TRAFFIC FLOW MODELING IN HIGHWAY NETWORKS

by

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(ABSTRACT)

The emergence of the Advanced Traffic Management System poses new challenges in traffic flow modeling of urban areas. The motivation of this project is to produce working freeway traffic simulations within a reasonable time-scale.

This project describes a *hybrid traffic modeling approach*, which is a combination of microscopic and macroscopic traffic modeling techniques. The traffic stream is composed of individual vehicles, while the interactions in the traffic stream are modeled macroscopically using the average speed-density relationship.

All existing freeway simulation models use the *time-driven* approach which advances the simulation clock after each fixed time-slice. However, this approach has a limitation of capturing the dynamic nature of traffic flow. The project proposes a new assumption of vehicular movement. This assumption leads to an easy implementation of a traffic simulation model using the *event-driven* approach which advances the simulation clock from one event to the next. The event-driven traffic model provides a new tool for the development of dynamic freeway simulation/assignment models.

A number of experimental results are provided from an empirical comparison of the event-driven approach versus the time-driven approach. These results indicate that the event-driven simulation model is competitive with the time-driven simulation model in both accuracy and efficiency. Finally, specific potential directions for future research are pinpointed.

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INTRODUCTION

1.1 Problem Statement

Growing traffic congestion in urban areas is drawing increasing attention from the public, government officials, and transportation professionals. Congestion results in closure of roads and reduction of traffic carrying capacity. Congestion on U.S. urban freeways, which carry nearly 30% of all traffic in urban areas, is estimated to cause 1.2 billion vehicle-hours of delay, 1.3 billion gallons of wasted fuel, and 9 billion dollars in excess user costs per year. Since urban freeway travel increases at a rate of 1.9% per year, the problem will continue to increase in severity [Lindley 1987].

Increasing the capacity of the highway by increasing the number of lanes is not always an acceptable solution. An alternative approach consists of exerting some kind of control over the flow of vehicles by means of signals, with the objective of avoiding unnecessary congestion and reducing the incident rate. Smulders [1990] addressed such freeway traffic control problems by means of the variable speed signs for the Dutch Motorway Control and Signaling System. This system allows the display of advisory speed signals to drivers and aims to improve traffic flow and safety, based on speed measurements and vehicle counts available at several locations along the freeway. Another approach is to *reroute* traffic through a highway network [Cremer and Fleischmann 1987 and Mahmassani et al. 1991].

This approach seems to be less well developed. The challenge is lack of a simulation model that is able to efficiently predict travel times and traffic densities for each link and each route of a network. It is the motivation of this project to solve this problem by appropriately modeling freeway flow on a computer.

There are three typical sources of congestion: (1) the general level of traffic along a link, including interactions between the traffic and the abutting land uses; (2) the junction delays and capacity restrictions due to the interactions and disruptions occurring when two or more traffic streams intersect; and (3) the adverse effects of incidents such as traffic accidents, road work, and sporting events. However, with the increasing traffic demand on a limited transportation infrastructure and the increasing sophistication of traffic control strategies, the comprehensive analysis of congestion is becoming increasingly complex. The process of describing such complex systems using only analytical or mathematical models can be difficult or even impossible. To progress beyond this point it is necessary to turn to a more sophisticated tool such as computer simulation.

In addition, it is an expensive operation to empirically study the effects of traffic management techniques on traffic flow and travel time along the highway network. Computer simulation models of traffic flow are also useful tools in this respect. Using a computer to simulate the operations of a real traffic network requires that a set of assumptions taking the form of logical or mathematical relationships be developed and shaped into a model. We can then use this model to gain an understanding of the dynamics at work in the transport network. The simulation program is evaluated numerically over a period of time, and statistical data is gathered to estimate the true characteristics of the actual system.

1.2 Simulation in Traffic Studies

Since the advent of electronic computers, traffic simulation was thought to be particularly useful for traffic studies. Traffic simulation is an attempt to replicate, on a computer, the sequence of events that make up a real transport system. There are many situations where simulation provides a powerful approach for transport professionals to assess the effects of changes in the traffic system and their consequences on its efficiency. A wide variety of specific or general purpose traffic simulation models have been built. These models can be classified into four groups [Young et al. 1989] according to their area of application:

1. *Transport and traffic demand models* which provide information on the overall demand for transport infrastructure in an urban context, such as EMME/2 [Florian et al. 1979], TRANSTEP [Nairn 1984], MICROTRIPS [Johnston 1984], MINUTP [UMTA 1985], and TRANPLAN [Benham, 1986].

2. *Dense network models* which are developed for the design of traffic networks, such as SATURN [Bolland et al. 1979], MULATM [Taylor 1988a,b], NETSIM [Lieberman et al. 1977 and Andrew et al. 1988], TRAFFICQ [Logie 1979], CONTRAM [Leonard 1978 and Leonard et al. 1989], TRANSYT [Vincent et al. 1980 and Wallace 1983], and METANET [Morin et al. 1991].

3. *Traffic route design or guidance models* which are developed for studying traffic movements on links, such as FREFLO [Payne 1979], INTRAS [Wicks et al. 1980], PASSER II [Rogness and Messer 1983], FREQ [Imada and May 1984], KONOS [Michalopoulos 1984], AUTOGUIDE [Jeffery 1987], and ROGUS [Harris et al. 1992].

4. *Intersection design models* which deal with the design of intersections, such as TEXAS [Lee et al. 1978], SIDRA-2 [Akcelik 1985], PICADY 2 [Semmens 1985], and INSECT [Nairn and Partners 1986].

There are a number of reasons for using simulation in traffic engineering in preference to other analysis techniques. Some prime reasons are as follows:

1. Reduce the risk and uncertainty associated with a given traffic system.

2. Allow experimentation to be made without disruptions to the existing system.

3. Allow concepts to be tested prior to installation.

4. Run the simulated system at speeds much greater than would be attainable in the real world.

5. Model any complex traffic system at any level of desired detail.

6. Model more realistically, with less need for dubious assumptions required by analytical models to make a complex system tractable.

7. Allow both input and output to be more extensive and more transparent.

8. Give insight to the true operating characteristics of the system being modeled.

However, the practice of simulation requires knowledge of a range of topics, including a detailed understanding of the situation to be modeled, insights into the modeling process, skills in correctly representing a model in computer-processable terms, data collection and analysis, design and conduct of experiments, analysis of output, and interpretation of results in the context of the situation that was modeled. Thus, there are a few *disadvantages* inherent with the use of simulation such as:

1. Time Consuming: Data collection, model development, analysis, and report generation will require a considerable amount of time.
2. Yields only approximate answers: Since a model is an approximation of the system being studied, it is computationally intractable to develop a full-scale representation for network transportation. In addition, simulation usually relies on the use of random number generators to provide model input, there is some uncertainty associated with the output that must be dealt with statistically. That is, all outputs are only estimates of the true behavior of the system.
3. Difficult to validate: When measurement of the real system does not exist, validation can become a formidable task.

The use of simulation can reduce the risk involved with implementing a new transport system or changing an existing one. However, unless simulation is used prudently, the possibility of developing an invalid model exists. There are several common pitfalls along the way to successful completion of a traffic simulation study [Law and Kelton 1991]:

1. Failure to have a well-defined set of objectives at the beginning of the simulation study.
2. Use of the false assumptions in model construction.
3. Selection of inappropriate level of model detail.
4. Failure to have people with operations-research and statistical training on the modeling team.
5. Failure to account correctly for sources of randomness in the actual system.
6. Making a single replication of a particular system design and treating the output statistics as the "true answers".

7. Poor selection of simulation software. Some commercial simulation software may not be well documented or implement the modeling logic desired.

In order to insure the success of a simulation project, care must be taken to avoid these pitfalls. To aid in the decision regarding credibility, McHaney [1991] has pinpointed six symptoms of a sick simulation. That is, if any of these symptoms is present, the credibility of the model should be questioned. The symptoms are as follows:

1. Inaccurate input data.
2. Improper run times.
3. Inconsistent output.
4. Vague references to assumptions.
5. Incomplete output.
6. No animation or detailed trace of events.

