vehicle sizes are modeled as packets of equivalent passenger car units. This packet size is then used in determining density, available capacity, inflow and outflow constraints. For example, buses are treated as having two passenger car units and following pre-defined paths. Currently, seven different classes are modeled in DYNASMART, including:

1. Passenger cars without ATIS,

2. Trucks without ATIS,

3. High occupancy passenger cars without ATIS,
4. Passenger cars with ATIS,
5. Trucks with ATIS,
6. High occupancy passenger cars with ATIS,
7. Buses.

DYNASMART also has the option of using the "Bounded Rationality" rule in its route choice component. This rule uses a set of user-defined thresholds to activate route switching by comparing the travel times of the current route versus the alternative ones. Route switching occurs when the travel time saving is larger than the thresholds. Currently, the threshold improvement is set to be identical across all trip makers. This option permits the modeling of perception factors, preferential indifference, or persistence and aversion to route switching.

As mentioned earlier, the current version of DYNASMART is only a traffic simulator. Routes are based on shortest paths by using traffic information. The version of DYNASMART available to us can calculate the k-shortest paths for each origin-destination pair, with vehicles assigned to them based on the route-switching rules mentioned earlier. In order to improve the model's computational performance, the k-shortest paths are not re-calculated at every simulation time step, but only at some pre-specified interval (20 from our observation). In the interim, the travel times of the k-shortest paths are updated using the prevailing link travel times at each time step.

DYNASMART can model pretimed signal control, pretimed coordinated control, multidial pretimed control, and actuated signal control. Since DYNASMART uses a fixed time increment for its simulation, all the signal operations can be readily modeled based on the simulation time clock. The required inputs include the number of phases, offset, green, red and amber times of every phase. Because DYNASMART is not intended for optimizing signal control, offsetsand detailed timing plans must be provided to the model.

For actuated signal control, DYNASMART uses a macroscopic method to determine the equivalent green time, which is updated to reflect prevailing approach volumes. Green splits are apportioned according to Webster's formula. The essential features of actuated signal control, namely "Max Out" and "Gap Out", are introduced through constraints on the calculated green times. If the required green time is larger (smaller) than the maximum (minimum) green time, the maximum (minimum) green time is assigned.

DYNASMART includes freeway management techniques, such as ramp metering and CMS. Pretimed ramp metering is modeled like an arterial signal according to the prespecified entry rate. The traffic-responsive ramp metering is modeled according to the current flow conditions. Also, a local feedback control rule, ALINEA (Hadj-Salem, Blossville, and Papageorgiou, 1991), is implemented in DYNASMART. Apparently, CMS are modeled to provide speed and route advice, and route congestion warning. How this CMS information used to alter route selection or traffic flow in the model is not clear, however.

Incidents are modeled by reducing the capacity (in terms of effective lane-miles) on the affected link by a specified fraction. Any number of incidents can be simulated by specifying their start and end times and capacity reduction factors. The reduction in effective lane-miles of the affected link instantly increases its density. If the resultant density is higher than the link's jam density, vehicles on the link are modeled to move at jam speed until the density falls below the maximum.

4.3 INTEGRATION

INTEGRATION uses the traditional link-node method of modeling networks. Vehicles are introduced to the network at origin nodes and removed from the network at destination nodes. Nodes may also be used as intermediate points connecting links. INTEGRATION allows the same node to serve different roles for different groups of vehicles. For example, a node may serve as an origin for vehicles of set 1 and a destination for vehicles of set 2 while vehicles of set 3 use it as a transition node. Nodes may also feature changeable message signs (CMS) and signalized traffic control. While the capacity of an intersection is not explicitly set by the user, this is a function of signal timing and the available capacity of the downstream links. INTEGRATION features an signal optimization subroutine that takes these into account.

INTEGRATION considers links as one-way connections between nodes, and can restrict their use to certain vehicles (i.e. HOV) and by time of day. Links are described by their length, number of lanes, saturation flow, free-flow speed, and jam density. In addition, the user can specify whether the link has a detector to simulate different information collection strategies. Incidents are modeled at the upstream end of the link, and thus reduce the flow of vehicles onto the link.

INTEGRATION is a mesoscopic traffic simulation model– tracking individual vehicles, while using aggregate measures to determine their individual characteristics such as speed and headways. Headways between vehicles may be varied by a user-defined random factor as well as how platoons are set to disperse over time. Version 1.5X3D (the one being tested in the study) does not model merging and weaving behavior. Queues caused by an incident or bottleneck are modeled at the link level and, if severe enough, the queues spill back to affect multiple upstream links. However, it is unclear as to whether INTEGRATION captures the dynamics of separate turning movements (i.e. different delays for different movements).

The traffic streams modeled by INTEGRATION consist solely of vehicles that self-assign themselves to routes with the lowest total travel time. The time-cost elasticity of these vehicles is fixed as perfectly elastic; vehicles will always switch their routes if they perceive that the new route will reduce their total travel time. Up to seven vehicle classes may be defined based on their source, accuracy and update frequency of information, as well as routing strategy. Sources of information include free-flow link travel times, historical link travel times, current link travel times and travel times calculated from flows (i.e. INTEGRATION's ASSIGN module based on a static Frank-Wolfe algorithm). Vehicles will always act on whatever information is available to them, although that information may be incorrect or outdated.

While a bias for or against certain roadway facilities (e.g. freeways, arterial streets) is not an explicit feature of INTEGRATION, this could be modeled with creative use of link restrictions for certain vehicle classes.

Depending on the specified routing strategy, vehicles can either follow a single path assignment or a multipath assignment. Finding the single shortest path is INTEGRATION's standard routing strategy, and it is claimed that this strategy, coupled with continuous updating of information (every 1 sec), produces results close to that of an user-optimal solution.

INTEGRATION models the real-time availability of travel time information across detectorized links, as well as its inaccuracy. Vehicles, however, may access this information at different intervals (e.g. at the start of the trip, every **15** minutes, etc.) or not at all. INTEGRATION captures the first part with its information update frequency parameter and the second part with the source of information, such as real-time link travel times, free-flow link travel times, historical travel times or externally specified information. This information is purely descriptive in nature. Except those vehicles whose routes are pre-specified by the user, vehicles in INTEGRATION are self-route-assigning, and the system has no control over them. Based on the information that it receives, the vehicle chooses its own route. If it receives knowledge of an incident, the vehicle prescribes its own solution. Link travel times from a previous INTEGRATION run can be used in a subsequent run to "predict" future link travel times. With an iterative process, the solution determined could converge to the user-optimal solution. However, this is not guaranteed.

Although INTEGRATION does not model road-pricing, it can model. several other, more conventional ATMS strategies, including a wide range of signal control strategies. These include fixed time control and phasing. It can also simulate ramp metering by locating a traffic signal at the end of an on-ramp. Using its "Adaptive ATMS Signal Optimization" subroutine, INTEGRATION can optimize and coordinate the signals of selected corridors.

Incidents are modeled by INTEGRATION as a percent reduction in the capacity of a specified link. As such, the effective location of the incident is at the upstream end of the link. The percent reduction in capacity is directly related to the severity of the incident. INTEGRATION also models the start and stop time of the incident (with the duration of the incident being the time in between). In response to congestion (both recurrent and non-recurrent), vehicles can reroute themselves in real-time. It is unclear from the documentation whether INTEGRATION can further relieve the situation by adjusting the signal timing of affected areas in real-time to accommodate the increase in traffic.

4.4 METS

METS models a roadway network as a group of connected links. Each link is defined by specifying the coordinates of its two endpoints rather than the nodes it is connected to. Therefore two adjacent links do not have to be jointed by a node. **A** node or intersection exists only when there is some type of control at the junction of links (e.g. CMS, traffic signal, stop sign, ramp metering, etc.). Consequently, a section of rural highway without cross traffic can be represented by a series of links with no nodes in between. METS defines links as unidirectional and their use can be restricted to certain vehicles (i.e. HOV) and by time of day. Links are described by their length, number of lanes, saturation flow, free-flow speed, and jam density.

Because of its unique network representation, METS defines origin and destination zones on links instead of nodes. Each OD zone can be optionally broken up into neighborhoods. **A** neighborhood can have no more than five links. Traffic to and from each origin or destination is uniformly distributed among the neighborhoods comprising the origin or destination.

Following the earlier definition, METS is a mesoscopic model — vehicles are tracked individually while aggregate measures are used to determine their characteristics such as speed, flow, and density. METS determines the free flow speed of a roadway section from the section's maximum flow and jam density. The relation of free flow speed to jam density (k_j) and maximum flow (q_m) is given by the following equation:

$$\text{Free Flow Speed} = \frac{4q_m(1-a)(1-b)}{k_j(1-ab)^2}$$

The a and b are constants defined in METS. The current values being used are **0.30** for a and 0.05 for b. Using these values the formula becomes:

$$\text{Free Flow Speed} = \frac{2.74q_m}{k_j}$$

Each vehicle is placed onto the appropriate outlink queue immediately after it enters a new link. No vehicle may depart a link until the vehicles preceding it on its outlink queue have already departed. The time at which a vehicle may depart from a link is determined by the vehicle's earliest link departure time (ELDT). This ELDT is not calculated until the vehicle reaches the front of the outlink queue. The ELDT is the maximum of the followings:

1. The vehicle's arrival time at its current link plus the minimum traversal time of the current link at its current density.

2. The next time the downstream link can accept a vehicle.

3. The last time a vehicle exited the current link plus the link's current headway at its exit.

Vehicles on the same link but heading for different downstream links are modeled to form separate queues. Dependent on the traffic conditions of the downstream links, vehicles in one queue might proceed more rapidly than others on the same link but different queues. This reflects the fact that vehicles intended for different destinations may pass one another in a real traffic situation. In other words, FIFO (first-in-first-out) conditions are not strictly enforced in METS under uncongested traffic state. However, if a link becomes sufficiently congested, METS switches that link to "clogged mode." In this mode, vehicles in different queues may not pass one another reflecting the fact that passing becomes nearly impossible under heavy congestion. In clogged mode, FIFO is strictly enforced and the link effectively becomes one large queue. Queues caused by an incident or bottleneck are modeled at the link level and, if severe enough, the queues spill back to affect multiple upstream links. It is, however, unclear from the documentation as to what other microscopic features might be modeled.

One of the distinctive features of METS is that it uses turning percentages to direct vehicle movements at intersections. Route choice is not explicitly captured in the simulation. METS records an individual destination for each vehicle as well as turn-ratio probabilities for each divergence (intersection). 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. Each route is a random selection of a set of possible routes resulting from a series of turning decisions. Therefore there is no guarantee that any optimal conditions with respect to some objective function, e.g. user-equilibrium or system optimal, can be reached.

METS has no predefined driver classes (behavior type); these must be defined by the user by specifying the following parameters: 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.

Intersection capacity is not explicitly specified, but capacity of downstream sections is considered before allowing a vehicle to enter a link or go through the intersection. As of the time of this study, the only control method available is the CYCLIC control method, which models a simple pretimed traffic signal. More control methods are planned for the future, including actuated signals, adaptive controlled signals and stop signs.

METS simulates incidents by reducing the capacity of the links affected by the incidents. The starting and end of an incident are controlled by updating the parameters of the links affected at the start and end time of the incident. Only the vehicles of dynamic behavior type will react to the incident. All vehicles of static behavior type will proceed as if there is no incident.

To model road pricing, METS designates a toll for each section of the network. This toll is expressed in cents/mile and is imposed on vehicles traversing the section. Each section defaults to a toll of 0 cents/mile. However, this toll can be updated during the course of simulation. Road price and travel time are combined, weighted by different factors, as the cost function which is used to calculate the shortest path for the dynamic behavior types.

5 Traffic Dynamics Comparison

Traffic dynamics can be represented in two levels — macroscopic and microscopic. At the microscopic level, each vehicle is treated as a single entity. The gross vehicular flow is thus determined by the movement of every single vehicle. The most important models that provide the microscopic description of traffic dynamics are car-following models (Pipes, **1953,** Chandler *et al* **1958).** At the macroscopic level, traffic is considered as a "fluid" with density and flow. Flow propagation is governed by the functional relationship between density and flow, instead of the relationship of vehicle-following. The most important models in this area are the hydrodynamic flow models (Lighthill and Whitham, **1955,** Richards, **1956).** The focus of our comparison study is on the macroscopic behavior of the traffic flow models, because this level of aggregation is most relevant to many applications in transportation.

There are three network settings adopted in our evaluation study: **(A)** a network with a single origin and a single destination (referred as the linear network hereinafter), (B) a network with a single origin and two destinations (referred as the diverge network hereinafter), and (C) a network with two origins and a single destination (referred as the merge network hereinafter).

In the following, we present the scenarios considered for comparison, including the network topology, the input data, and output results. For each of the networks described above, we examine traffic dynamics produced by the models for both non-recurrent (scenarios **1-3)** and recurrent (scenarios **4-6)** traffic conditions. **A** brief discussion of our observations is given in the section.

5.1 Scenarios 1: The Linear Network with Non Recurrent Congestion

5.1.1 Scenario Description

A linear network with an incident Traffic demands remain the same but the capacity of the incident link experiences a significant reduction for some period of time due to an incident. **As** the incident is removed, queue starts to dissipate. The relationship between the demand and the capacity is such that the queue generated by the incident will be fully cleared at a finite time after the incident is removed. The network topology and the incident location is given in Figure 3

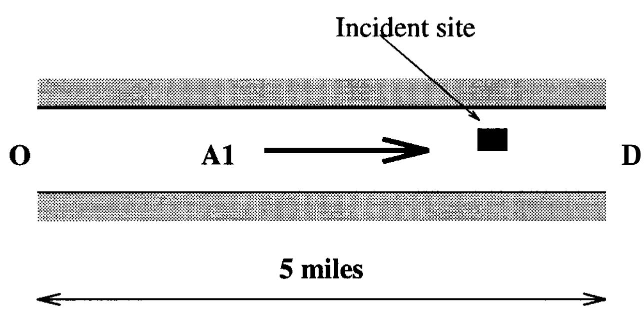


Figure **3:** The linear network with an incident

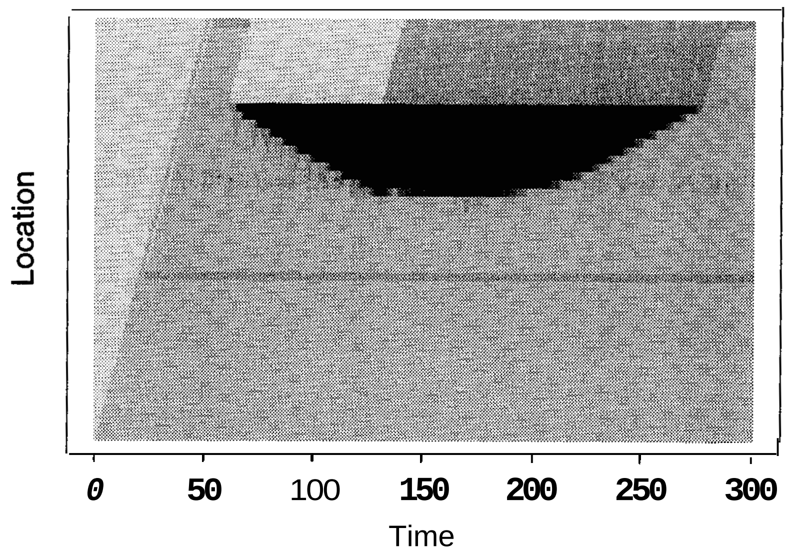
5.1.2 Input Data

The input data for this scenario is as follows:

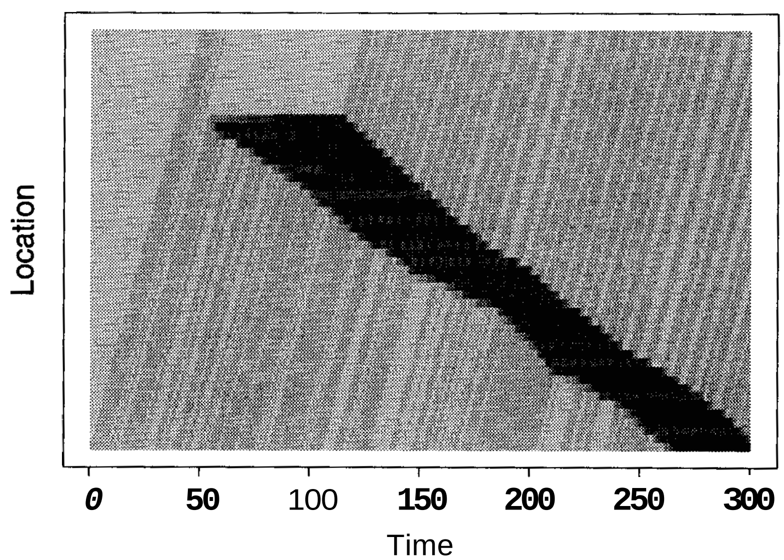
- Roadway geometry
  - jam density: 210 vehicles per mile
  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane
- Run time parameters
  - time step: 6 sec.
  - total time: **30** min.
- Traffic demand
  - O-D: 1200 vph for 30 min.
- Incident characteristics
  - start time: 5.5 min.
  - location: 1 mile from D
  - capacity reduction: 100% blockage
  - duration: 6 min.

5.1.3 Output Results

Versions of DINOSAUR or DYNASMART available to us are not able to model the incident case. Only the occupancy over time and space plots for INTEGRATION and METS are produced in Figure **4** (a) and (b).



a. INTEGRATION result for Scenario 1



b. METS result for Scenario 1

Figure **4:** Link occupancy **vs.** time and space for Scenario 1 (linear network; non-recurrent congestion)

5.1.4 Observations

The observations below are based mainly on the plots shown in Figure **4** as well as the output data for making the plots (not shown in this report for brevity).

- Both models exhibit physical queues located upstream of the incident site. The queuing densities under these two models are different (METS at 120 vpm and INTEGRATION at 160 vpm). Both of them are much lower than the jam density (210 vpm, specified as the model input) which is expected under an incident with 100% capacity reduction.

- There is a substantial difference in the queue dissipation pattern for these two models both quantitatively and qualitatively. In INTEGRATION, the queue formed by the incident is fully dissipated before the end of the simulation run; whereas in METS, the queue continues to propagate towards the upstream direction and shows no sign of stopping even at the end of the simulation run. The discontinuity in traffic at the incident site (i.e., the horizontal line that separates the two regions of traffic) disappears in METS after the incident is removed but persists in INTEGRATION until the queue is fully dissipated.

- In the queue dissipation process, METS discharges 2 or **3** vehicles at each time unit. The average discharging rate is around 1200 vph, instead of 1800 vph as specified in the input.

- Both models reveal some random effects unknown to the users despite all random effects that could be specified in the input were disabled. They are represented by the alternate light and dark stripes as one can easily identify in Figure **4.**

- A small fraction of vehicle is observed to traverse the incident site in INTEGRATION every few time units even though the blockage is 100%. This cannot be observed from the Figure **4** but can be identified in the output data file.

5.2 Scenarios 2: The Diverge Network with Non-recurrent Congestion

5.2.1 Scenario Description

A diverge network with an incident The network topology and the incident location is given in Figure **5**. Two traffic streams, going to D1 and D2, are generated for the entire period of simulation. **A** significant reduction in capacity takes place for some period of time in a link at diverge branch B2, resulting in a queue propagating back and passing the junction. We evaluate the capabilities of the models in capturing **1)** how queues are formed at the junction area; 2) how vehicles going to the unblocked branch are affected by the queue backing up from the incident site to the junction.

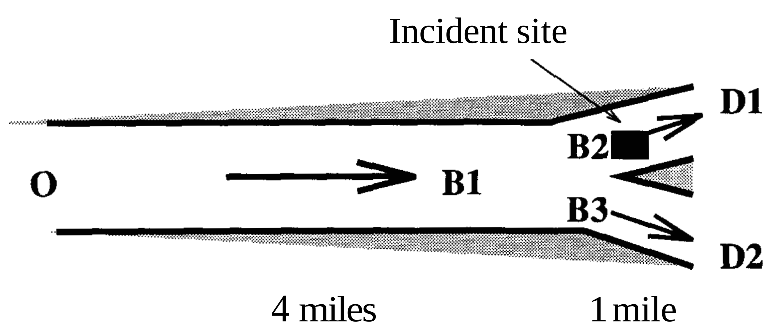


Figure 5: The diverge network with an incident

5.2.2 Input Data

The input data for this scenario is as follows:

- Roadway geometry
  - jam density: 210 vehicles per mile

  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane
  - number of lanes: main branch (B1) = **2;** diverge branch (B2) = **1;** diverge branch (B3) = 1

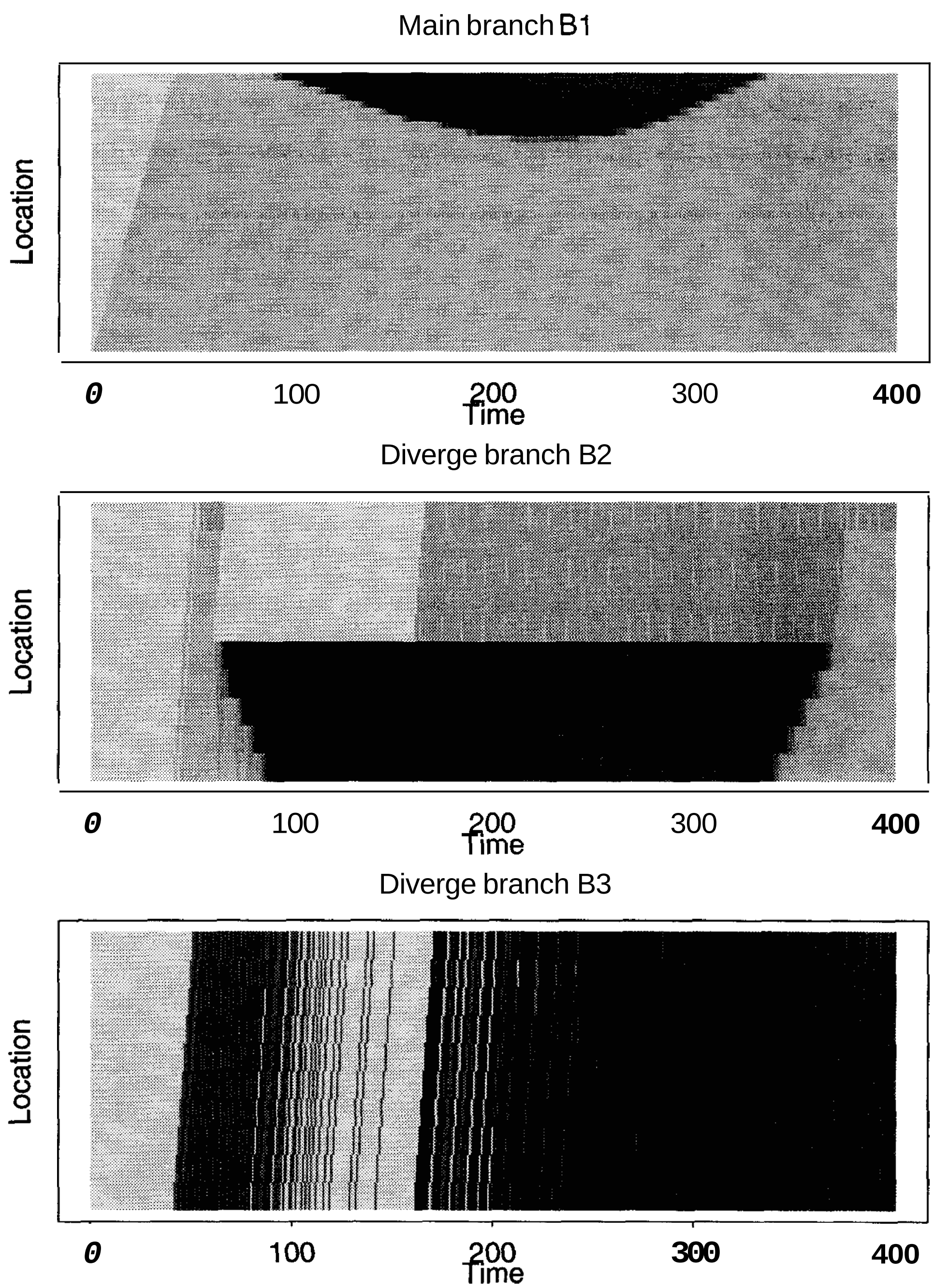
- Run time parameters
  - time step: 6 sec.
  - total time: **30** min or until the time queue is cleared.

- Traffic demand
  - 0-Dl: 1200 vph for 30 min.
  - O-D2: 900 vph for 30 min.

- Incident characteristics
  - start time: ***5.5*** min.
  - location: 0.5 mile from Dl
  - capacity reduction: 100% blockage
  - duration: 9 min.

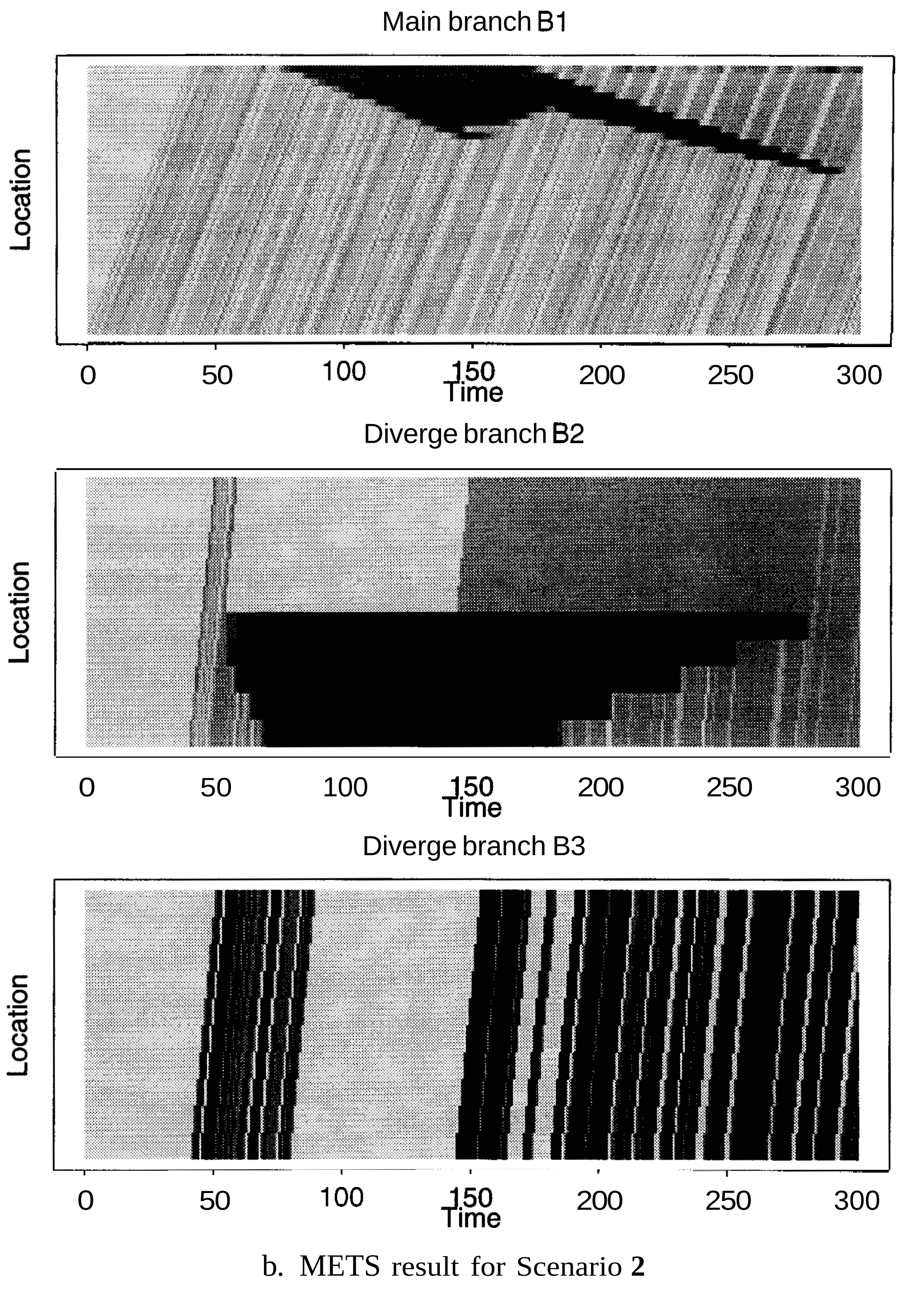
5.2.3 Output Results

Versions of DINOSAUR or DYNASMART available to us are not ready for running the incident case. Only the occupancy over time and space plots for INTEGRATION and METS are produced in Figure 6 *(a)* and (b). The occupancies for the main branch (B1) and the two diverge branches (B2 and B3) are plotted on three separate parts in each plot. The upper portion of the plot for the main branch and the bottom portion of the plots for the two diverge branches correspond to the diverge junction.



(a) INTEGRATION result for Scenario **2**

Figure 6: Link occupancy vs. time and space for Scenario 2 (diverge network; non-recurrent congestion)



b. METS result for Scenario **2**

Figure 6: Link occupancy vs. time and space for Scenario **2** (diverge network; non-recurrent congestion) (continued)

5.2.4 Observations

The observations below are based mainly on the plots shown in Figure 6, as well as the output data for making the plots (not shown in this report for brevity).

- METS has a faster queue propagation rate. Its queue reaches the junction at time step 70, whereas the queue in INTEGRATION reaches the junction almost at time step 100. This observation is consistent with the fact that the jam density in METS is lower than that in INTEGRATION (Both of them are lower than the input jam density).

- The queue dissipation process is captured differently under these two models. Upon the removal of the incident (at time step 145), the upstream end of the queue in INTEGRATION continues to grow, whereas the queue in METS stops to grow at the moment as shown in the top plots in (a) and (b) of Figure 6.

- Both models show that when the queue propagates back from diverge branch B1 to the junction area the flow into the unblocked diverge branch (B2) is reduced simultaneously.

- Both models exhibit vehicle holdings. For some time periods of time, no flow is observed to enter an uncongested link from its upstream link, even though the demand is non-zero (see the light stripe between time 150 and 200 at the bottom plots of (a) and (b) in Figure 6). METS holds vehicles for as long as 6 time steps. INTEGRATION holds vehicles for one or two time steps.

- Whereas the recovery wave is very pronounced in INTEGRATION, it is not visible in METS (see plots for diverge branch B2). In METS, queues start to dissipate at the upstream end.

- Residual queues remain at the junction area till the end of the simulation run for METS (not quite visible from the plot but clearly shown in the output data).

5.3 Scenarios 3: The Merge Network with Non-recurrent Congestion

5.3.1 Scenario Description

The merge network with an incident The network topology and the incident location are given in Figure **7.** The network can be viewed as a representation for on-ramp areas or interchanges in a large scale network. Two traffic streams, going from **O1** and 0 2 to D, are generated for the entire period of simulation. **A** significant reduction in capacity takes place for some period of time in a link at the main branch **C3,** resulting in a queue propagating back and passing the merge junction. We evaluate how different models behave in capturing 1) the formation of queues at the junction area; 2) the merge priority before and after queues are formed at the junction.

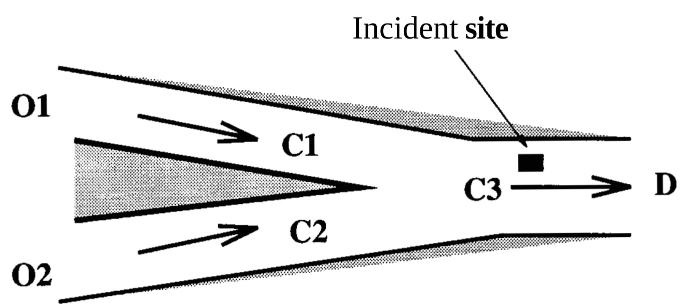


Figure **7:** The merge network with an incident

5.3.2 Input Data

The input data for this scenario is as follows:

- Roadway geometry
  - jam density: 210 vehicles per mile
  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane

   - number of lanes: main branch **C1 = 2;** merge branch **C2 = 1;** merge branch **c 3 = 1**

- Run time parameters
   - time step: 6 sec.
   - total time: **30** min. or until the queue is cleared

- Traffic demand
   - 01-D: 1200 vph for **30** min.
   - 02-D: 900 vph for **30** min.

- Incident characteristics
   - start time: 5.5 min.
   - location: 0.5 mile from D
   - capacity reduction: 100% blockage
   - duration: 9 min.

5.3.3 Output Results

Versions of DINOSAUR or DYNASMART available to us are not ready for running the incident case. Only the occupancy over time and space plots for INTEGRATION and METS are produced in Figure 8 (a) and (b). For each plot, flow propagates in the upward direction. The upper portion of the first and second plots and the bottom portion of the third plot correspond to the area of the merge junction.

5.3.4 Observations

The observations below are based mainly on the plots shown in Figure 8 as well as the output data for making the plots (not shown in this report for brevity) . Some common queue-related behavior emerges again in this scenario for both models.