1.3 Background

1.3.1 Terminology

An important part of any discipline is developing a grasp of the terminology commonly used by its practitioners. Listed below are a few words and phrases with special meaning that are used in this project.

- **Model and Simulation**. A *model* is an abstraction of reality. *Modeling* is the process of building a model. *Simulation* is the process of defining, creating, and studying a model with the intention of drawing inferences and forming conclusions as to the behavior of the actual system. *Computer simulation* not only includes building a mathematical model for a system but also conducting experiments with this model on a computer.

- **State Variables and Events**. The variables whose values define the state of the system are called *state variables*. An *event* denotes a change in the state of the system being simulated, and contains a time-stamp that indicates when this change occurs. There are two distinct types of events:

1. a *bound (i.e., unconditional) event* is one whose occurrence is predictable and can thus be scheduled;
2. a *conditional event* is one whose occurrence is dependent upon the fulfilment of certain conditions.

- **Deterministic and Probabilistic Models**. If the output of a model can be predicted with certainty, it is a *deterministic model.* A *probabilistic model*, on the other hand, gives a different result on repetitions for the same set of input parameters.
- **Static and Dynamic**. A model in which time is not a variable is called *static.* If the system state changes with time, the model is *dynamic.*
- **Discrete Simulations and Steady-State Simulations**. A *discrete simulation* is a simulation where the state of the system changes only at some discrete points in time. A variable is in a *steady state* if its average value remains the same over the time period under consideration. A *steady-state simulation* is one where each output variable will attain a steady state after a long enough period of time.
- **Simulation Clocks and Simulation Strategies**. Each simulation has a global variable called *simulation clock* representing the current value of simulated time. The simulation clock has two features different from the physical system *real time*: (1) starting with zero; and (2) stopping at some (pre-specified) time. A *simulation strategy*, also referred to as a *world view* or *conceptual framework*, is an underlying structure and organization of ideas which constitute the outline and basic frame that guide a modeler in representing a system in the form of a model [Derrick 1992].

1.3.2 System Identification and Model Scope

System identification establishes relationships between an analyzer and some part of reality. A *system* is defined as a collection of objects, their relationships and behavior relevant to a set of purposes, characterizing some relevant part of reality. That is, modeling should be a purpose-driven activity, and a model's validity always depends on objectives and context of its application [Kreutzer 1986]. The objectives specify what questions the simulation needs to answer.

Model scope is defined as that portion of the system that will be represented by the model. The necessary level of detail is a determination of how closely the model has to emulate the real world system to still provide the required information [McHaney 1991]. Since a model is an approximation of the system being studied, it is not always best to develop a full-scale representation. Modeling in too much details leads to excessive development time. On the other hand, too little detail may result in a model that does not realistically predict actual world behavior. Therefore, it is very important to the success of a traffic simulation project for us to insure that the model adequately reflects transport network operation.

1.3.3 Queueing Systems

Queues are a common aspect of any irregular process operating in an environment with limited capacity. A **queueing system** consists of a service facility that provides service of some kind to arriving customers. The service facility requires a certain time to serve each customer and is capable of serving only a limited number of customers at a time. If customers arrive faster than the facility can serve them, they must wait in a queue for facility. In the highway network, customers are vehicles and servers are the transportation infrastructure such as links and intersections. *Congestion* will occur in the system if there is sufficient irregularity. To predict and prevent congestion the system must be specified in sufficient detail, usually including the following three basic components:

- *Arrival pattern* describes how customers arrive to the system, including both the average rate of arrival for customers and the statistical pattern of the arrivals.
- *Service mechanism* specifies the condition of servers, such as whether each server has its own queue or there is one queue feeding some servers, how many customers can be served at one time, and how long each service takes.
- *Queue discipline* refers to the rule that a server uses to choose the next customer from the queue (if any) when the server is available.

1.4 Project Organization

This chapter introduces background material and some basic simulation concepts used in this project. Chapter 2 describes two typical discrete-event traffic simulations, and covers some simulation methodologies such as how to test a traffic simulation model and how to obtain desired results from a simulation.

Chapter 3, 4 and 5 form the core of the project. Chapter 3 reviews the previous work in modeling network traffic and then focuses on describing a hybrid traffic modeling approach. Chapter 4 describes the implementation of the time-driven and event-driven traffic simulation models. Chapter 5 focuses on comparing these two models by some typical experiments.

Finally, Chapter 6 presents conclusions on this research and pinpoint some potential directions for future research.

1.5 Summary of Contributions

This project gives the following eight significant contributions:

1. Summarizes previous work in traffic simulation, including traffic model classification, traffic simulation advantages and disadvantages, and pitfalls in traffic modeling.

2. Builds the fundamental relationship among volume, density and speed from Little's Law.

3. Presents a hybrid traffic modeling approach, which is a combination of microscopic and macroscopic traffic simulation techniques.

4. Modifies and implements a time-driven simulation model of network traffic flow.

5. Designs, creates and implements an event-driven simulation model of network traffic flow, which opens a new simulation environment for network traffic study.

6. Develops a series of traffic simulation routines that range from vehicle generation to output analysis. These routines are flexible and well-documented.

7. Presents three typical scenarios for traffic simulations that can be combined to form more complicated traffic networks, and conducts experimental comparisons between the event-driven and time-driven simulations.

8. Proposes a concurrent algorithm for parallel traffic simulation and some suggestions for future work.

Chapter 2

BUILDING A TRAFFIC SIMULATION

Many traffic simulations use *discrete-event simulation models.* Although these traffic simulations have their different objectives and utilities, their models still share a number of common components and a logic organization for these components. These components include:

- Data Structures for System State Variables: These are global variables necessary to describe the state of system.
- A Simulation Clock: To keep track of simulation process dynamically.
- Event Routines: Each event is simulated by its routine. These routines update the system state variables and schedule other events.
- Initialization Routines: These set the initial state of the system state variables and initialize various random-number generation streams.
- Input Routines: These get the model parameters, such as physical features for each link segment.
- Statistical Records: These data structures store statistical information used later to compute the desired measures of performance.
- Report Generators: These are the output routines executed at the end of the simulation. They calculate the final result from the statistical records and print in a specified format.

- Main Program: This brings all the routines together. It calls input routines, initializes the simulation, executes various iterations, and finally, calls the report generators.

In practice, the selection of a simulation strategy is critical for the modeler. The appropriate selection enables a modeler to implement a simulation with significantly reduced complexity [Balci 1988]. There are two selection guidelines for modelers:

1. Understand the problem domain, since some specific problems match one simulation strategy better than another.
2. Consider simulation model characteristics such as maintainability, efficiency, modifiability, reusability, and ease of development.

There are two typical approaches that may be used in traffic simulations: *time-driven* and *event-driven* approaches.

2.1 Time-Driven Approach

The *time-driven* approach updates the simulation clock at discrete points in time to keep track of the physical positions of vehicles on the roadway. The simulation begins with the traffic system in its initial state at time T_0. The time clock is then advanced one increment, ΔT, to $T_0 + \Delta T$, and the updated state of the system is determined. This process is repeated until the simulation is complete. The time-driven approach is most appropriate when there are a large number of events to be considered or events are not discrete. We refer to a traffic simulation as a *Time-Driven Simulation (TDS)* if the simulation uses the time-driven approach.

2.2 Event-Driven Approach

The *event-driven* approach advances the simulation clock only when the next event occurs. We refer to a traffic simulation as an *Event-Driven Simulation (EDS)* if the simulation uses the event-driven approach.

Event scheduling is the most commonly used simulation strategy when implementing an EDS in a high-level programming language. Under this simulation strategy, the modeler considers the system of interest to be described in terms of *events.* An *event routine*, a set of actions following a state change in the system, is associated with an event. After initialization, the next event is determined and executed. The simulation clock is updated at this time. The event routine associated with the next event is then executed. When applicable, the conditions for termination of the simulation are checked. If the termination condition is satisfied, the simulation output is produced and the simulation ends. Otherwise, the (new) next event is selected and the algorithm repeats itself.