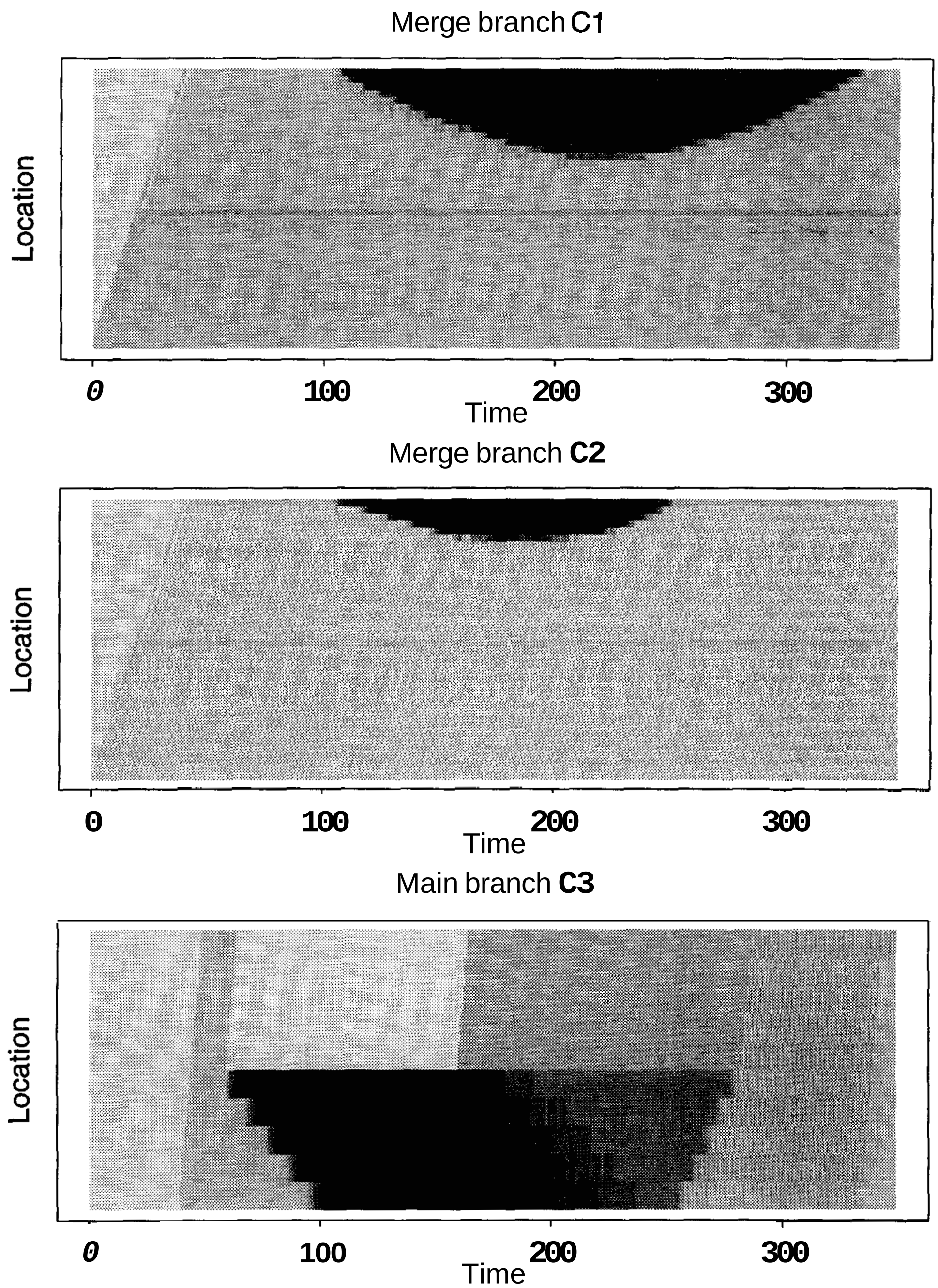
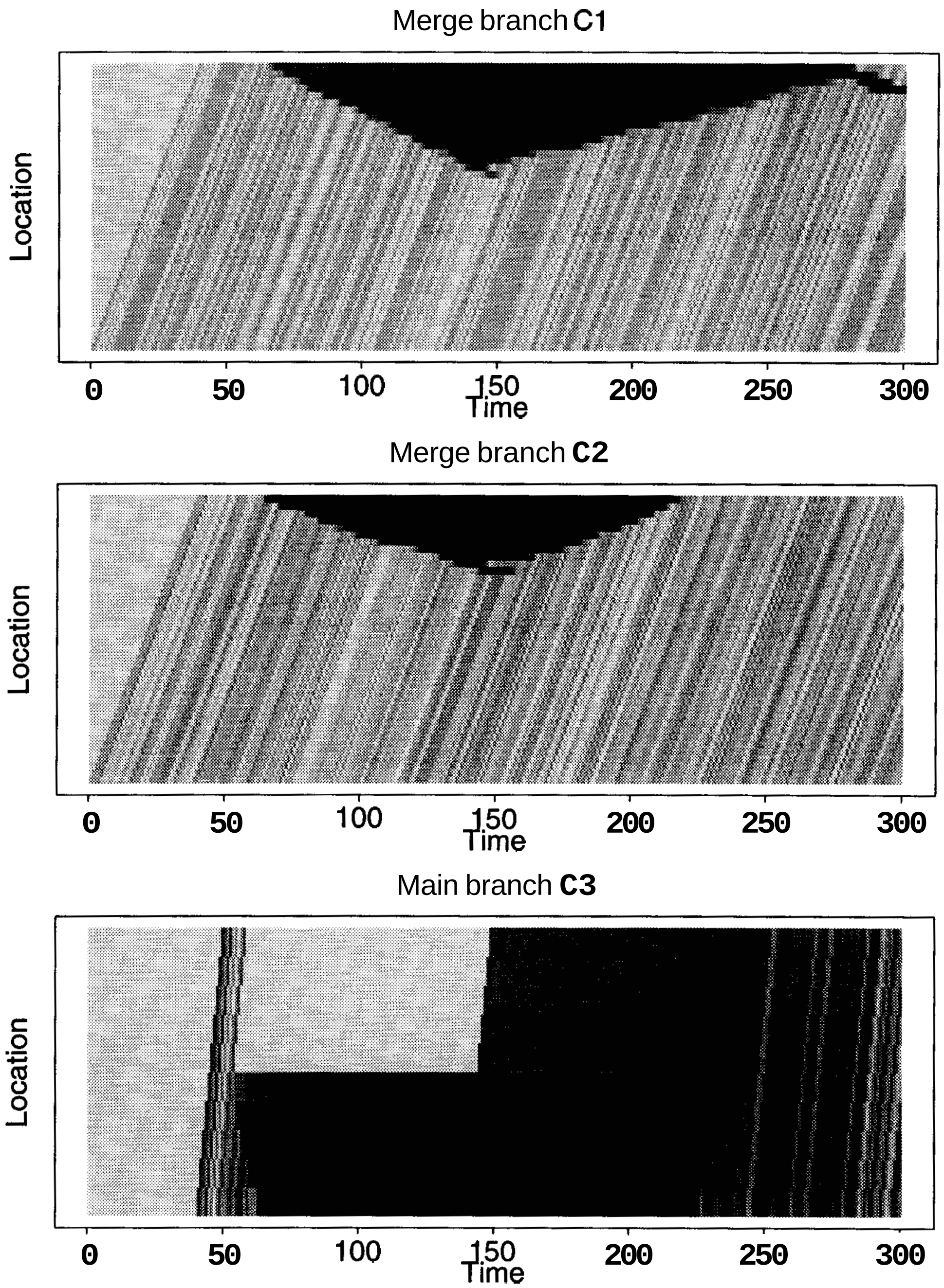


Figure 8: Link occupancy **vs.** time and space for Scenario **3** (the merge network; non-recurrent congestion)

a. INTEGRATION result **for** Scenario **3**



b. METS result for Scenario **3**

Figure 8: Link occupancy **vs.** time and space for Scenario **3** (the merge network; non-recurrent congestion)

- *o* Observations regarding the queue dissipation process in scenario **2** also apply to this scenario. For the queuing dissipation process, both models show similar patterns as those revealed in Scenario **2.** The upstream end of the queue for METS stops growing right at the time the incident is cleared, whereas the queue in INTEGRATION continues to grow for some period of time until the effect of the queuing discharge reaches the tail of the queue. For METS, the queue dissipation processes in the merge and diverge scenarios differ substantially from that in the linear network scenario.
- *o* The demand in INTEGRATION shows little stochastic effects and its volume agrees with the input data. The demand in METS exhibits high fluctuation and the average rate is lower than that specified in the input.
- *o* The queue in METS is cleared earlier than that in INTEGRATION.

5.4 Scenarios 4: The Linear Network with Recurrent Congestion

5.4.1 Scenario Description

A linear network with a bottleneck The network topology and the bottleneck location are given in Figure 9. Three levels of traffic demands are generated for the entire simulation run, representing the peak and off-peak hour traffic. Congestion occurs when traffic demands exceed the bottleneck capacity during the peak hour. When the peak hour is over and the demand is reduced to the level below capacity, the queue should dissipate.

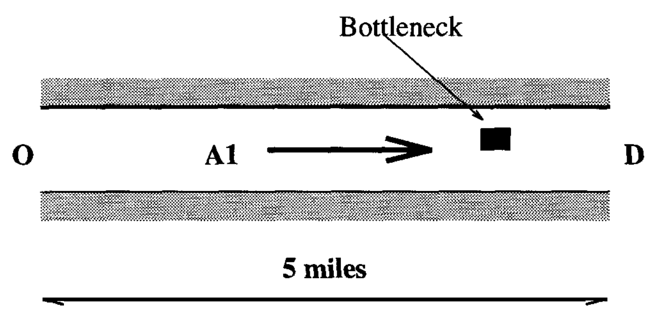


Figure 9: The linear network with a bottleneck

5.4.2 Input Data

The input data for this scenario is as follows:

- Roadway geometry
  - jam density: 210 vehicles per mile
  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane
- Run time parameters
  - time step: 6 sec.

  - total time: **30** min.

- Traffic demand

  - 0 - 300 sec: 600 vehicles per hour
  - 301 - 600 sec: 1800 vehicles per hour
  - 601 - 1800 sec: 600 vehicles per hour

- Bottleneck characteristics

  - start time: 5.5 min.
  - location: 1 mile from D
  - capacity: 900 vehicles per hour
  - jam density: 105 vehicles per mile

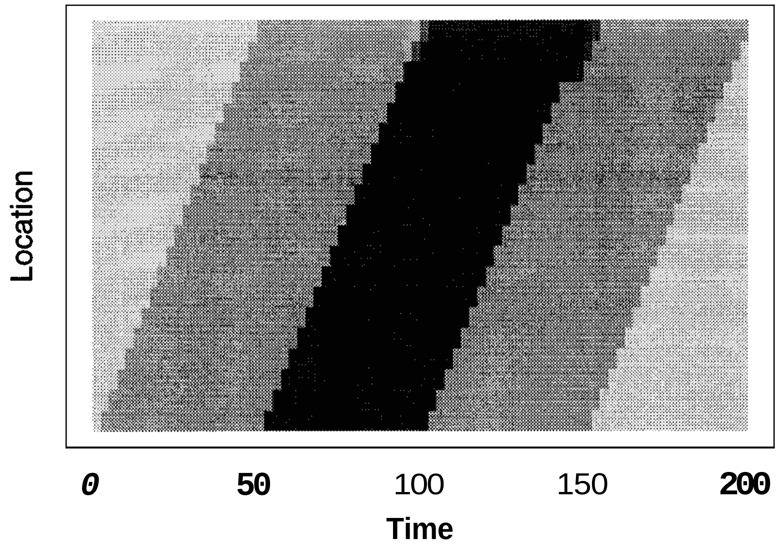
The above data is used as input for DYNASMART, INTEGRATION, and METS. It does not apply to DINOSAUR since the memory required to run DINOSAUR for this scenario exceeds the capability of the computing machine used for this project. We thus simplified the input for DINOSAUR by increasing time step duration and the link length so that the total number of links and the duration of the simulation run were reduced. In doing so, we kept the comparison with other models valid at the qualitative level. For DINOSAUR, The same adjustments were made for Scenarios 5 and 6 in the next two subsections. For each plot, flow propagates in the upward direction.

5.4.3 Output Results

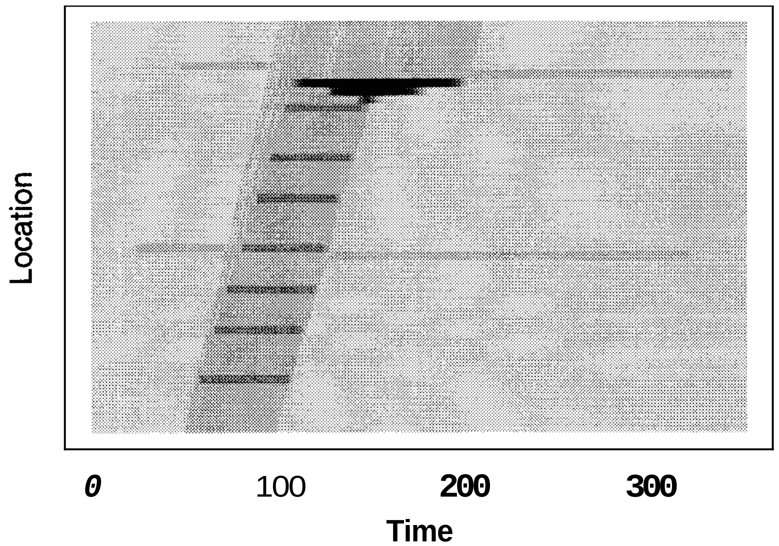
The occupancy over time and space plots for all four models are produced in Figure 10 (a) — (d).

5.4.4 Observations

The observations made below are based mainly on the plots shown in Figure 10. Occasionally, they are based directly on the output data for making the plots.

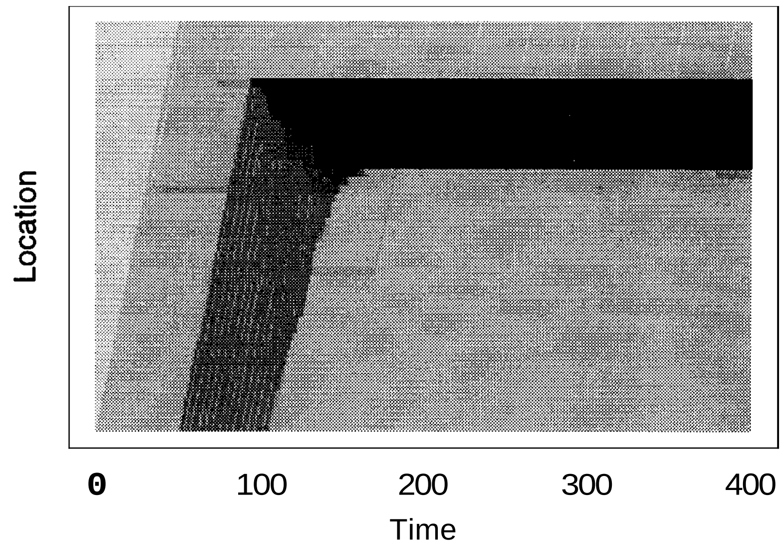


a. DINOSAUR result for Scenario 4

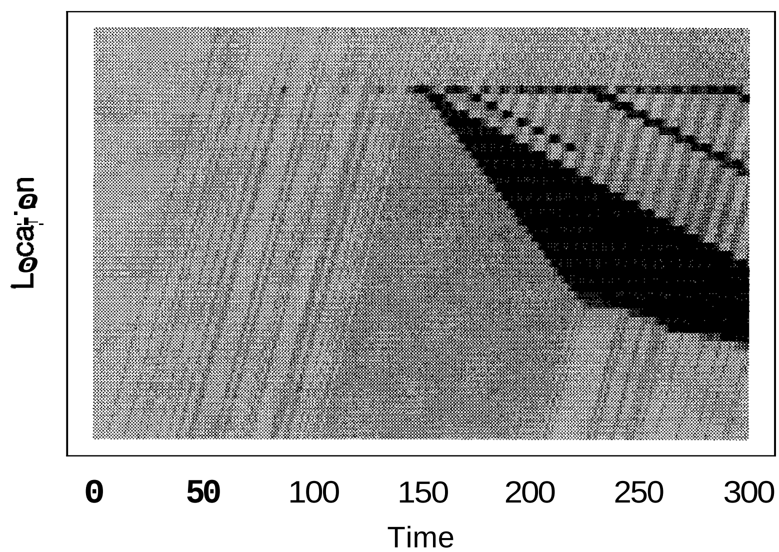


b. DYNASMART result for Scenario 4

Figure 10: Link occupancy vs. time and space for Scenario 4 (The linear network; recurrent congestion)



c. INTEGRATION result **for** Scenario **4**



d. METS result **for** Scenario **4**

Figure **10:** Link occupancy **vs.** time and space **for** Scenario **4** (The linear network; recurrent congestion) (continued)

- In DINOSAUR, queue spill back is not modeled. Heavy congestion occurs on the link with the bottleneck. In the other three models, physical queues are shown upstream of the bottleneck, though the details of the queue vary substantially across these models.

- The queuing periods for the four models are very different. In DINOSAUR and DYNASMART, the queuing periods end shortly after the demand drops to the level below capacity. In METS and INTEGRATION, queues do not clear at the end of the simulation run and have no tendency to clear. The queue in METS continues to propagate in the upstream direction, whereas the queue in INTEGRATION remains unchanged.

- The static queue in INTEGRATION is possibly caused by round-off errors. According to the input data, the demand was 3 vehicles per time step during the peak period and 1 vehicle per time step during the off peak period; the capacity was 1.5 vehicles per time step. It appears that the actual capacity used in the simulation run was truncated to 1 vehicle per time step. Consequently, the queues formed during the peak hour sustained after the peak period. We made another INTEGRATION run in which the time steps and the link length were both doubled so that the truncation effect was eliminated. The queue was then cleared before the end of the simulation run as expected. The result is shown in Figure 11. Note that the time unit in Figure 11 is 12 seconds per time step.

5.5 Scenarios 5: The Diverge Network with Recurrent Congestion

5.5.1 Scenario Description

A diverge network with a bottleneck The network topology and the bottleneck location are given in Figure 12. The network can be viewed as a representation for off-ramp areas or interchanges in a large scale network. Three levels of traffic demands, going from O to D1 and D2, are generated for the entire period of simulation. Traffic demands vary over time,

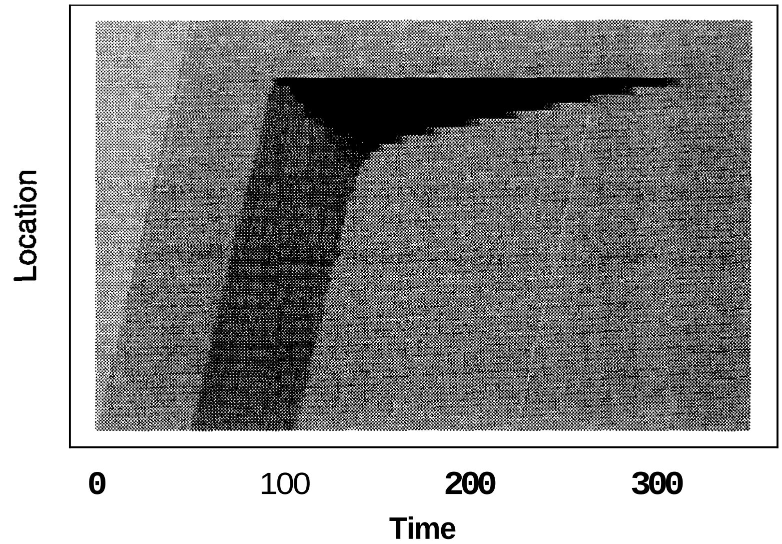


Figure 11: INTEGRATION result for Scenario 4 (time step, demand, and capacity doubled)

representing the peak and off-peak hour traffic. During the peak hour, congestion occurs when traffic demands exceed the bottleneck capacity. We evaluate how different models capture the impact of the queue formed at the junction on vehicles going to the unblocked branch.

5.5.2 Input Data

The input data for this scenario is as follows:

- Roadway geometry
  - jam density: 210 vehicles per mile
  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane
  - number of lanes: main branch (B1) = 2; diverge branch (B2) = 1; diverge branch (B3) = 1
- Run time parameters

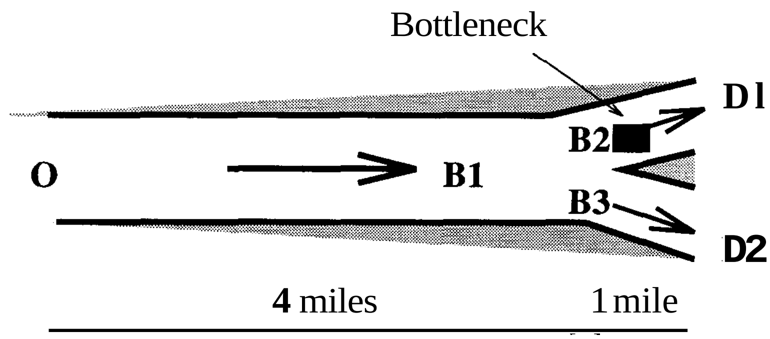


Figure 12: The diverge network with a bottleneck

- time step: 6 sec.
- total time: 30 min.

- Traffic demand
  - O-D1:
    - 0 - 300 sec: 600 vehicles per hour
    - 301 - 600 sec: 1800 vehicles per hour
    - 601 - 1800 sec: 600 vehicles per hour
  - O-D2:
    - 0 - 300 sec: 600 vehicles per hour
    - 301 - 600 sec: 1200 vehicles per hour
    - 601 - 1800 sec: 600 vehicles per hour

- Bottleneck characteristics
  - location: 0.5 mile from D1
  - length: 0.2 mile (2 links)
  - capacity: 900 vehicles per hour
  - density: 105 vehicles per mile

5.5.3 Output Results

The occupancy over time and space plots for **all** four models are produced in Figure **13** (a) — (d). The occupancies for the main branch (B1) and the two diverge branches **(B2** and **B3)** are plotted on three separate parts in each plot. The upper portion of the part for the main branch and the bottom portion of the parts for the two diverge branches correspond to the diverge junction.

5.5.4 Observations

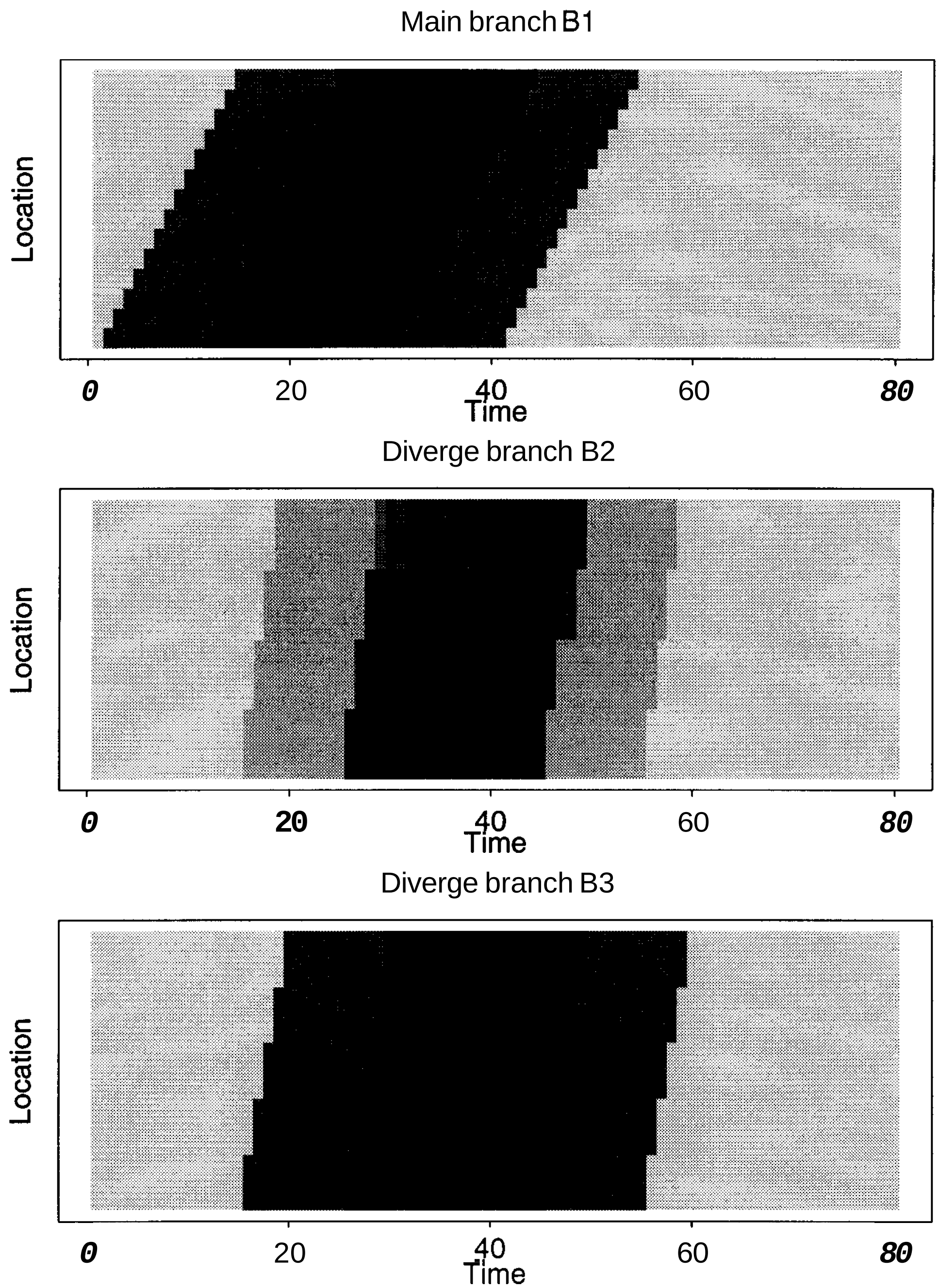
The observations made below are based mainly on the plots shown in Figure **13** as well as the output data for making the plots (not shown here for brevity).

- The result from DINOSAUR does not exhibit any physical queues. Congestion occurs only to the link with the bottleneck. Thus no queuing spill back to the junction is observed. Vehicles going to the other branch are not affected during the queuing period.

- The result from DYNASMART shows a high density physical queue located upstream of the bottleneck. The queue does propagate back but does not reach the junction area. Vehicles going to the other branch are not affected.

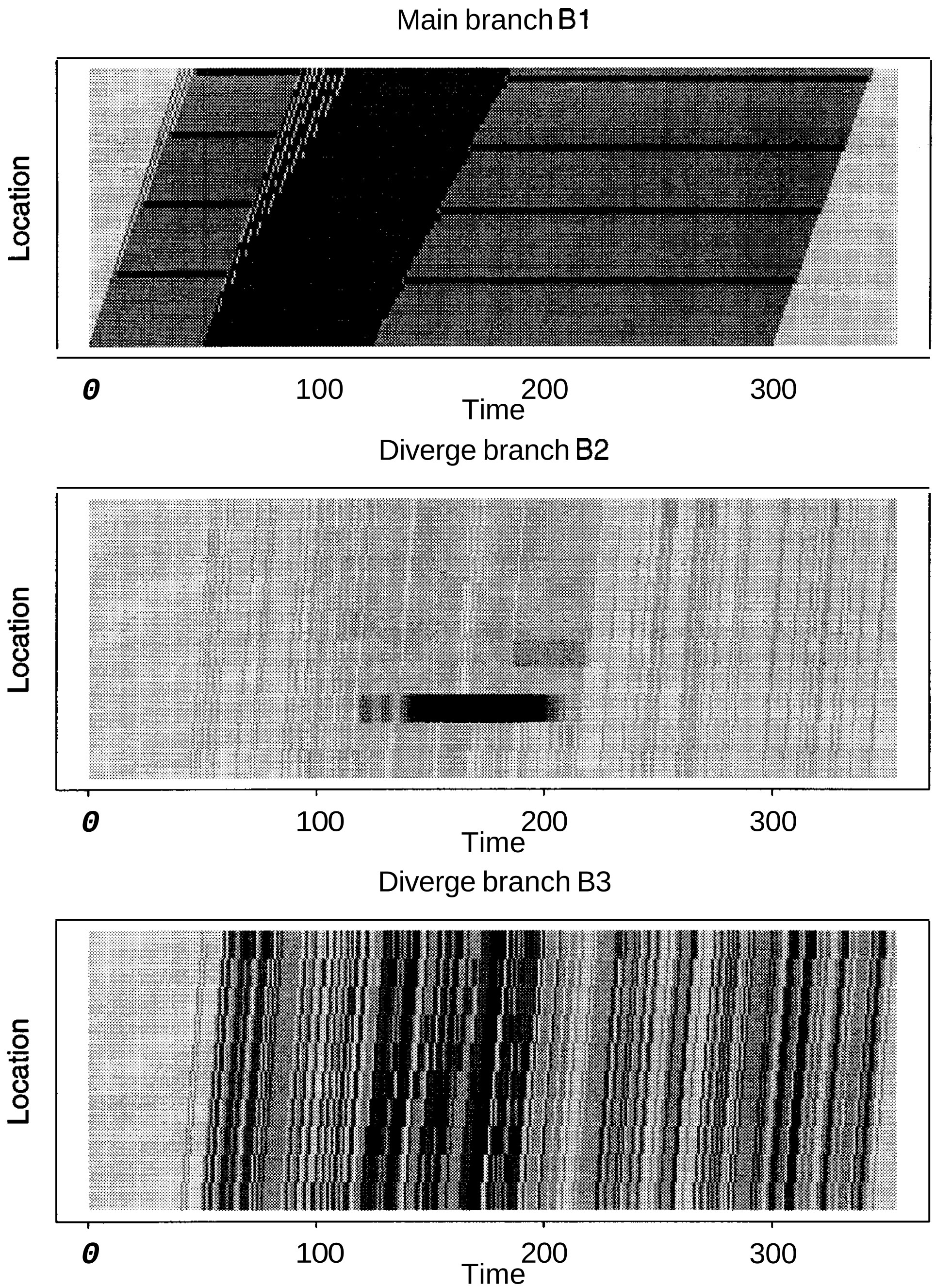
- The result from INTEGRATION shows a physical queue that spills back to the junction. Vehicles going to diverge branch **B3** are reduced during the peak period. Due to the round off error, shown also in the previous scenario, the queue does not clear at the end of the simulation run.

- The result from METS does not show the bottleneck effect. Free-flow condition is observed from the entire simulation period.



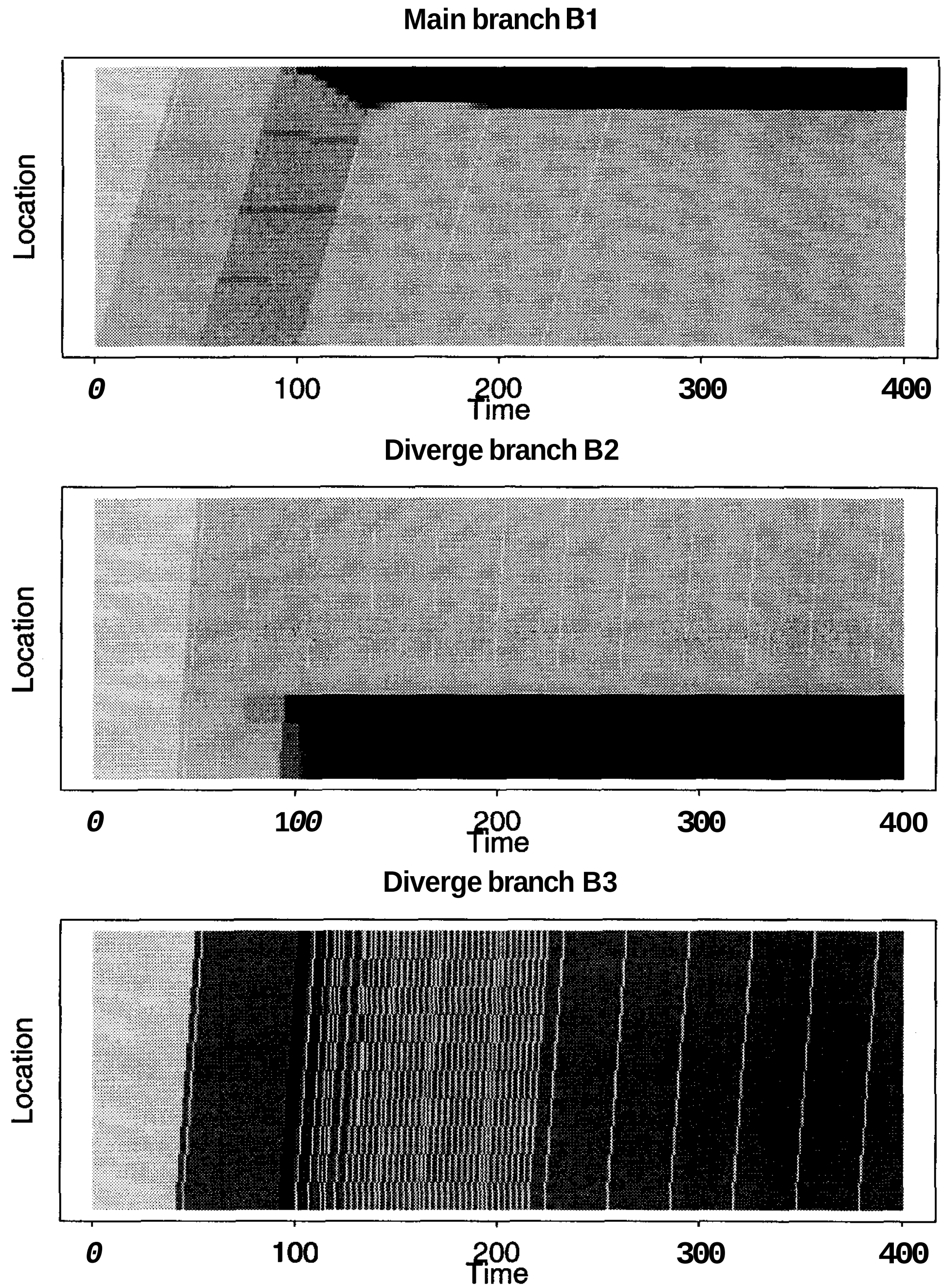
a. DINOSAUR result for Scenario 5

Figure **13:** Link occupancy vs. time and space for Scenario 5 (diverge network; recurrent congestion)



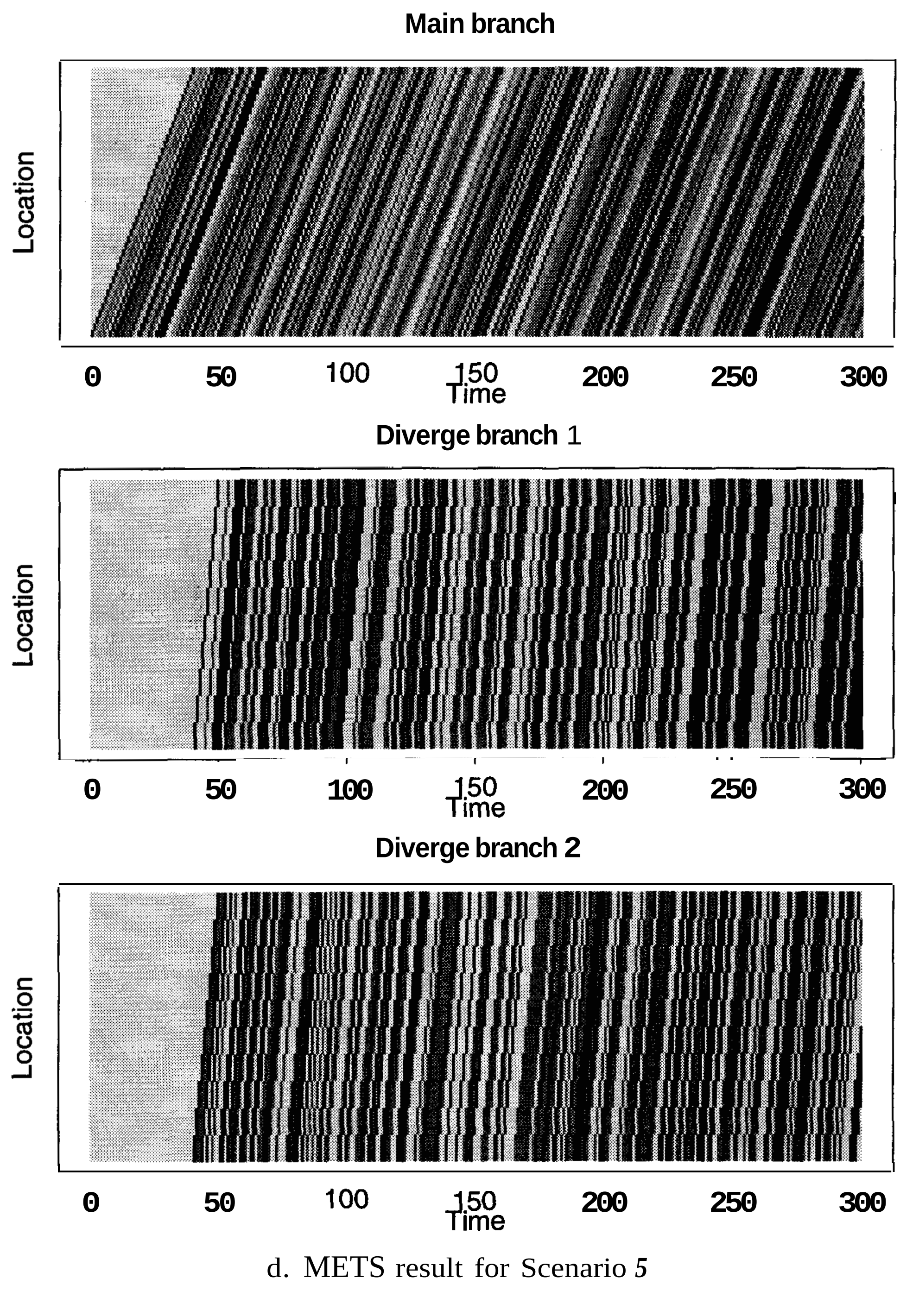
b. DYNASMART result for Scenario **5**

Figure **13:** Link occupancy vs. time and space for Scenario 5 (diverge network; recurrent congestion) (continued)



c. INTEGRATION result for Scenario *5*

Figure **13:** Link occupancy **vs.** time and space for Scenario 5 (diverge network; recurrent congestion) (continued)



d. METS result for Scenario 5

Figure **13:** Link occupancy vs. time and space for Scenario 5 (diverge network; recurrent congestion) (continued)

5.6 Scenarios 6: The Merge Network with Recurrent Congestion

5.6.1 Scenario Description

The network topology and the bottleneck location are given in Figure **14.** The network can be viewed as a representation for on-ramp areas or interchanges in a large scale network. Three levels of traffic demands, going from **0 1** and 0 2 to D, are generated for the entire period of simulation, representing the peak and off-peak traffic. Initially, traffic is free-flow. During the peak hour when the demand exceeds the bottleneck capacity, congestion occurs. The queue starts to dissipate when the peak hour is over. We evaluate how different models behave in capturing the formation of queues at the junction area.