Event routines associated with unconditional events can be explicitly scheduled with the implementation of an *event-set algorithm*, an algorithm that facilitates the selection and processing of events. Two operations are performed frequently on this set — one to insert new events in the set and one to find the next event and remove it from the set. The choice of the data structure used to maintain the event set affects the processor time required for the two operations. A popular *event-set algorithm* is to keep an ordered linked list of future event records. Each record contains the time at which the event should occur and a pointer to the code that must be executed at that time. Conditional events occur at the satisfaction of some set of conditions that cannot be predicted in advance. The checks for conditional events are contained within unconditional event routines.

The simulation termination condition is usually based on the number of departures in a queueing network, and thus needs to be checked after executing the events associated with departures. However, other events (e.g., arrivals) do not affect this termination condition, so the termination condition does not need to be tested after completion of these routines.

2.3 Simulation Models as a Black Box

To consider a simulation as part of a decision-making process, it is helpful to regard the simulation model as a *black box* that frees us from the complicated internal logic of the

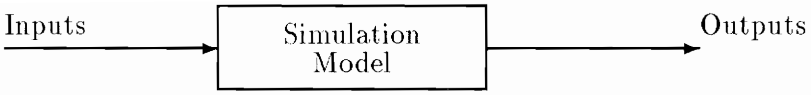


Figure 2.1: Black-Box View of a Simulation Model

simulation model. Figure 2.1 shows a simulation as a black box together with the inputs to and the outputs from the model. Generally, the inputs to the model include the physical and operational features of a highway network such as:

1. Arrival pattern of each source
2. Number of links
3. Length of each link
4. Number of lanes for each link
5. Free flow speed for each link
6. Capacity for each link
7. Number of intersections
8. Control pattern for each intersection
9. Incident pattern, which describes how incident occurs and disappears
10. Geometric features of each link

The outputs from the simulation include the following three network characteristics:

1. *Travel cost*, including mean travel time for each link and each route.
2. *Average density* for each link and each freeway
3. *Mean traffic volume* for each link.

From the black-box point of view, we find Little's law [Little, 1961] that can be used to relate the mean number of vehicles with the mean travel time on a network (link):

$$\text{Mean vehicle number } (N) = \text{Traffic arrival rate } (q) \times \text{Mean travel time } (t)$$

where *traffic arrival rate* (q) is the average number of vehicles passing a source in a link (segment) per unit of time, or traffic *volume* at that source.

Let L be the length of a link (segment), then the above formula is equivalent to the following equation:

$$q = \frac{N}{L} \times \frac{L}{t} \tag{2.1}$$

Equation 2.1 actually describes the following fundamental relationship of the three basic traffic characteristics (*volume, density* and *speed*):

$$q = KV \tag{2.2}$$

where V is the average speed of vehicles along the link (segment) at some instant, and K is the mean density, or the average number of vehicles occupying a unit length of lane.

Notice that Little's law can be used as long as the number of the vehicles entering the network (link) is equal to those exited from the network (link). That is, inside the network (link) no new vehicles are created and no vehicles are lost.

2.4 Validation and Verification

Validation is the process of making sure that the simulation model accurately represents the system being modeled [Balci 1991]. Validation deals with building the *right* simulation model. A valid model would possess a sufficiently accurate representation of the problem.

Verification is the process of making sure that the simulation model has been transformed from one form (i.e., conceptual model) into another (i.e., working simulation model) as intended with sufficient accuracy. Verification deals with building the simulation model *right*. Sometimes, model verification and model validation are referred to as *model testing* [Balci 1991].

2.5 Transient Removal and Stopping Criteria

After model development is complete, we need to decide how many of the initial observations should be discarded to ensure that the model has reached a steady state and how long to run the simulation. These two issues are called *transient removal* and *stopping criterion*, respectively [Law and Kelton 1991].

Our network traffic flow simulation is intended to be a steady-state simulation. Only the *steady-state performance*, that is, the performance after the system has reached a stable state, is of interest. The results of the initial part of the simulation should not be included in the final computations. This initial part is called the *transient state*, and the time interval associated with the transient state is called the *warmup period.* The main difficulty of transient removal is that it is impossible to define exactly what constitutes the transient state and when that transient state ends. All methods for transient removal are therefore heuristic.

For traffic simulations, we find that *Welch's procedure* [Welch 1983] is the most useful method to determine the warmup period. To reduce the effect of randomness, the method requires first averaging across several replications. Each replication consists of a complete run of the simulation with no change in input parameter values. The replications differ only in the seed values used in the random-number generators. Averaging across the replications results in an average trajectory $\overline{Y}_i$. To further smooth out $\overline{Y}_i$, the method defines the moving average $\overline{Y}_i(w)$, where w called *window* is a positive integer less than half size of each replication.

Suppose there are n replications of length m each. Let Y_{ji} denote the ith observation in the jth replication ($j = 1, 2, ..., n; i = 1, 2, ..., m$). Welch's procedure consists of the following three steps:

1. Get an average trajectory across replications: $\overline{Y}_i = \frac{1}{n}\sum_{j=1}^{n} Y_{ji}$, $i = 1, 2, ..., m$
2. Compute the moving average $\overline{Y}_i(w)$ as follows:

$$\overline{Y}_i(w) = \begin{cases} \frac{1}{2i-1}\sum_{s=-(i-1)}^{i-1} \overline{Y}_{i+s} & \text{if } 1 \le i \le w \\ \frac{1}{2w+1}\sum_{s=-w}^{w} \overline{Y}_{i+s} & \text{if } w+1 \le i \le m-w \end{cases}$$

3. Plot $\overline{Y}_i(w)$ for $i = 1, 2, ..., m - w$ and choose l to be that value of i beyond which $\overline{Y}_1(w)$, $\overline{Y}_2(w)$, ... appears to have converged. The value of l is the warmup period.

It is important that the length of the simulation be properly chosen. If the simulation is too short, the results may be highly variable. On the other hand, if the simulation is too long, computing resources and manpower may be unnecessarily wasted. Generally, the simulation should be run until the confidence interval for the mean response narrows to a desired width. If the sample mean is $\overline{x}$ and its variance is $Var(\overline{x})$, a $100(1-\alpha)\%$ confidence interval for the mean is given by $[\overline{x} - z_{1-\alpha/2}Var(\overline{x}), \overline{x} + z_{1-\alpha/2}Var(\overline{x})]$, where $z_{1-\alpha/2}$ is the $(1 - \alpha/2)$th quantile of a unit normal variate. Some commonly used normal quantiles are: $z_{0.95} = 1.645, z_{0.975} = 1.960, z_{0.99} = 2.326$, and $z_{0.995} = 2.576$.

We use a statistical method called *replication/deletion approach* to obtain an estimate and confidence interval for $\overline{x}$. The method consists of conducting n replications of size $m+l$ each, where l is the warmup period determined by Welch's procedure and m is much larger than l [Law and Kelton 1991]. The remaining steps are as follows:

1. Compute a mean for each replication: $\overline{x}_j = \frac{1}{m}\sum_{i=l+1}^{l+m} x_{ji}$, j = 1,2,...,n
2. Compute an overall mean for all replications: $\overline{\overline{x}} = \frac{1}{n}\sum_{j=1}^{n} \overline{x}_j$
3. Calculate the variance of replicate means: $Var(\overline{x}) = \frac{1}{n-1}\sum_{j=1}^{n}(\overline{x}_j - \overline{\overline{x}})^2$

The confidence interval for $\overline{x}$ is $[\overline{\overline{x}} - z_{1-\alpha/2}Var(\overline{x}), \overline{\overline{x}} + z_{1-\alpha/2}Var(\overline{x})]$. Notice that this method requires discarding nl initial observations, and the confidence interval width is inversely proportional to $\sqrt{mn}$. Thus, a narrower confidence interval can be obtained equally well by increasing either m or n. However, to reduce the waste (nl initial observations), we usually keep n fairly small (e.g., 10) and take m big enough to obtain the desired confidence.

Chapter 3

MODELING NETWORK TRAFFIC FLOW

A congestion problem may be analyzed as follows:

1. Identify the congestion influence area.
2. Collect data on network geometries and origin-destination demands.
3. Assign traffic and simulate different control strategies.
4. Evaluate alternatives and select the best of traffic control strategies.