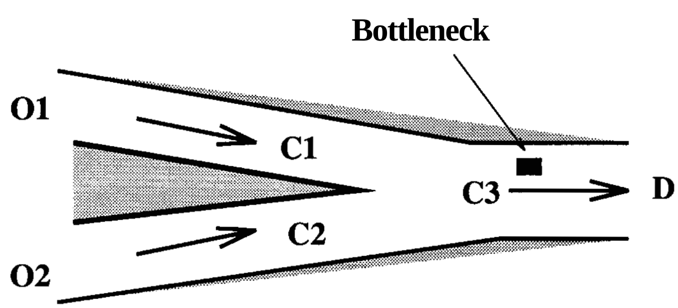


Figure **14:** The merge network with a bottleneck

5.6.2 Input Data

The input data for this scenario is as follows:

- Roadway geometry
  - jam density: **210** vehicles per mile
  - free-flow speed and speed at capacity: 60 miles per hour
  - capacity: 1800 vehicles per hour per lane

  - number of lanes: merge branch (C1) = 1; merge branch (C2) = 1; main branch (C3) = 2

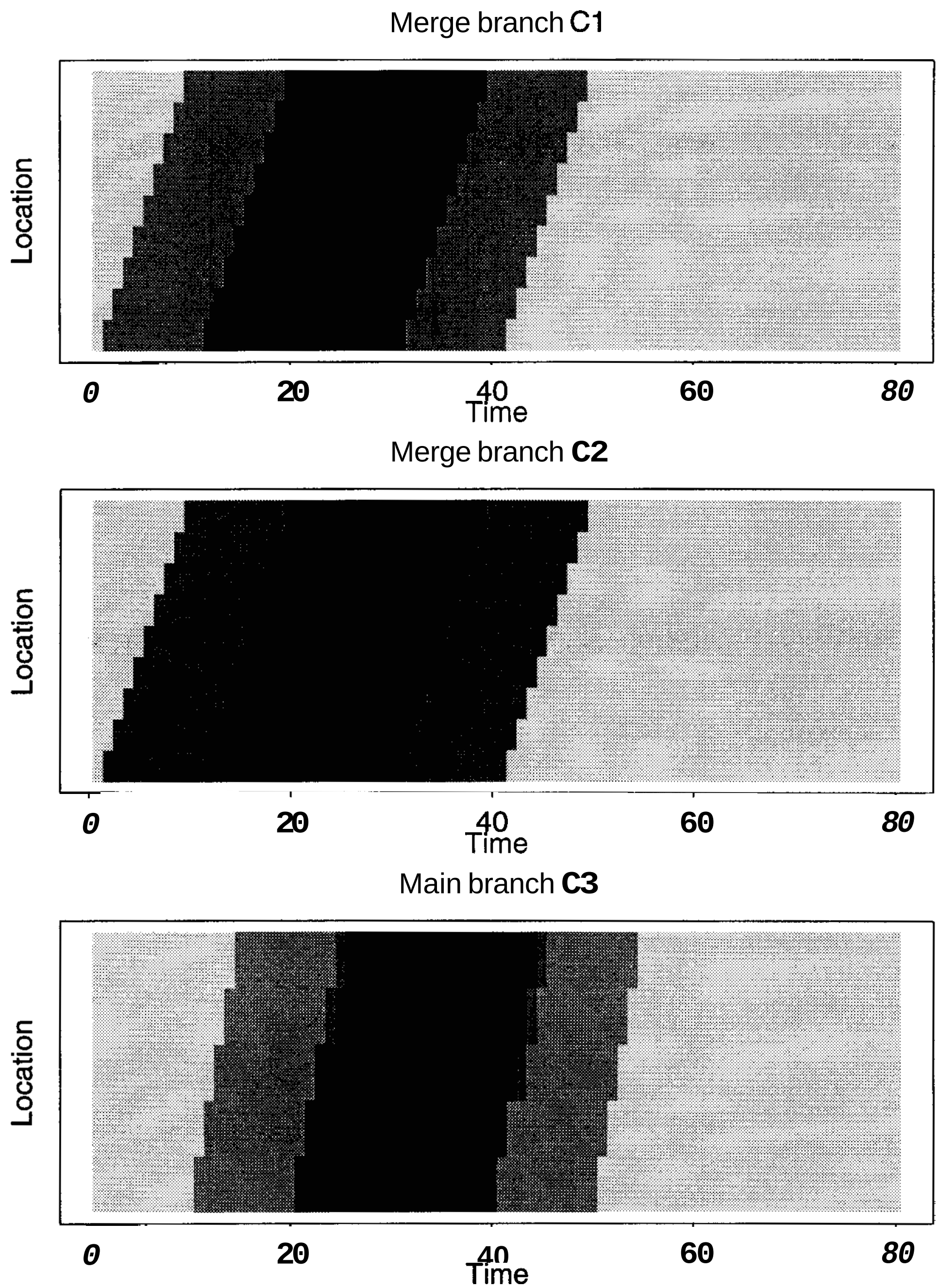
- Run time parameters
  - time step: 6 sec.
  - total time: 30 min. or until traffic is cleared

- Traffic demand
  - O1-D:
    * 0-300 sec: 600 vehicles per hour
    * 301-600 sec: 1800 vehicles per hour
    * 601-1800 sec: 600 vehicles per hour
  - O2-D:
    * 0-300 sec: 600 vehicles per hour
    * 301-600 sec: 1200 vehicles per hour
    * 601-1800 sec: 600 vehicles per hour

- Bottleneck characteristics
  - start time: 5.5 min.
  - location: 1 mile from D
  - capacity: 900 vehicles per hour
  - jam density: 105 vehicles per mile

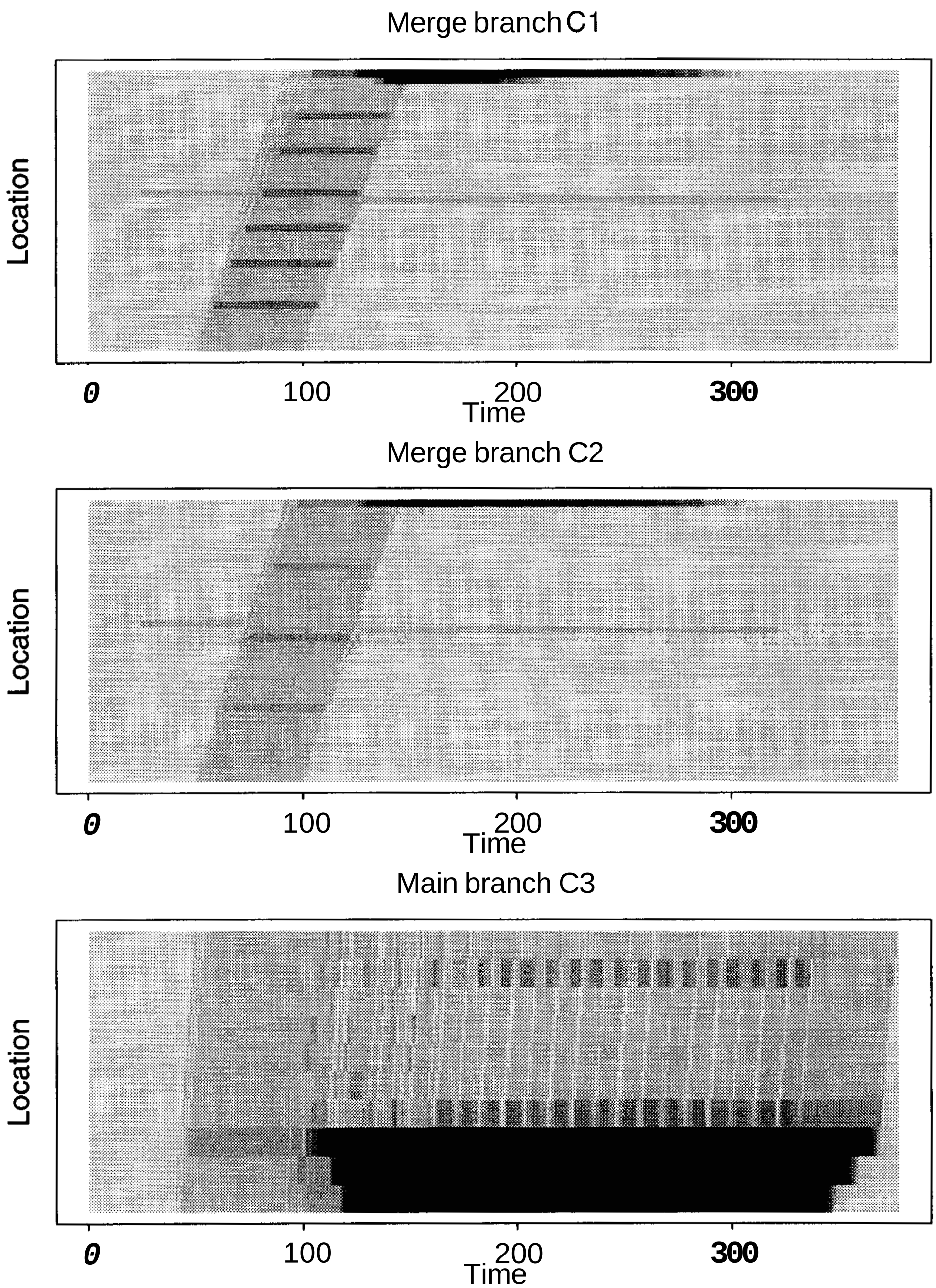
5.6.3 Output Results

The occupancy over time and space plots for all four models are produced in Figure 15 (a) — (d). For each plot, flow propagates in the upward direction. The upper portion of the part for the merge branches and the bottom portion of the part **for** the main branch correspond to the area of the merge junction.



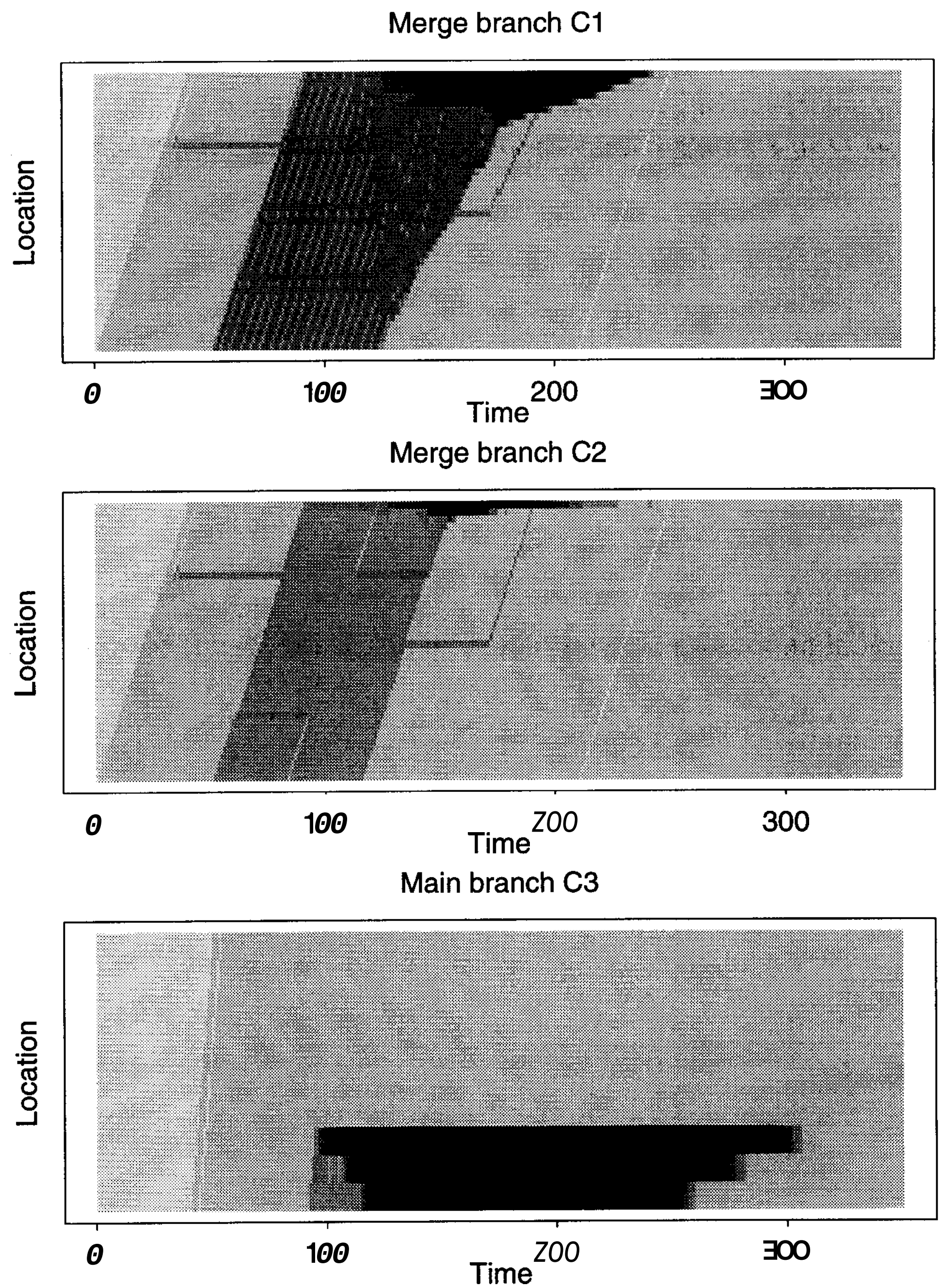
a. DINOSAUR result for Scenario 6

Figure 15: Link occupancy vs. time and space for Scenario 6 (the merge network; recurrent congestion)



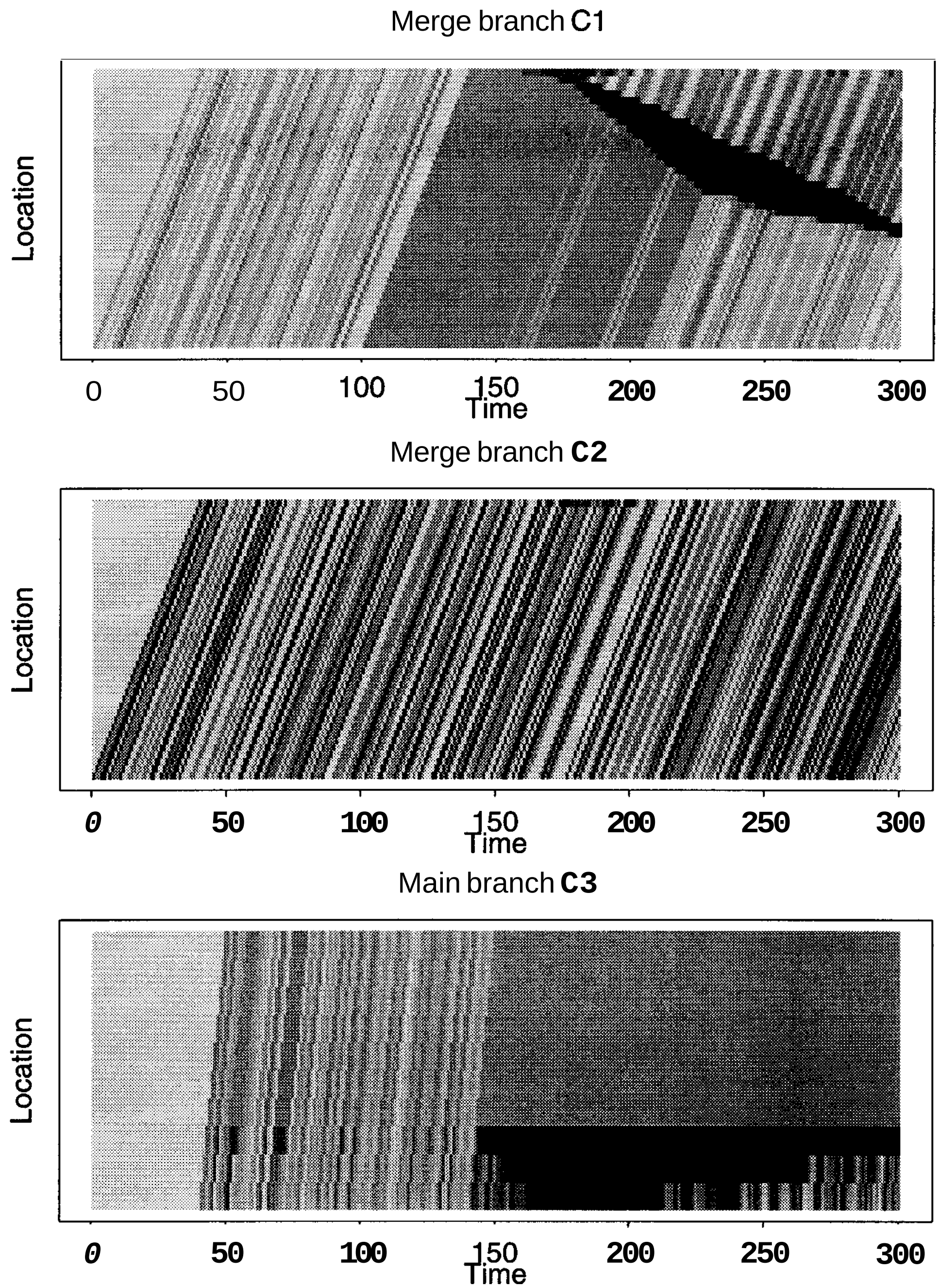
b. DYNASMART result for Scenario 6

Figure 15: Link occupancy vs. time and space for Scenario 6 (the merge network; recurrent congestion) (continued)



c. INTEGRATION result for Scenario 6

Figure 15: Link occupancy vs. time and space for Scenario 6 (the merge network; recurrent congestion) (continued)



d. METS result for Scenario 6

Figure 15: Link occupancy **vs.** time and space for Scenario 6 (the merge network; recurrent congestion) (continued)

5.6.4 Observations

The observations below are based mainly on the plots shown in Figure 15 as well as the output data for making the plots (not shown here for brevity).

- The result from DINOSAUR is consistent with those from the previous two scenarios. Congestion remains in the link with the bottleneck. No queuing spill back is observed. Vehicles from the two merge branches can enter the junction freely.
- The result from DYNASMART shows a high density queue. The queue propagates back to the junction. Under congestion, the merge priority is 1:1 for vehicles from C1 and C2, following the roadway geometry given in the input data.
- The result from INTEGRATION shows a physical queue that spills back to the junction. Under congestion, the merge priority is also 1:1 for vehicles from C1 and c2.
- The result from METS shows a physical queue that spills back to the junction and dissipates when the peak period is over. The relationship between the queues in merge branch C2 and the queues in main branch C3 is unclear.

6 Route Choice Comparison

In addition to traffic dynamics, route choice mechanism is also essential to a dynamic route choice traffic model. The route choice decision in DRCTMs determines how vehicles are distributed on the road for a given set of OD demands. Under the system optimal condition, vehicles are distributed in such a way that the total vehicle delay is minimized. Under the user-optimal condition, vehicles are assumed to be well-informed of the real time traffic condition and choose paths that minimize the travel time of each driver. The former can be employed to develop some alternative traffic control strategies, whereas the latter is mostly used to predict traffic flow patterns,

In the subsection that follows, we compare the route-choice capabilities of each traffic simulation/assignment model selected for our study. To make the tests simple and the results from different models comparable, we select the test scenarios with the following characteristics:

- Route selection is entirely based on real-time link travel times updated every second.
- The travel time information is available to every vehicle on the road and is flawless.
- The network consists of only a single class of vehicles that comply with information fully.
- Random factors (such as the platoon dispersion factor and pulsing) are disabled.