The core of this solution is the third part. Most assignment models proposed in the literature are made up of different modules simulating *demand* (drivers' choice behavior) and *supply* (network flows and costs). A *static* assignment model cannot deal with variations in demand and supply. Since traffic flow is always fluctuating, it is difficult to determine precise travel time before a trip is made. However, a number of experiments have shown that traffic can be brought much closer to the equilibrium [Sheffi, 1985] if adequate information on the route choice is given to drivers. Therefore, a *dynamic* traffic model is required and must be fast enough to provide predictive information under changing conditions [Ben Akiva et al. 1991]. This chapter addresses the modeling methodology involved in producing working freeway simulations within an efficient computing environment.

3.1 Previous Work in Traffic Modeling

Dynamic modeling of network traffic is generally considered to be a complex problem. The challenge is lack of a perfect modeling tool that would reflect a comprehensive theory covering (in a consistent fashion) all aspects of vehicular movement in the network. Such a theory remains a remote prospect, even to the optimists among traffic theorists [Young et al. 1989]. Theoretical studies in the past introduced a number of simplifications such as:

1. Steady-state instead of time varying conditions [Payne and Thompson 1974].
2. Single destination networks [Mahmassani et al. 1988 and Wie 1991].
3. Fixed route choice or fixed traffic demand at the origins [Gazis 1974, Bolland et al. 1979 and Papageorgiou 1990].

Traffic simulation models can be typically divided into two categories in terms of their representation of traffic: (1) *microscopic models* that consider traffic as *individual* vehicles, and simulate their trajectories as they traverse the roadway; and (2) *macroscopic models* that treat traffic as vehicle flows (i.e., platoons), and simulate the flow behavior as a whole.

3.1.1 Microscopic Models of Traffic Flow

Microscopic models of traffic flow are derived from the behavior of the individual driver and seek to describe his dynamic reaction to various external influences. There are two dimensional reactions for the driver: (1) to accelerate or brake in an effort to maintain his desired speed without running into the vehicle ahead; and (2) to change lanes.

Work on the first aspect has largely concentrated on *car-following* models, which have the general form [Young et al. 1989]:

$$a_n(t+\tau) = \frac{l_n(V_{n-1}(t) - V_n(t))|V_{n-1}(t) - V_n(t)|^{m-1}}{[P_{n-1}(t) - P_n(t) - S_{n-1}]^p}$$

where $a_n(t+\tau)$ is the acceleration of vehicle n at time $t+\tau$; τ is reaction time; l_n, m, and p are parameters that need to be estimated; S_n is the effective length of vehicle n; and, $P_n(t)$ and $V_n(t)$ are the location and speed of vehicle n at time t, respectively.

Although car-following models have served well in many situations, they are not well-suited for use in traffic flow simulation. They are essentially designed as continuous functions, and to maintain stability in a simulation environment where position, speed and acceleration are updated at discrete points in time, it is desirable for the interval between successive recalculations to be a fraction of the reaction time. This requires storing large quantities of historical data and takes considerable computing time to evaluate general power functions.

However, *lane-changing models* are much more complex than car-following models because the decision to change lanes depends on a number of objectives, and at times they may conflict. There are lack of well-defined lane-changing models.

The most widely-used microscopic model is NETSIM which is a stochastic simulation model of traffic movement on networks [Lieberman et al. 1977 and Lieberman 1981]. The network is described as a set of unidirectional links and nodes. The simulation logic uses the *time-driven* approach with a *one second* time-slice. Vehicle motion is governed by car-following, lane changing and queueing algorithms, vehicles being randomly assigned characteristics on entry to the network. A recent version of NETSIM has the feature of graphic input/output displays [Andrew et al. 1988]. However, NETSIM still has "bugs" and needs to be refined.

3.1.2 Macroscopic Models of Traffic Flow

Macroscopic models typically consider traffic as composed of the movements of platoons. A *platoon* is a group of vehicles, traveling at short headways and moving at roughly the same speed. Platoons are created at network locations corresponding to origins of transportation demand at a given time, travel through the network and disappear at their destination. The majority of existing freeway simulation models falls into the category of macroscopic models. There are three popular macroscopic models:

- SATURN is a static equilibrium assignment program [Bolland et al. 1979], based on a *time-driven* simulation model of intersection delays. For signalized links travel times are estimated using a platoon dispersion approach [Young et al. 1989]. The solution algorithm requires flow/delay relationships for a link as a function of link flow. SATURN assumes the total traffic volume over time to be static.

- CONTRAM is a *time-driven* traffic model, which uses an iterative procedure to assign vehicles to their minimum cost routes through a network under a user-imposed traffic demand [Leonard 1978 and Leonard et al. 1989]. CONTRAM is a time-dependent model that predicts flows, queues and routes of vehicles at each time interval over the simulation period. CONTRAM is not based on a mathematical solution for an equilibrium equation, and so is not guaranteed to converge to a solution.
- *Macroparticle Simulation Model* (MPSM) is a deterministic, time-driven traffic model to simulate vehicular movement on freeways and arterials given time-dependent input functions [Chang et al. 1985 and Mahmassani et al. 1988].

In dynamic modeling of network traffic, MPSM has played an important role and initiated this research work. We follow to discuss MPSM in more detail.

Recently, MPSM uses a time-slice of *0.1 minute* [Mahmassani et al. 1991] to update the position of vehicles. The MPSM logic, adapted from plasma physics [Leboeuf et al. 1979], is retained for traffic movement on individual links. Traffic is not treated as a compressible fluid; vehicles are moved in *macroparticles* at the prevailing local speeds, consistent with a relation between the average speed and the prevailing density. Here macroparticle means that a group of vehicles always move together like a packet. Formally, MPSM assumes that:

- Traffic demand and system capacity is fixed over the simulation period.
- Vehicles move along each link as a collection of macroparticles with fixed sizes.
- Time is discretized into small fixed time-slices, and each link can be divided into a set of segments such that all macroparticles on a segment travel at the same mean speed during each time-slice.
- Each macroparticle movement satisfies the following modified Greenshields model:

  $$V = V_0 + (V_f - V_0)(1 - K/K_j)^\alpha$$

  where V and K are the average speed and density, respectively, in the given segment; V_f and V_0 are the free mean speed and minimum speed, respectively; K_j is the jam density; and α is a speed-density parameter.

These assumptions provide a macroscopic and discrete representation of traffic flow. Since MPSM assumes that the state of the network is changed at the end of each time-slice, MPSM is well-suited to implementation by the time-driven approach. However, MPSM assumptions are not realistic in that the arrivals of newly entered vehicles can affect the behavior of vehicles further along in the same segment, because the speed of all vehicles on the segment slows down when the number of newly entered vehicles is more than the number of vehicles exiting that segment during the same time-slice. The validity of the model is lowered in that the size of each macroparticle assumes as constant throughout the network. The macroparticle also makes a conflict with a dynamic assignment requirement that simulation models be applied at the individual driver level. An alternative is to formally move vehicle one by one, this has been mentioned in their recent version [Mahmassani et al. 1991]. In addition, MPSM has the following disadvantages:

- MPSM uses uniform arrival patterns and introduces new vehicles only at the end of some time-slices.
- Accuracy of simulation outputs is sensitive to the selection of a time-slice (ΔT). Smaller ΔT may or may not increase accuracy but must cost much longer execution time.
- The time-slice length specifies the dynamic resolution and limitation of the model, because MPSM assumes the modeled quantities (e.g., density and congestion) remain constant with a given time-slice.

3.2 A Hybrid Modeling Approach

Since there is no precise traffic flow theory that can be used to build a "perfect" model, we should abandon models that prove to be too intractable, either mathematically or computationally. For this reason, the microscopic model like NETSIM can not be used to perform real-time traffic management of the highway network. However, some macroscopic models like SATURN assume traffic to be uniformly distributed during the modeled time interval and fails to capture essential features of traffic congestions [Ben Akiva et al. 1991]. To improve traffic modeling, an alternative approach turns to a combination of microscopic and macroscopic modeling techniques, or a *hybrid modeling approach.* That is, we consider the traffic stream as individual vehicles, but model their interactions macroscopically using the average speed-density relationship. Our motivation is to use this kind of approach to develop a traffic model that can be applied at the individual driver level and operated in a real-time, or at least efficient, computing environment.

We describe the hybrid modeling approach by considering the three key issues of traffic modeling: vehicle generation, network representation and vehicular movement.

3.2.1 Vehicle Generation

Vehicle generation describes how a traffic model generates or introduces simulated vehicle arrival at a study network, or generates an *arrival pattern.* The arrival pattern can be modeled by using the vehicle interarrival times (i.e., the times between two successive arrivals) at each entry (source) to a network. These interarrival times are also called *headways* in traffic simulation study. Headways at sources usually follow specific distributions, which can be determined from observation and data analysis. A *time-dependent arrival pattern* is required for a dynamic network flow modeling. That is, the arrival pattern should vary with time.

For our present experiments, we simply use the negative exponential distribution to represent the interarrival times. The probability density functions for this distribution is:

$$f(t) = qe^{-qt}$$

Let $F(t) = \int_0^t f(s)ds$, then $F(t) = 1 - e^{-qt}$ or,

$$t = -\frac{1}{q}ln[1 - F(t)]$$

Hence, if the distribution of $F(t)$ is uniform between zero and one, the above equation will generate headways in traffic. However it is not completely satisfactory when dealing with reasonably heavy traffic flows, as the negative exponential distribution tends to overestimate the number of small headways (between zero and two seconds). To overcome this a

displaced exponential distribution is used [Young et al. 1989]. This distribution has no headways less than a certain minimum size, τ, called by the *headway-threshold.*

The probability of a headway greater than τ is given by

$$F(t) = 1 - exp[-q(t - \tau)/(1 - q\tau)]$$

or,

$$t = \tau - (\frac{1}{q} - \tau)ln[1 - F(t)]$$

Thus, the arrival pattern at a specified source s is:

$$t_n(s) = t_{n-1}(s) + \tau - (\frac{1}{q(s)} - \tau)ln(R) \tag{3.1}$$

where $t_n(s)$ is the arrival time (second) of the n-th vehicle at source s,

τ is a constant and usually $0.0 < \tau \leq 2.0$,

$q(s)$ is the *arrival rate* (vehicles/lane/second) at source s and less than $1/\tau$, and

R is a random number between zero and one.

Arrival rate $q(s)$ is usually computed from the statistics of traffic data at source s during some specified time interval. Let the total arrivals of vehicles during the measured period (T) be $N(T)$, then $q(s) = N(T)/T$.

However, as a module of our traffic models, vehicle generation is able to support a variety of traffic headway distributions at each source in the network. The module is also capable of running on trace data from traffic sensors. Sometimes, we can generate or prepare arrival times for all vehicles before the simulation and store these in a file. Then, the module of vehicle generation may read these data in the file.

3.2.2 A Flexible Network Representation

A *highway network* consists of a set of nodes and a set of links. The nodes are the intersections in the network where different traffic streams interact each other. The links are

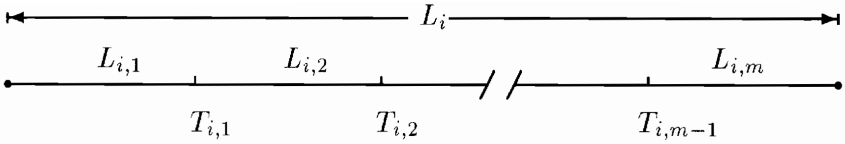


Figure 3.1: A Division of Link L_i

Table 3.1: The Representation of a Segment

ATTRIBUTE		*MEANING*
NAME	SYMBOL	
SegmentID	$L_{i,j}$	the identifier of the segment
Length	$\Delta L_{i,j}$	the length of the segment
JamDensity	$K^J_{i,j}$	the density at which all movement stops on the segment
FreeFlowSpeed	$V^F_{i,j}$	the free-flow speed of the segment
MinSpeed	$V^J_{i,j}$	the minimum speed on the segment
SD_Parameter	$\Theta_{i,j}$	sensitivity of speed to changes in density
NumLanes	$l_{i,j}$	the number of lanes of the segment

the road sections between intersections. Traffic movement takes place along each link, and vehicles can only change their general direction of travel at the nodes. The characteristics of a route from an origin to a destination is the sum of the characteristics (e.g., travel time) of all the links that form the route. Users prefer a route that provides characteristics that satisfy some particular objectives (e.g., minimum travel time, or minimum cost).

A flexible network representation is necessary to accurately predict dynamic traffic characteristics. The network representation should be easily adapted and modified to better reflect the driver's perception of the network. For this reason, we divide each link L_i into a set of link segments $L_{i,j}$ by adding *dummy nodes* $T_{i,j}$ at the end of segment $L_{i,j}$, as shown in Figure 3.1. It is suggested that segment length not exceed 1 mile [Chang et al. 1985]. Each segment requires homogeneous geometry and similar physical features which may be represented by the data structure shown in Figure 3.1.

After the original network is divided, the "divided" network and the associated data structures for these segments constitute a **network representation**. However, the dynamic nature of a traffic model requires that a network have different representations in peak hour as opposed to off-peak, on sunny days as opposed to rainy, on weekends as opposed to week days, in day as opposed to night, and so on. Therefore, a network representation should be associated with some *time domain*, say, $[a, b]$, where the length of $[a, b]$ reflects the dynamic nature of traffic flow. In addition, since each model has its own specific assumptions, different models may require different network representations.

In the following section, we will see this data structure of the link segment is well-suited to represent two modified Greenshields models.

3.2.3 Vehicular Movement: Two Assumptions

Giving a network representation during $[a, b]$, let $Q_{i,j}(t)$ be the number of vehicles on segment $L_{i,j}$ at time $t \in [a, b]$. Since the *mean density* of a segment is the average number of vehicles per lane-mile in that segment, we may calculate the mean density $K_{i,j}(t)$ of segment $L_{i,j}$ at time t by the following formula:

$$K_{i,j}(t) = \frac{Q_{i,j}(t)}{l_{i,j} \times \Delta L_{i,j}}$$

To predict the dynamics of network traffic flow, we present two formal assumptions of vehicular movement. The first assumption is formulated according to the logic of MPSM [Mahmassani et al. 1988 and 1991]:

Assumption 1 *Given a network representation during $[a, b]$ and a fixed time-slice (ΔT), all vehicles on a segment ($L_{i,j}$) travel at the same mean speed during each ΔT, which is determined by the following equation:*

$$V_{i,j}(t) = V_{i,j}^J + (V_{i,j}^F - V_{i,j}^J)(1 - \frac{K_{i,j}(t)}{K_{i,j}^J})^{\Theta_{i,j}} \tag{3.2}$$

where $V_{i,j}(t)$ is the mean speed for all vehicles in $L_{i,j}$ during the t-th time-slice in $[a, b]$.

Assumption 1 implies that vehicles change their (mean) speeds after each time-slice (ΔT), and leads to an easy implementation for the time-driven simulation. However, as previously described, **Assumption 1** is not realistic in that the arrivals of newly entered vehicles in a segment affect the behaviors of vehicles that previously entered that segment, because **Assumption 1** implies that the mean speed of all vehicles on a segment slows down (speeds up) when the number of newly entered vehicles is more (less) than the number of the vehicles just exiting that segment. In addition, **Assumption 1** increases the sensitivity of the model's accuracy to the selection of the time-slice, and leads to the constant state of the modeled quantities such as traffic flow and congestion during the given time-slice. Therefore, the time-slice length (ΔT) specifies the dynamic resolution and limitation of the traffic model based on this assumption. We call equation 3.2 the *modified Greenshields model I.*

To further improve traffic modeling, we present a new assumption:

Assumption 2 *Given a network representation during* $[a, b]$, *the average speed of each vehicle* (n) *on a segment* $(L_{i,j})$ *can be determined by the following equation:*

$$V_{i,j}(n) = V_{i,j}^J + (V_{i,j}^F - V_{i,j}^J)(1 - \frac{K_{i,j}(t(n))}{K_{i,j}^J})^{\Theta_{i,j}+\epsilon} \tag{3.3}$$

where, $t(n)$ *is the time when vehicle* n *is entering* $L_{i,j}$, ϵ *is a constant, and* $V_{i,j}(n)$ *is the average speed of vehicle* n *on* $L_{i,j}$.