6.1 Scenarios 7 - 10: The Four-Path Network with Two Bottlenecks

6.1.1 Scenario Description

The topology of the test network is given in Figure 16. It is a network with a single origin and a single destination. Node 1 is the origin and node 7 the destination. Links are unidirectional and are all of equal length. For the given network configuration, route choice decision making could occur to each driver at two places, nodes 1 and 4. The two paths 1-3 and 2-4 in the upper loop are symmetrical. They have identical capacities

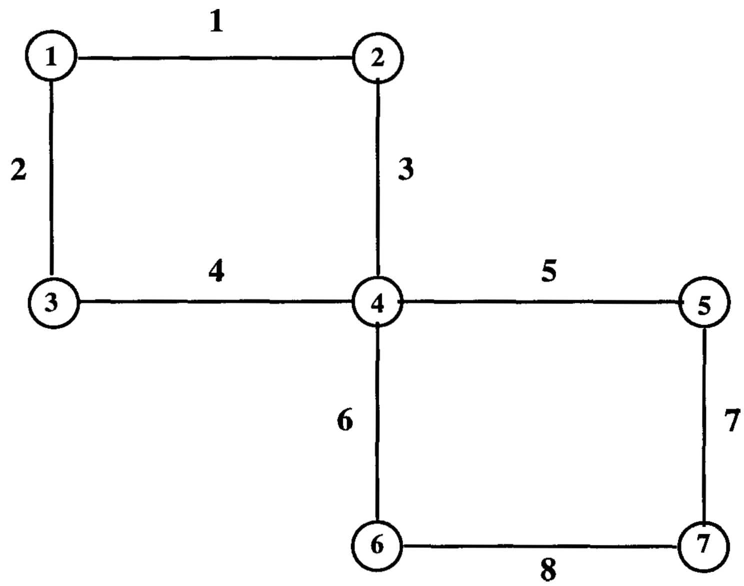


Figure 16: The network topology for route choice comparison

and jam densities. The capacity conditions for links in the lower loop vary in different scenarios. The scenarios are set up to address the following three questions:

1. Are the DUO or DSO objectives used in the model for route choice selection?

2. Does the model incorporate queuing phenomena in its route assignment procedure?

3. Does the model have any intrinsic biases in its route assignment that a user should be aware of?

6.1.2 Input Data

In the following, we present the four test scenarios considered for route choice comparison. For the convenience of cross scenario comparison, we will discuss all four scenarios in a single section.

The roadway geometry of the network for each test scenario is given in Tables 1 and 2. For each test scenario, a constant demand of 1800 vehicles per hour is generated at the origin for one hour and then the network is allowed to clear. We assume that all vehicles comply with the route guidance they receive and there is no background traffic using some fixed routes.

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

Table 2: Link characteristics in the test network for route choice comparison

Scenario	Runtime parameters	Traffic Demand	Link Capacities
7	Time slice: 6 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: 6 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: 6 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: 6 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

Table 3: Description of scenarios 7, 8, 9, and 10

6.1.3 Output Results

The plots of link-occupancy over time for each scenario is given in Figures 17 to 20. In our initial test, DINOSAUR was also considered. Results from DINOSAUR for these four scenarios have floating point errors and thus were excluded from further comparison. Only results from INTEGRATION and DYNASMART are given here.

6.1.4 Observations

It should be noted that the version of DYNASMART that we have was an earlier one, which does not have the capabilities to do user-optimal or system optimal assignments. Route choice in that version is based on the path with the shortest free-flow travel time instead of the path with the shortest flow-dependent travel time.

As shown in the input data, the speed at capacity in all four scenarios (7 – 10) was defined to be equal to the free flow speed. Since all the four paths from the origin to the destination have the same distance, the free flow travel time for all paths should also be the same. Link capacities, however, are not all identical. Each path has a single bottleneck located at the lower loop of the network. The total network throughput is bounded by the bottleneck capacities. We set up the demand so that it does not exceed the system throughput capacity. Theoretically speaking, with these input parameters, the results generated under either dynamic user optimal (DUO) or dynamic system optimal (DSO) conditions should be identical and there should be no queues existing in any part of the network. The model results do not seem to converge or approximate this theoretical prediction. In all four scenarios, significant queues can be found upstream of the bottleneck under both INTEGRATION and DYNASMART.

We examined further if the discrepancy between the model output and the theoretical prediction is introduced by the location of the bottlenecks and their capacities. In scenarios 7 and 8, the bottlenecks are located on links 5 and 6. For vehicles arriving at node 4, they should have the freedom to select either path 6-8 or path 5-7 to travel in, though in either way they should encounter one of the bottlenecks. The result shown in scenario 7 indicates that path 6-8 is completely unused even though path 5-7 is operating at capacity and queues are formed upstream of node 4. Since route choice is based on the travel time,

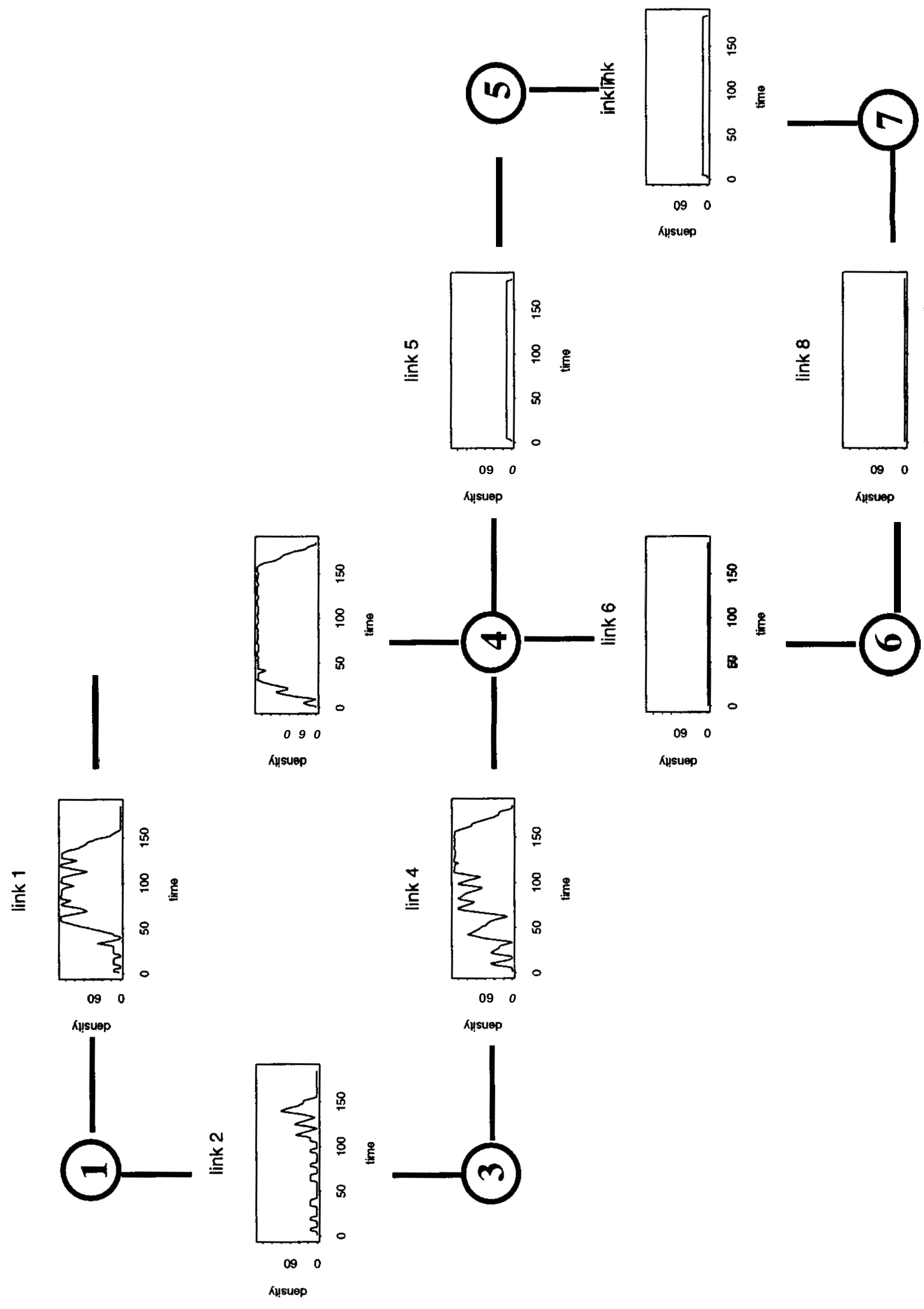


Figure 17: (a) DYNASMART result for Scenario 7

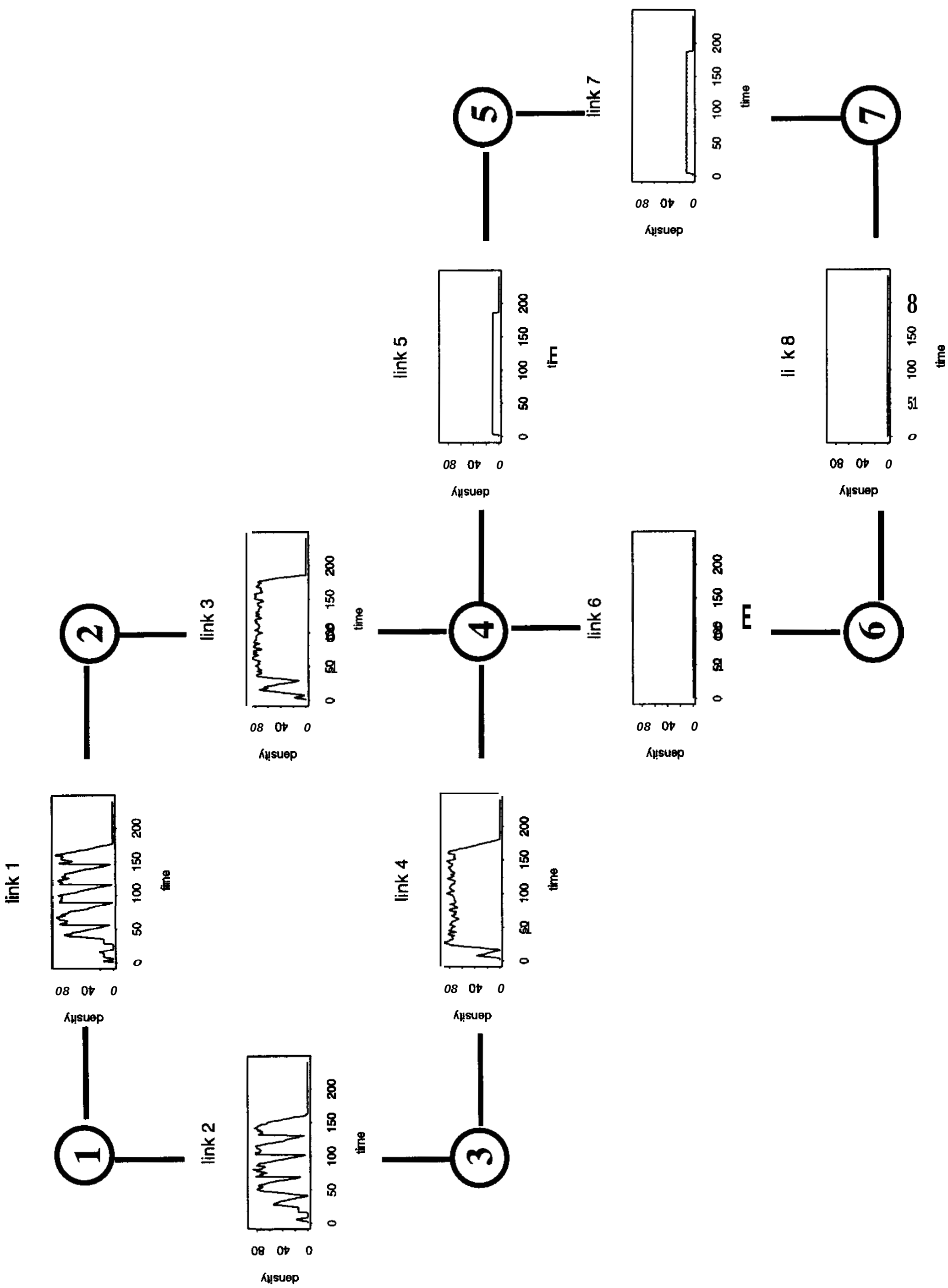


Figure **17:** (b) INTEGRATION result for Scenario **7**

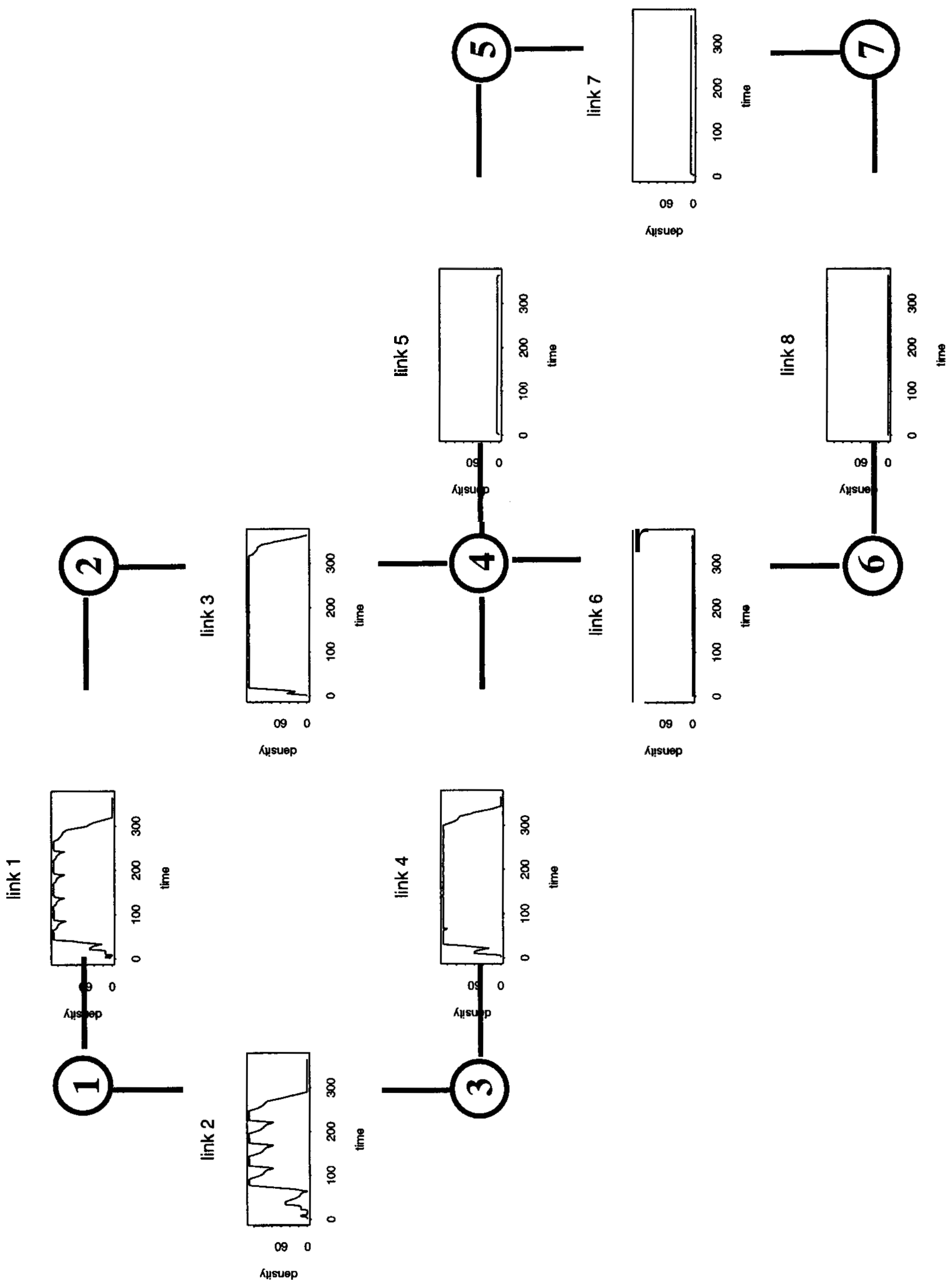


Figure 18: (a) DYNASMART **result** for Scenario 8

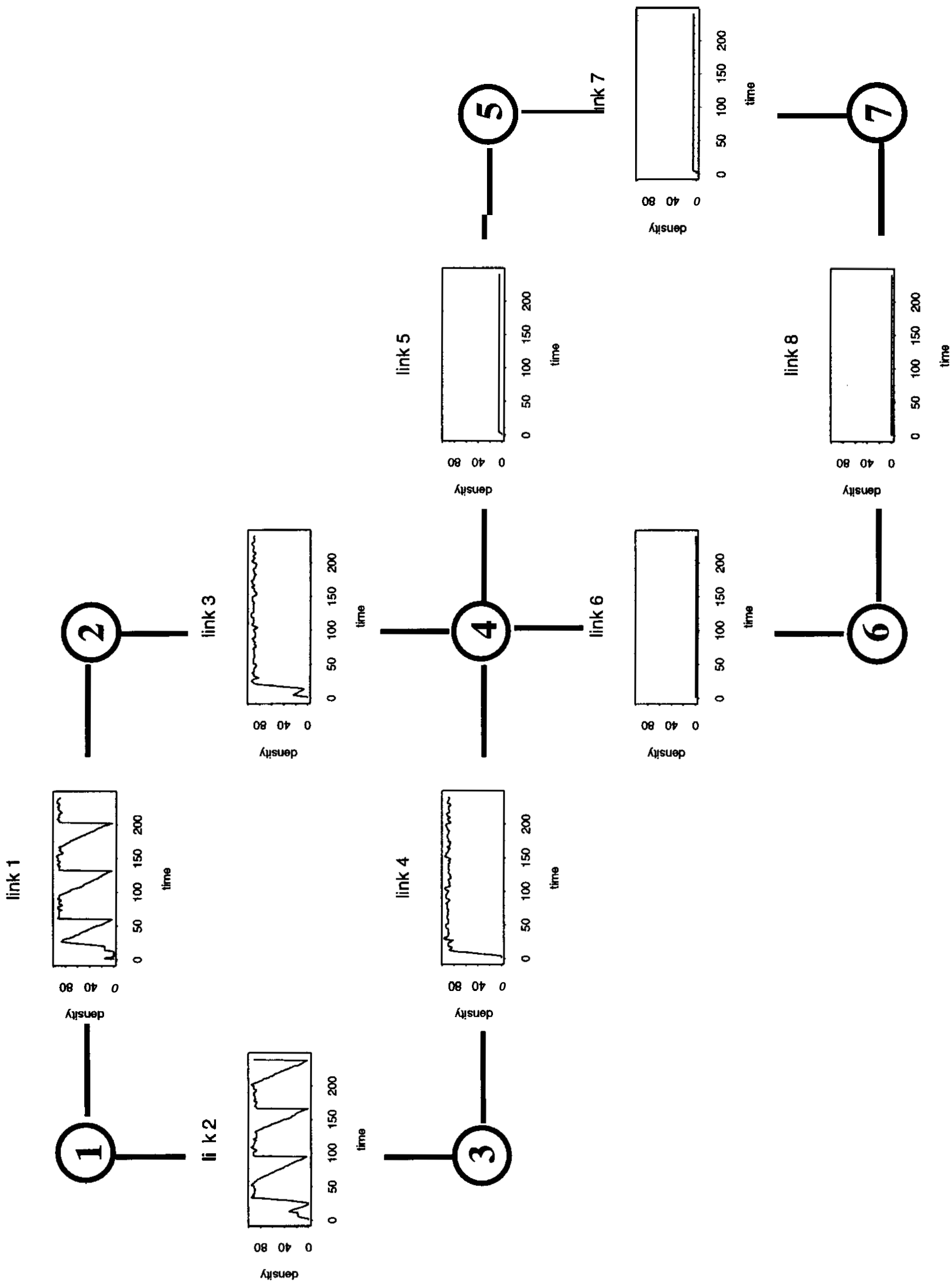


Figure 18: (b) INTEGRATION result for Scenario 8

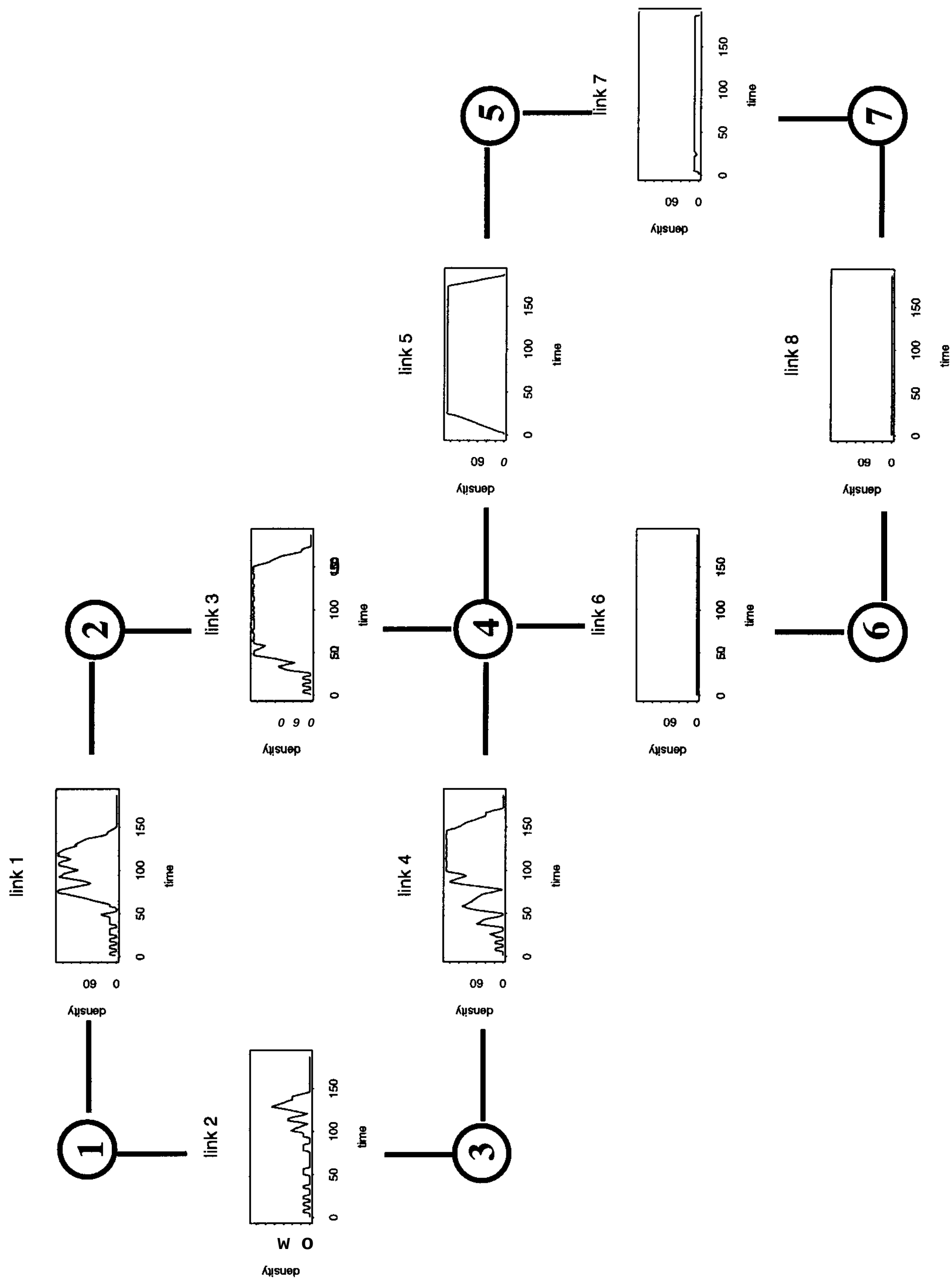


Figure 19: (a) DYNASMART result for Scenario 9

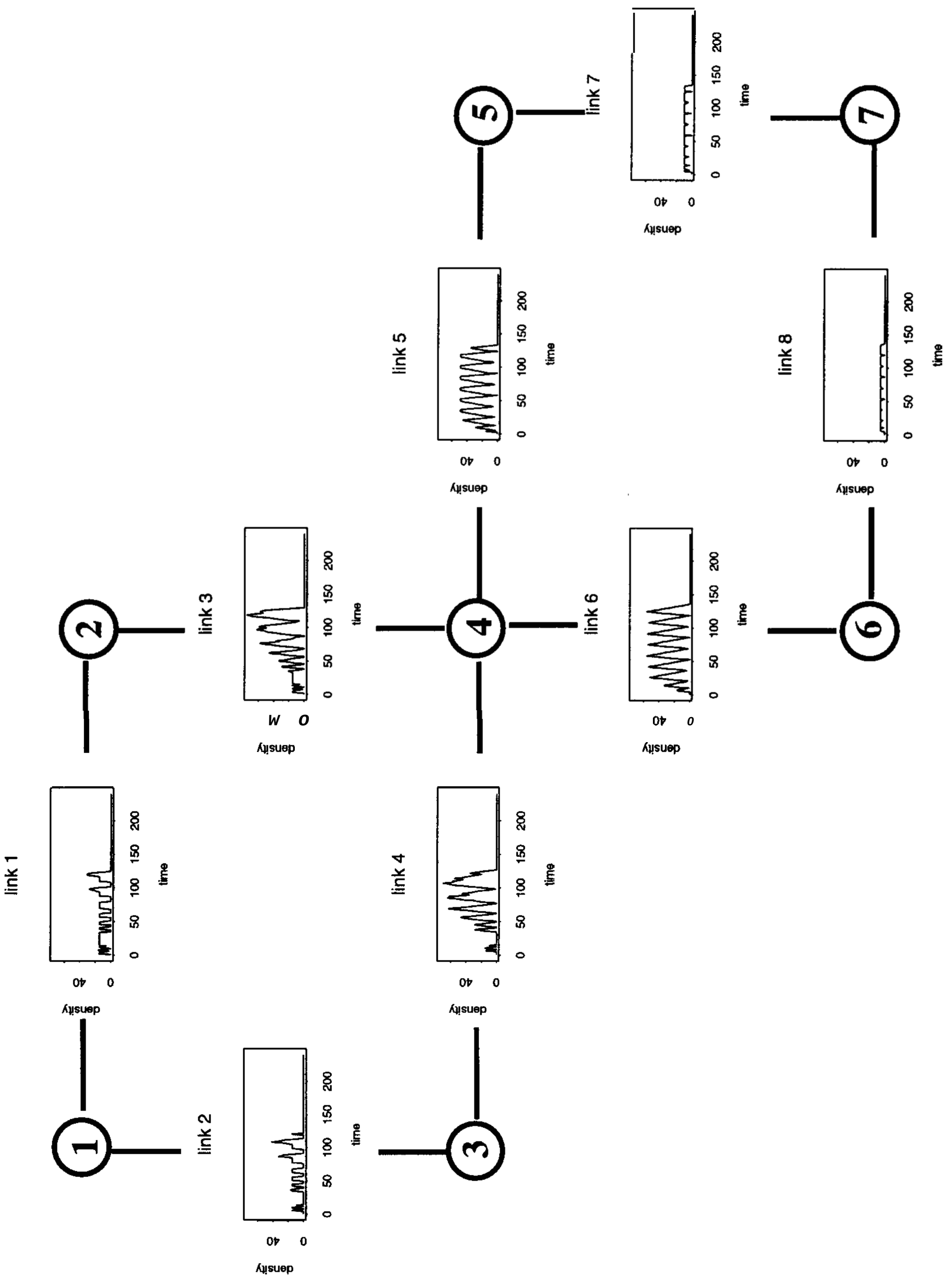


Figure 19: (b) INTEGRATION result for Scenario 9

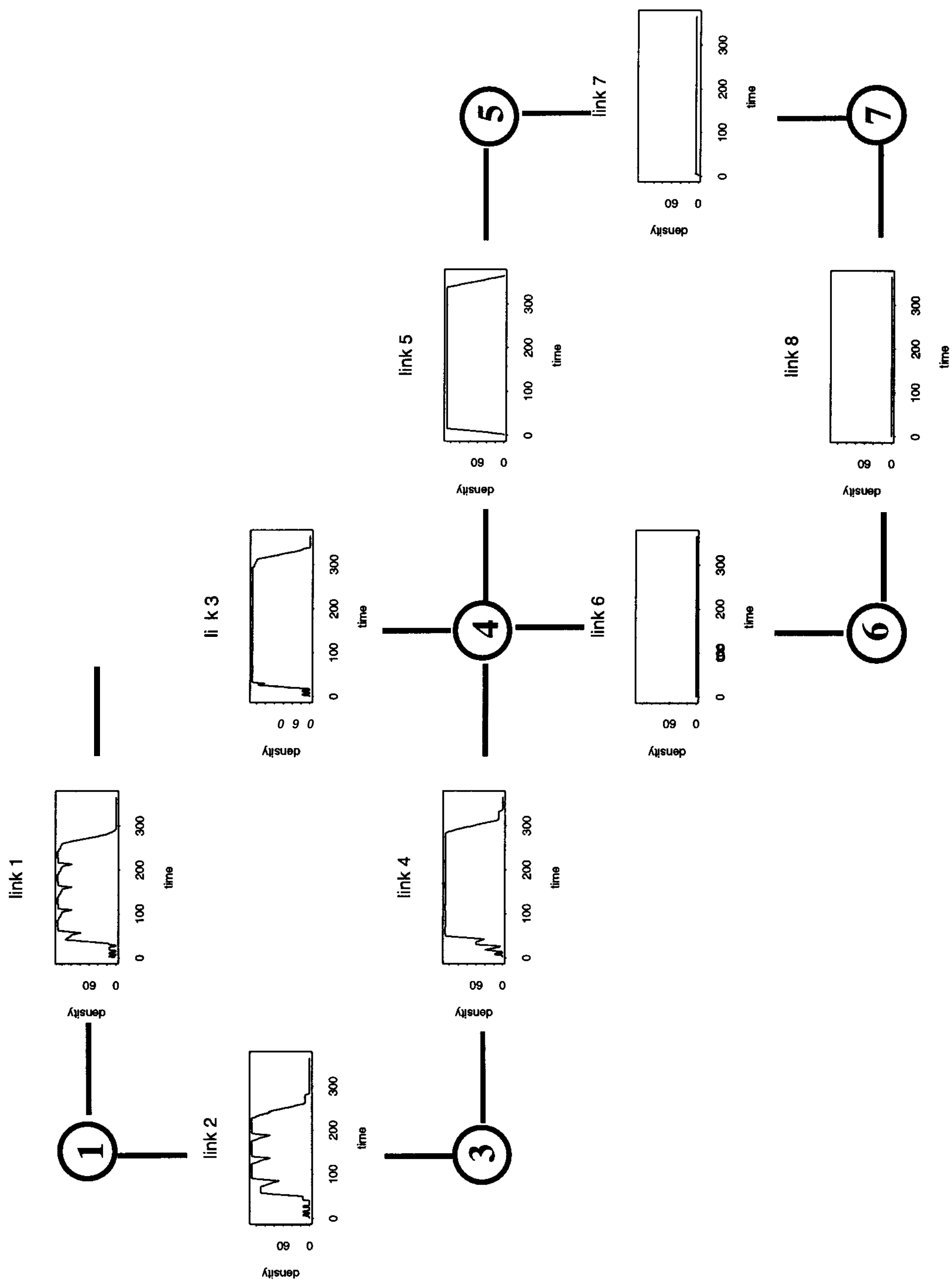


Figure 20: (a) DYNASMART result **for** Scenario 10

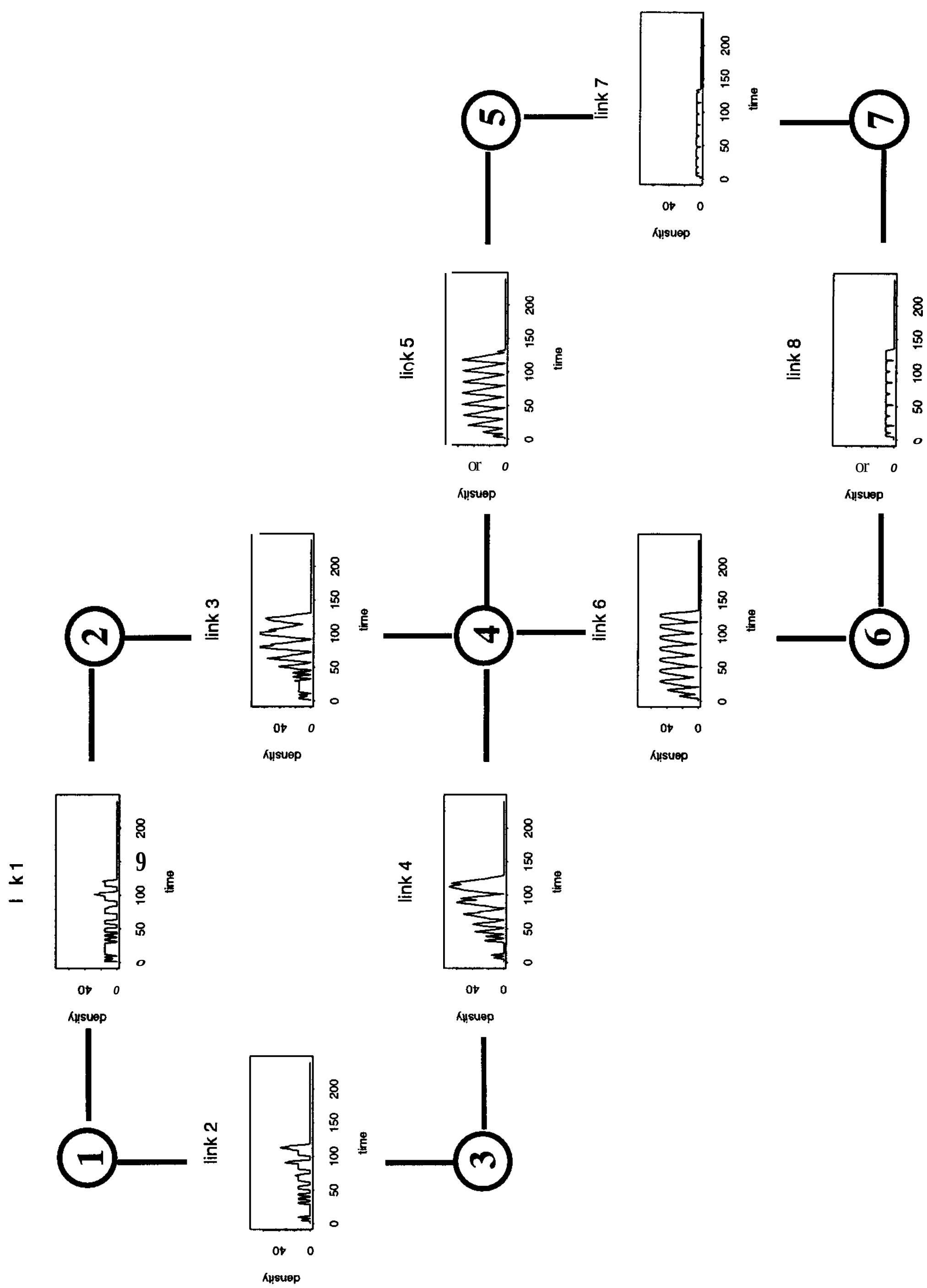


Figure 20: (b) INTEGRATION result for Scenario 10

the result can be valid if path *5-7* has a shorter travel time and the route choice decision is made to achieve a user optimal state. To evaluate if this is true and if path *5-7* indeed has a lower travel cost than path 6-8 because of the capacity, we exchanged the capacities between links *5* and **6** in scenario 8 to test if vehicles will then be routed to path 6-8. This did not happen as the result still shows a preference of path *5-7* to path 6-8 under both INTEGRATION and DYNASMART. Apparently, under an identical free flow travel time condition, it is not the capacity that influences the route choice decision. Further investigation reveals that both models have a bias to assign vehicles to the link with the lowest label (or number) among downstream contender links that have identical travel times. The available capacities of the other contender links are ignored.