Assumption 2 means that each vehicle determines its average speed on a segment when it enters that segment, and thus this average speed determines its travel time on the segment. That is, **Assumption 2** implies that each vehicle may change its average speed after each segment ($L_{i,j}$), and leads to an easy implementation for the event-driven simulation. Since different vehicles may have different speeds on a segment at any time, there is no limitation of dynamic resolution for the model caused by **Assumption 2**. Therefore, **Assumption 2** seems more realistic than **Assumption 1**, and provides a new theoretical tool for the development of dynamic traffic models.

We call equation 3.3 the *modified Greenshields model II*, by which the *travel time* $t_{i,j}(n)$ for vehicle n on $L_{i,j}$ can be easily obtained by $\Delta L_{i,j}/V_{i,j}(n)$. In contrast, we cannot directly compute the travel time $t_{i,j}(n)$ for vehicle n on $L_{i,j}$ by equation 3.2. Instead, $t_{i,j}(n)$ is obtained by adding all time-slices during which vehicle n traveled entirely on $L_{i,j}$ plus the appropriate fractions of the time-slices when vehicle n entered and exited $L_{i,j}$. Therefore, equation 3.3 can be used to compute the travel time for each vehicle on a segment more efficiently than equation 3.2.

For both assumptions, the travel time $t_i(n)$ of vehicle n through link L_i is the sum of all travel times for n on the segments making up L_i: $\sum_j t_{i,j}(n)$. The *total travel time* $t(n)$ of vehicle n is the sum of all travel times for n on the links making up its route: $\sum_i t_i(n)$. The *mean travel time* for N vehicles on the same route is $\sum_{n=1}^{N} t(n)/N$. When N is large enough, we refer to this mean travel time as the *mean travel time of the route.*

Notice that a *traffic jam* occurs in link L_i when $K_{i,j}(t)$ for $L_{i,j}$ (i.e., a segment of L_i) equals or exceeds the jam density $K^J_{i,j}$. In this case, our implementation holds all vehicles that intend to enter $L_{i,j}$ on a queue before $L_{i,j}$ until $K_{i,j}(t)$ falls below $K^J_{i,j}$. A *queue discipline* is required, which describes how vehicles are to be selected for service from the pool of vehicles that have arrived at the queueing node. We use the standard *First-In and First-Out* principle to process vehicle arrivals on a node.

3.3 Summary

In this chapter, we evaluate the previous work in freeway traffic modeling. All existing freeway simulations use the time-driven approach. We describe a hybrid traffic modeling approach through vehicle generation, network representation, and vehicular movement. The hybrid modeling approach is a combination of microscopic traffic modeling techniques and macroscopic modeling logic of traffic flow. That is, the traffic steam is composed of individual vehicles, while the interactions in the traffic stream are modeled macroscopically using the average speed-density relationship, and microscopic details of car following, lane changing, and signalized operation at junctions are not modeled.

A network representation depends on modeling requirements, along with physical road and traffic conditions. A proper representation will enhance the credibility of a traffic model. Since the speed-density parameters considerably affects the accuracy of simulation results, they should be estimated by considering weather conditions and vehicle types as well as physical road conditions.

The modified Greenshields model II makes it easy to compute the travel time of a vehicle on each segment and route. **Assumption 2** leads to an easy implementation of an event-driven simulation.

Chapter 4

IMPLEMENTATION OF TWO TRAFFIC MODELS

Chapter 1 introduced the concept of time-driven simulation and event-driven simulation. Chapter 3 described the two assumptions of vehicular movement. This chapter describes the implementation of a modified time-driven simulation and the event-driven simulation based on these assumptions.

4.1 A Modified Time-Driven Simulation

According to **Assumption 1** and the time-driven approach, we have implemented a *modified* time-driven traffic simulation model (MTDS). The simulation begins with the first vehicle in the network at simulation clock, $t = 0$. The time clock is then advanced one time-slice to ΔT, the positions of vehicles in the network are updated, and new states of each link and the network are determined. This process is repeated until the termination condition of the simulation is reached. Figure 4.1 show the simulation logic of MTDS. Here the major object of interest is the vehicle which has a data structure with it, as shown in Table 4.1. MTDS supports random arrival patterns and simulates vehicular movement one by one. MTDS loads each vehicle immediately when it arrives at a source. The mean

Table 4.1: The Data Structure of a Vehicle

ATTRIBUTE	*MEANING*
ArrivalTime	the time when the vehicle entered the network
VehType	the type of the vehicle
RouteNo	the number of the route the vehicle is taking
Position	the current position of the vehicle
TravelTimeOnL[i]	the travel time of the vehicle on Link[i]

speed of a new arrival, during the fraction of some time-slice, is dependent on the number of vehicles on its entering segment. Sometimes, we use MTDS-ΔT to represent the MTDS with the time-slice ΔT *(seconds)*.

The major loop of MTDS-ΔT keeps track of the physical positions of vehicles by advancing the simulation clock in increments of ΔT. Each route has an associated *vehicle queue*, which is sorted by the distances from the locations of vehicles to the destination along this route. A *PositionUpdating routine* is used to update the positions of a vehicle queue for each time-slice ΔT. Let $P_{i,j}(n,t)$ denote the position of vehicle n in $L_{i,j}$ at the end of the t-th time slice, and $R_{i,j}(n,t)$ the distance from its current position to the beginning of the next segment. Thus, $R_{i,j}(n,t) = \Delta L_{i,j} - P_{i,j}(n,t)$. Let $D(n,t+1) = \Delta T \times V_{i,j}(t+1)$, with two cases:

1. $D(n,t+1) \leq R_{i,j}(n,t)$. In this case, the new position of vehicle n remains in $L_{i,j}$ at the end of the $(t+1)$-th time-slice, and is obtained by advancing n by the distance $D(n,t+1)$.
2. $D(n,t+1) > R_{i,j}(n,t)$. In this case, vehicle n must travel in the next segment, $L_{i',j'}$, during $\Delta T' = \Delta T - R_{i,j}(n,t)/V_{i,j}(t+1)$. Denote the distance that n will travel during $\Delta T'$ by $R'_{i',j'}(n,t+1)$, as shown in Figure 4.2. That is, the new position of n is obtained by advancing n by the distance $R'_{i',j'}(n,t+1)$ on $L_{i',j'}$. There are the following two approaches to compute $R'_{i',j'}(n,t+1)$:

   [A] Take $V_{i',j'}(t+1)$ as the mean speed for n traveling on $L_{i',j'}$ during $\Delta T'$, then

$$R'_{i',j'}(n,t+1) = \Delta T' \times V_{i',j'}(t+1)$$

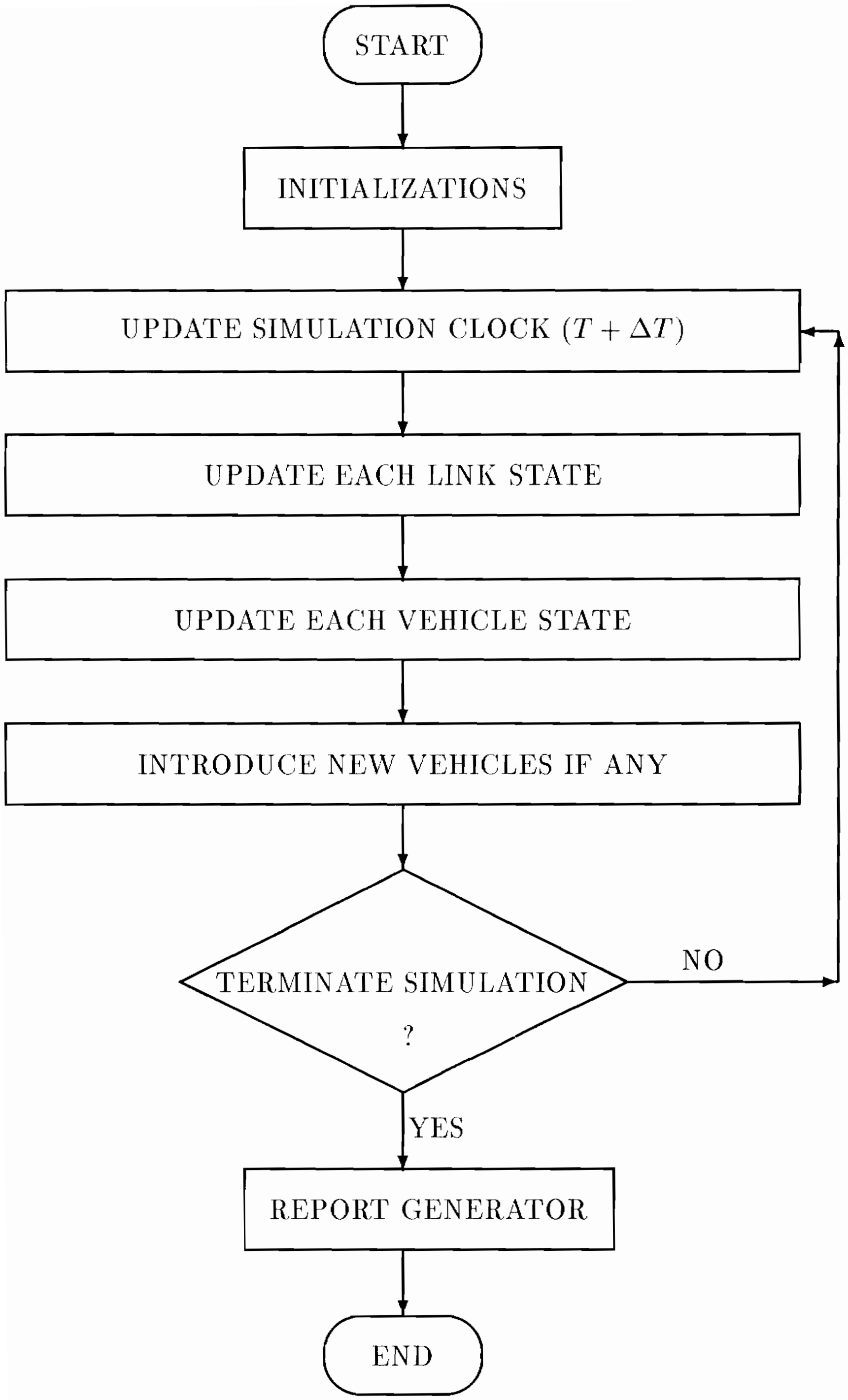

START
INITIALIZATIONS
UPDATE SIMULATION CLOCK $(T + \Delta T)$
UPDATE EACH LINK STATE
UPDATE EACH VEHICLE STATE
INTRODUCE NEW VEHICLES IF ANY
TERMINATE SIMULATION
?
NO
YES
REPORT GENERATOR
END

Figure 4.1: A Flowchart of MTDS

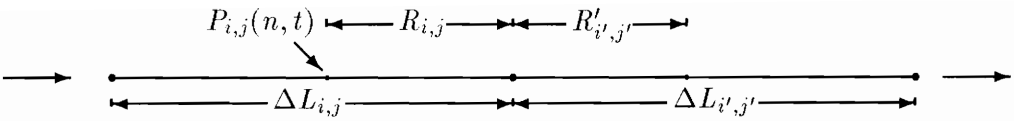


Figure 4.2: Vehicle Moving Process

Table 4.2: Physical Link Data

LinkID	L_1	L_2	L_3	L_4	L_5	L_6
Length (mile)	1	1	1	1	1	1
JamDensity (veh/lane/mile)	170	180	200	190	185	185
FreeFlowSpeed (miles/hr)	55	60	65	65	55	50
MinSpeed (miles/hr)	6	6	6	6	6	6
SD_Parameter	1.2	1.2	1.2	1.2	1.2	1.2
NumLanes	2	2	2	2	2	2

[B] Take the average speed $\frac{V_{i,j}(t+1)+V_{i',j'}(t+1)}{2}$ as the mean speed for n traveling on $L_{i',j'}$ during $\Delta T'$ [Chang et al. 1985], then

$$R'_{i',j'}(n,t+1) = \frac{\Delta T'}{2}(V_{i,j}(t+1) + V_{i',j'}(t+1))$$

These two approaches are called by *Approach A* and *Approach B*, respectively. We conduct a simple experiment to compare these two approaches. Figure 4.3 shows a section of freeway, with link data given in Table 4.2. Table 4.3 gives the simulated results of travel times, where the arrival rate at S is 0.25 veh/lane/sec. In MTDS-10 and MTDS-30, the travel times on L_3 and L_4 from Approach B make conflicts with the fact that the travel time on L_3 must be less than that on L_4 according to the physical data of L_3 and L_4. This

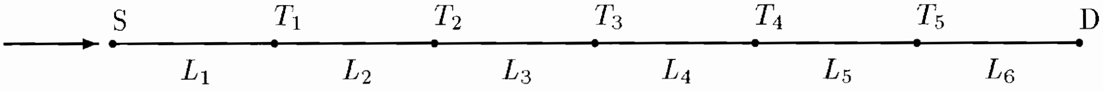


Figure 4.3: A Section of Freeway

Table 4.3: Comparison of Mean Travel Times (min)

LINK ID	MTDS-1		MTDS-10		MTDS-30	
	A	B	A	B	A	B
L_1	1.239	1.239	1.238	1.238	1.238	1.238
L_2	1.115	1.115	1.114	1.119	1.113	1.127
L_3	1.009	1.009	1.008	*1.013*	1.007	*1.020*
L_4	1.014	1.014	1.014	*1.013*	1.013	*1.013*
L_5	1.224	1.223	1.223	1.214	1.221	1.197
L_6	1.362	1.361	1.361	1.355	1.359	1.343
Total	6.963	6.961	6.958	6.952	6.951	6.937

simple experiment shows that Approach A is a little better than Approach B. Therefore, we choose Approach A to implement MTDS models.

4.2 An Event-Driven Simulation

According to **Assumption 2** and the event-driven approach, we developed an event-driven traffic simulation (EDS) model. There are four basic types of events: e_1 reaches a source; e_2 reaches an intersection; e_3 reaches a dummy node; and e_4 departs from a destination. Since an event is invoked by some vehicle, the representation of the event includes information on the corresponding vehicle. The contents of the event consists of six elements: *OccurrenceTime, EventType, NodeNo, ArrivalTime, VehType*, and *RouteNo*, as shown in Table 4.4. That is, we can use $(t, T(e), N, t_0(n), T(n), R(n))$ to represent an event e corresponding to vehicle n. For example, $(9.00, 2, T_1, 8.00, car, R_3)$ represents: "the *car* that entered the network at *8:00 AM* is arriving at *intersection* T_1 at *9:00 AM* along route R_3". These events are *unconditional events* that can be scheduled in advance. However, an *incident* is a *conditional event* that occurs somewhere and sometime in the network, and is specified by the time at which the set of *incident boolean conditions* becomes true.

The basic execution loop of the simulation repeatly removes the smallest time-stamped event from the *event set (queue)* and processes that event. The event set is sorted by the

Table 4.4: The Data Structure of an Event

ATTRIBUTE		*MEANING*
NAME	SYMBOL	
OccurrenceTime	t	the time when event e occurs
EventType	$T(e)$	the type of event e
NodeNo	N	the number of the node where event e occurs
ArrivalTime	$t_0(n)$	the time when vehicle n entered the network
VehType	$T(n)$	the type of vehicle n
RouteNo	$R(n)$	the number of the route vehicle n is taking

occurrence times of pending events. Each of four event types has its own processing routine:

[Routine 1] Process event $e_1 = (t, 1, N, t_0(n), T(n), R(n))$ as follows:

1. Increment by one the number of vehicles in the segment that n is entering.
2. Increment by one the number of vehicles in the network.
3. Check if the simulation has reached the steady state. If so, update the areas under the number of vehicles in the entering link versus time curve and under the number of vehicles in the network versus time curve, respectively.
4. Introduce a new vehicle to reach the same source and merge it into the event set.
5. Check the traffic congestion condition. If no congestion, update the speed for n, schedule a new arrival at next node along $R(n)$ and then merge it into the event set; if yes, set congestion flag to true and put vehicle n in the waiting queue of origin N.
6. Delete e_1 from the event set.