In scenarios 9 and 10, the bottlenecks are located on links *7* and *8*. **As** in the previous two scenarios, initially all vehicles arriving at node **4** select path *5-7.* When queues are built up on link *5*, the travel time for path *5-7* exceeds the travel time on path 6-8. Under INTEGRATION some vehicles start to divert to path 6-8. Under DYNASMART, no diversion happens. Little comments can be made here since the version of DYNASMART available to us is not yet ready for route choice operations.

7 Overall Network Performance Comparison

The initial objective of this last comparison is to examine if the models with different modeling approaches will produce comparable traffic flow patterns at the network level to support planning activities or detailed traffic operations. If the traffic flow patterns turn out to be very different, then we intend to examine further the impact of the difference on different types of applications. The status of the models we have would not allow us to pursue the scope of comparison initially planned. For reasons explained earlier, DINOSAUR and METS were not ready for comparison. Though results from DYNASMART and INTEGRATION can be produced in this study, the comparison would be inconclusive because the route choice component in DYNASMART was not available for this study. Therefore, the comparison given in this section is kept at a very high and qualitative level. Nevertheless, we demonstrate that how, at a network level, the measures of performance of models are related to the network congestion level and the internal route choice mechanism. We define three scenarios for a network with multiple origins and multiple destinations and vary the demand level to generate light, slightly congested, and severely congested traffic. We then compare the traffic flow pattern, link usage, and the average travel time under these three scenarios.

7.1 Scenario 11 - 13: Congested and Uncongested Networks

7.1.1 Scenario Description

We adopt the network depicted in the INTEGRATION user manual (Van Aerde, 1992) as our test network, referred to as QNET. The topology of the test network is given in Figure 21. It is a network with **5** origins and 2 destinations. The origins include nodes

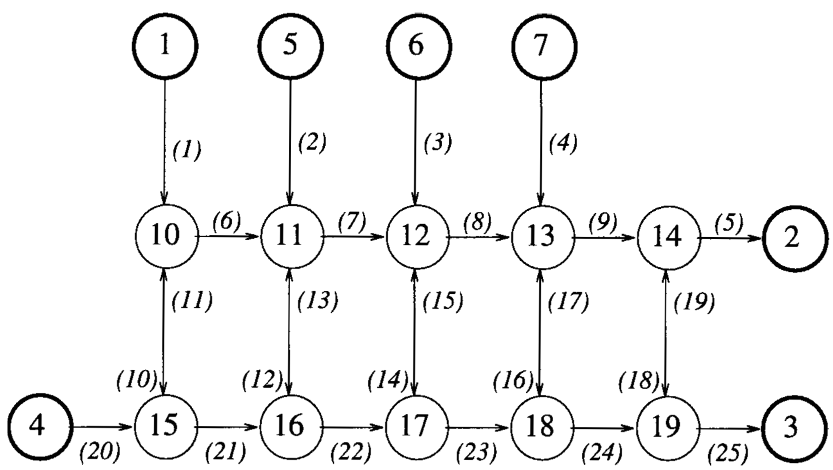


Figure 21: The network topology for overall network comparison

1, 4, **5**, 6, **7**, and the destinations nodes 2 and 3. One can think of QNET as a typical network with two parallel routes (routes 6-7-8-9 and 21-22-23-24) leading to a central business district. For our purposes, signals at the intersections have been turned off and the network has been changed to only permit flow in one direction, except for the short connectors roads between the two main routes.

7.1.2 Input Data

The network geometry is given in Table 4. The OD demands for scenarios 11 to 13 are given in Tables 5 to 7. In each of the three scenarios, the network is loaded for twenty 30-second time intervals (or a total of 600 seconds) according to the OD demand rates.

Link	Length (mile)	No. of lanes	Free-flow speed (mph)	Speed at capacity (mph)	Capacity (vph)	Jam density (vpm)
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	1.400	1	60	60	1800	210
9	0.938	1	60	60	1800	210
10	0.938	2	60	60	1800	210
11	0.500	2	60	60	1800	210
12	0.500	1	60	60	1800	210
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

Table 4: Link characteristics in the test network for overall network comparison

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

Table 5: OD demand rates (vph) for Scenario 11: the uncongested case.

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

Table 6: OD demand rates (vph) for Scenario 12: the slightly congested case.

7.1.3 Output

The plots of link-occupancy over time for each scenario is given in Figures 22 to 24. In addition, we compute the average vehicle travel time from each model. The results are displayed in Table 8. Only results from INTEGRATION and DYNASMART are given here.

7.1.4 Observations

The focus of this last comparison is on the relationship between queues and the network performance measurements, such as the average trip time.. Given the results from the traffic dynamics and route choice comparison, the result from this part is very much predictable.

The results shown in Table 8 reveal that the travel time in INTEGRATION is lower than that in DYNASMART under uncongested traffic and larger under congested traffic, indicating that INTEGRATION is more sensitive to congestion. The travel time from

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

Table 7: OD demand rates (vph) for Scenario 13: the severely congested case.

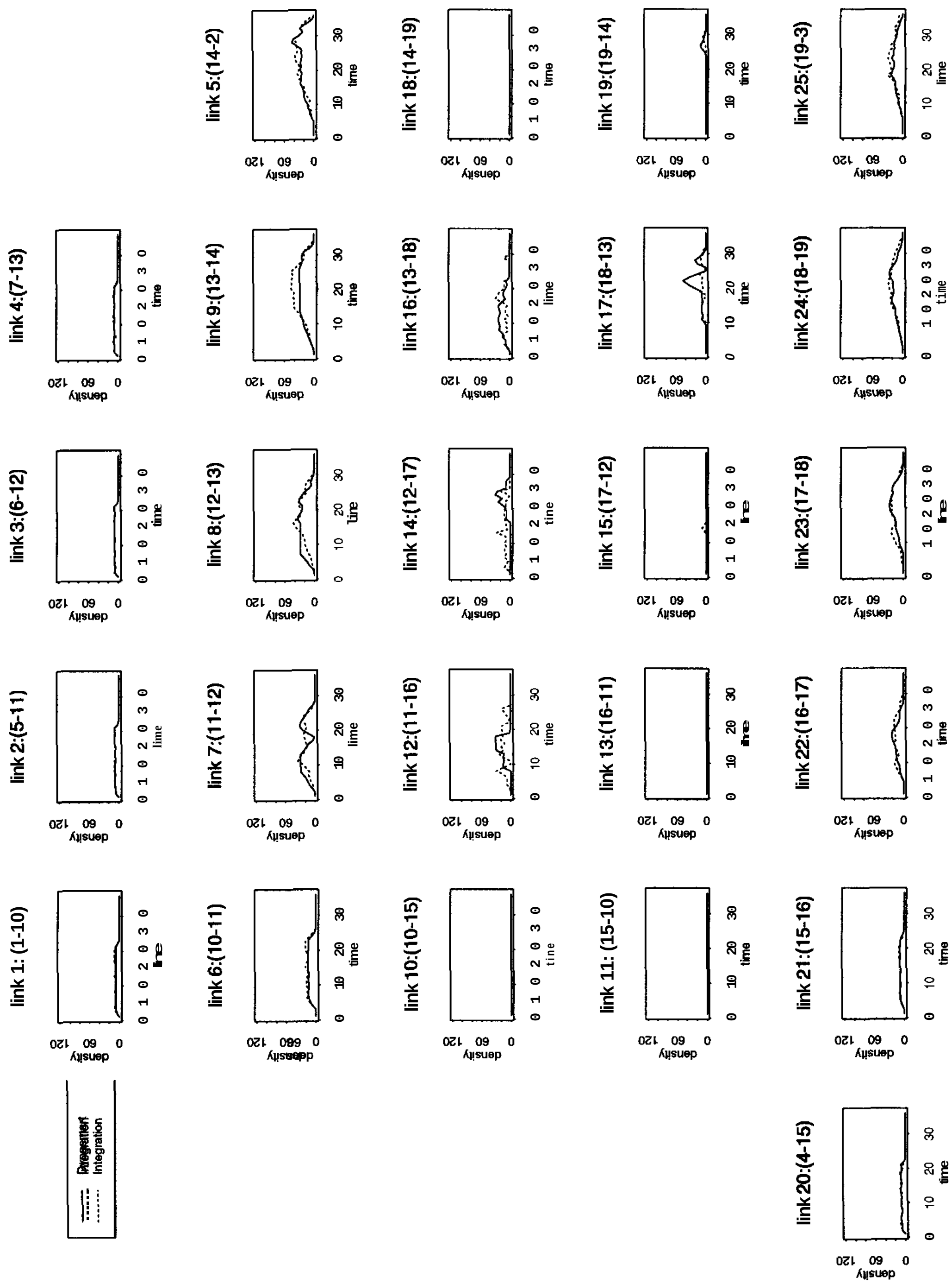


Figure 22: DYNASMART and INTEGRATION results for Scenario 11

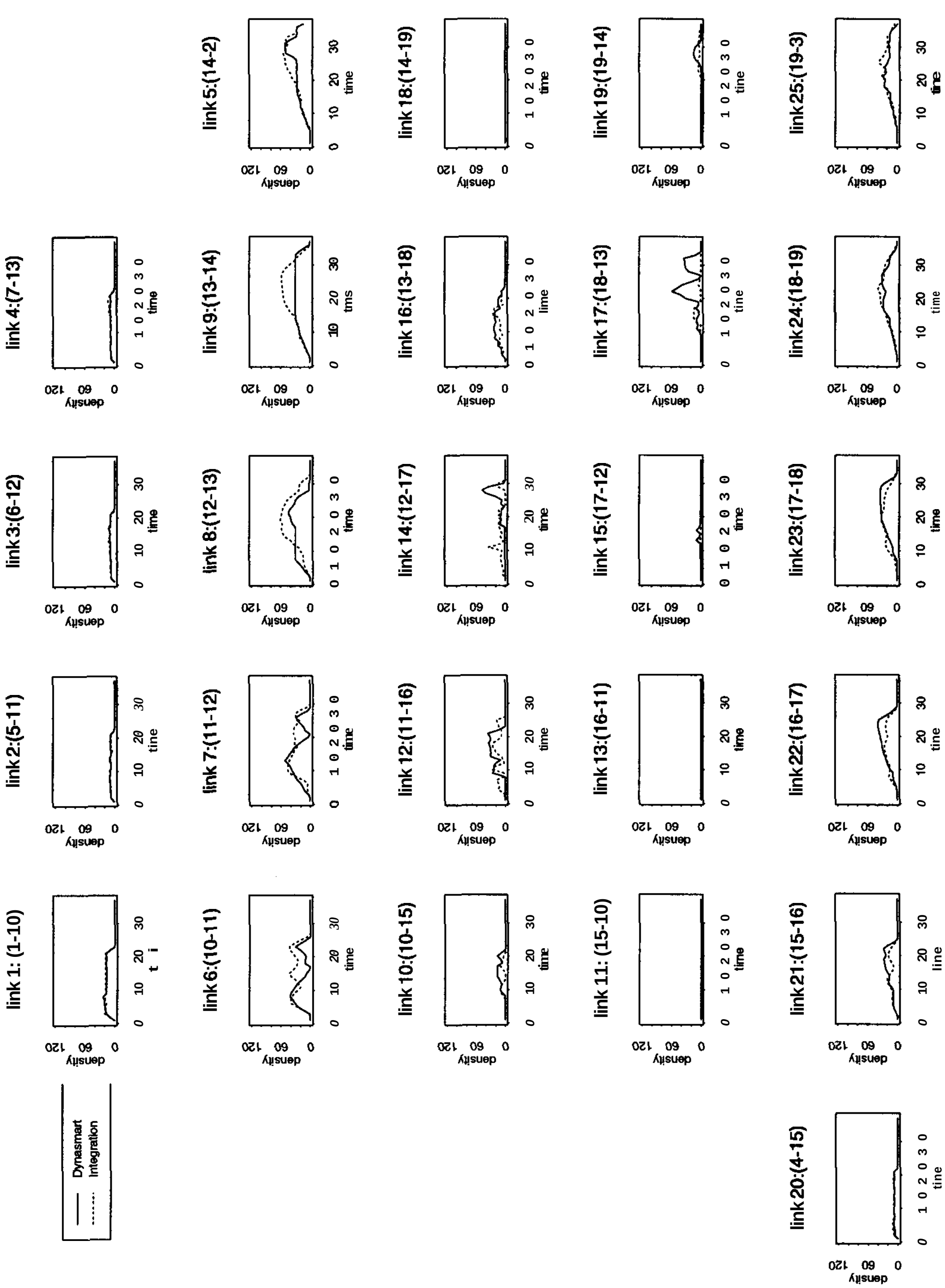


Figure 23: DYNASMART and INTEGRATION results for Scenario 12

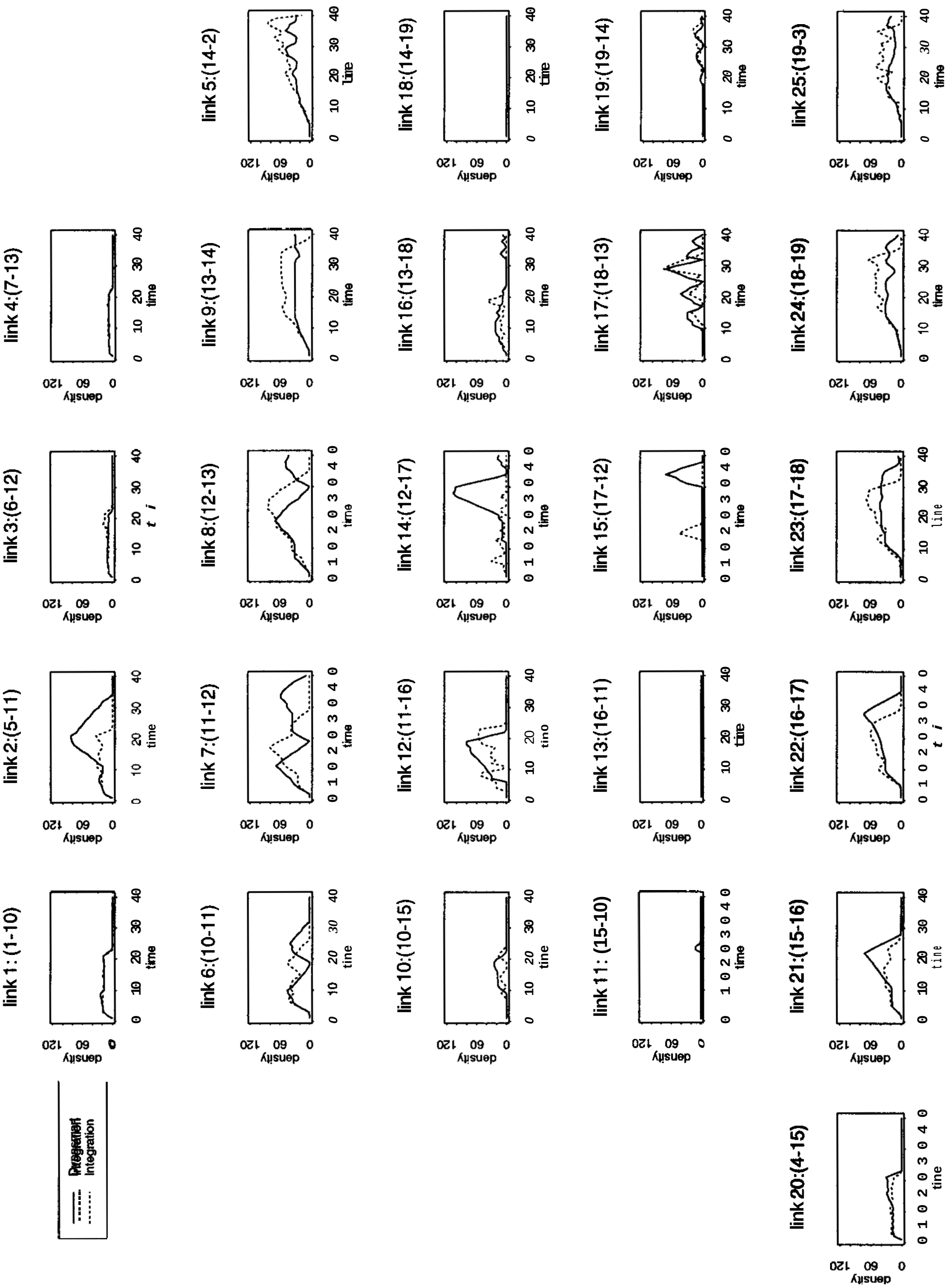


Figure 24: DYNASMART and INTEGRATION results for Scenario 13

	Scenario **11**	Scenario **12**	Scenario **13**
DYNASMART	**6.26** (min.)	**7.04**	**8.07**
INTEGRATION	**5.61**	**6.53**	**8.59**

Table 8: Averge travel time

scenario **11** to scenario **13** has an increase as high as **53%** in INTEGRATION, compared with a **29%** increase in DYNASMART. This can be explained by the result from traffic dynamics comparison. At the network level, vehicles from different origins to different destinations may interact with each other when they share some common paths. A long physical queue caused by a single bottleneck in one path could extend to other paths and becomes bottlenecks to vehicles on other paths. As shown in the section for traffic dynamics comparison, when it comes to congestion, DYNASMART usually has queues with higher densities than INTEGRATION. Consequently, the queues in INTEGRATION would influence a larger region than that in DYNASMART. It can be expected that the "queue-made bottlenecks" should be more severe in INTEGRATION than that in DYNASMART. Other results obtained from this study but not shown here also suggest that when the congestion level increases further, the average travel time from the two models becomes further apart.

8 Summary Remarks

This report is the second part of a series that covers the scope of study for MOU **148.** The traffic models selected for this study are DINOSAUR, DYNASMART, INTEGRATION, and METS. The areas of comparison comprise functionality, traffic dynamics, route choice mechanism, and network performance.

The output from our study shows that very different results can be produced by the different models even for the same scenario especially when queues are involved. This is understandable because models are not developed based on the same theoretical ground. Each model adopts its own rules to describe traffic dynamics. The discrepancy between these rules is less significant under free-flow traffic condition but becomes very different under congested traffic (as in the bottleneck and incident situations used in many scenarios in our study).

The choice of congested scenarios to evaluate various functions of the models is motivated by the fact that the very need for DRCTMs stems from the deficiency of static traffic flow models in describing congested traffic. In practice, it is the congestion in traffic that calls for attention and thus requires better management and better models to design control strategies. It should be noted that we are not in a position to determine which models are better since all of these models are still at a development stage. To users, caution should always be exercised in applying any traffic flow models. **A** better understanding of a model's internal mechanism and how it behaves in the simpliest scenarios would help users in determining the validity of the results.

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