[Routine 2] Process event $e_2 = (t, 2, N, t_0(n), T(n), R(n))$ as follows:

1. Subtract one from the number of vehicles in the segment where n just exited.
2. Increment by one the number of vehicles in the segment vehicle n is entering.
3. Increment by one the number of vehicles in the link containing the entering segment.
4. Check if the simulation has reached the steady state. If so, update the areas under the number of vehicles in the entering link versus time curve and under the number of vehicles in the exited link versus time curve, respectively.

5. Check the traffic congestion condition. If no congestion, update the speed for n, schedule a new arrival at the next node along $R(n)$ and then merge it into the event set; if yes, set congestion flag to true and put n in the waiting queue of node N.
6. Delete e_2 from the event set.
7. If any vehicle reaches intersection N from outside of the network, go to **Routine 1**.

[Routine 3] Process event $e_3 = (t, 3, N, t_0(n), T(n), R(n))$ as follows:

1. Subtract one from the number of vehicles in the segment where n just exited.
2. Increment by one the number of vehicles in the segment vehicle n is entering.
3. Update the speed of vehicle n.
4. Create a new arrival at the next node along $R(n)$ and merge it into the event set
5. Delete e_3 from the event set.

[Routine 4] Process event $e_4 = (t, 4, N, t_0(n), T(n), R(n))$ as follows:

1. Subtract one from the number of vehicles in the segment where n just exited.
2. Subtract one from the number of vehicles in the link where n just exited.
3. Subtract one from the number of vehicles in the network.
4. Check if the simulation has reached the steady state. If so, update the areas under the number of vehicles in the exited link versus time curve and under the number of vehicles in the network versus time curve, respectively.
5. Delete e_4 from the event set.

Each routine tells what the simulation must do to process a particular event e if it is chosen for processing. The current implementation of the simulation terminates each run after the prespecified number of vehicles has been processed. The simulation logic of EDS is illustrated in Figure 4.4 [Balci 1988].

4.3 Computational Complexities of EDS and MTDS

Let M be the total number of nodes in the network representation and N be the number of vehicles to be simulated. The EDS model costs $O(\sum_{i,j \in R_n} 1)$ to simulate a vehicle n

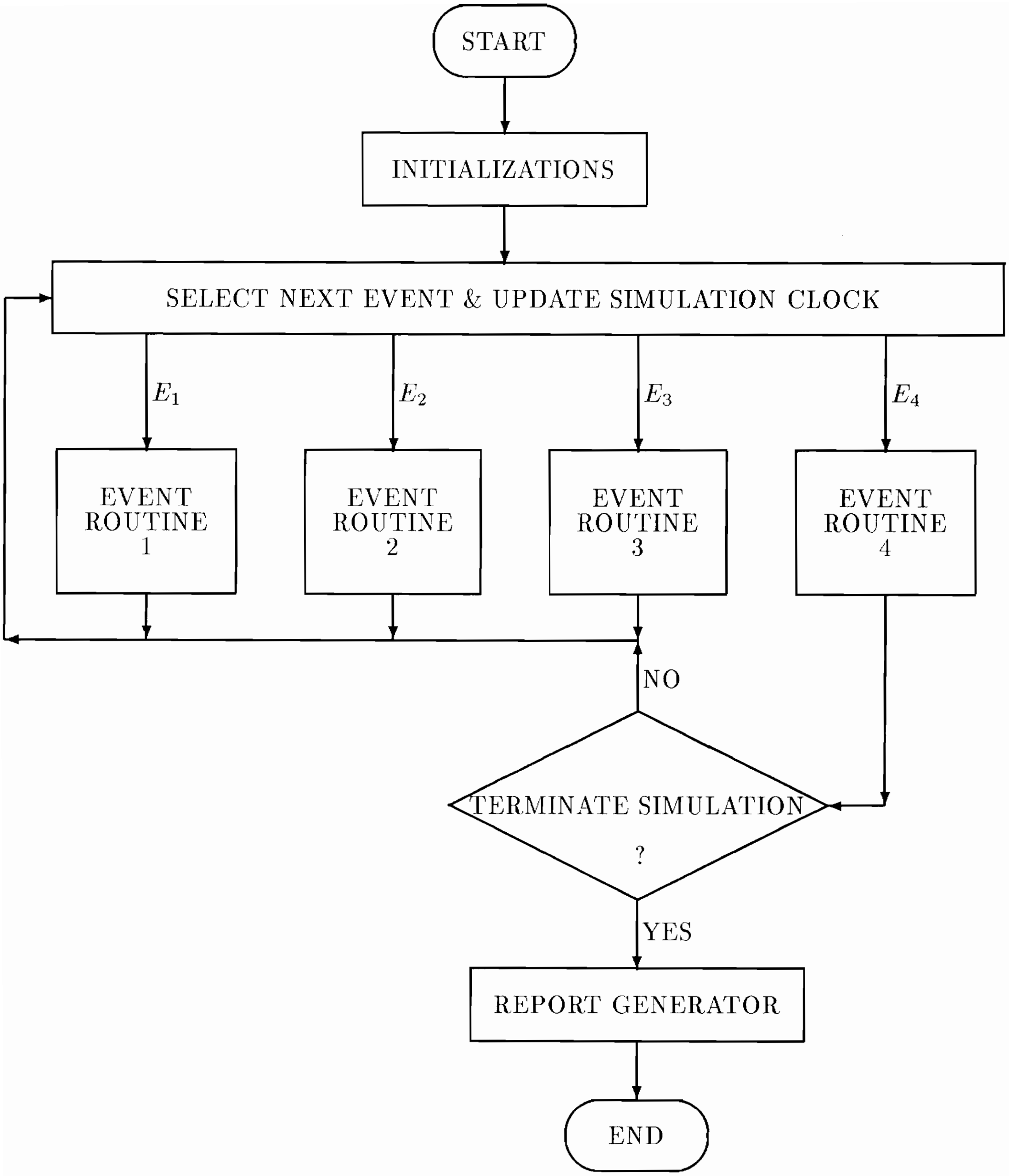


Figure 4.4: A Flowchart of EDS

through route R_n, and thus, the complexity of EDS is $O(NM)$. On the other hand, let the *free travel time* on $L_{i,j}$ be $T^F_{i,j}$, then $T^F_{i,j} = \Delta L_{i,j}/V^F_{i,j}$. The MTDS-$\Delta T$ model costs $O(\sum_{i,j \in R_n}(T^F_{i,j}/\Delta T))$ to simulate vehicle n through route R_n, so the complexity of MTDS is $O(NMT_F/\Delta T)$, where T_F is the *average free travel time* on all segments consisting of R_n, and usually $T_F \gg \Delta T$. Therefore, EDS is theoretically expected to be faster than MTDS-ΔT for a small ΔT.

4.4 Summary

We develop an event-driven simulation model, which opens a new simulation environment for network traffic study. We compare the time-driven simulation models using a new processing approach versus the traditional one of vehicular movement over nodes during one time-slice. The results show that the new approach is a little better than the traditional one. We also give the theoretical analysis of the computational complexities of both event-driven simulations and time-driven simulations.

Chapter 5

EXPERIMENTAL COMPARISONS BETWEEN EDS AND MTDS

Chapter 4 implemented an event-driven traffic model (EDS) and a modified time-driven traffic model (MTDS). This chapter will focus on comparing the accuracy and efficiency of these two models based on three typical situations.

The objectives of this study are to:

1. investigate the effect of network configuration on traffic characteristics (i.e., travel time, traffic density and volume)
2. predict travel time and congestion situation for each link of a network as traffic flow changes dynamically at each source of the network
3. provide a tool to observe how the dynamics of route choice behavior affects the traffic density and travel time of the network
4. determine (if possible) which of the two simulation models is better in accuracy and efficiency for network traffic flow simulation

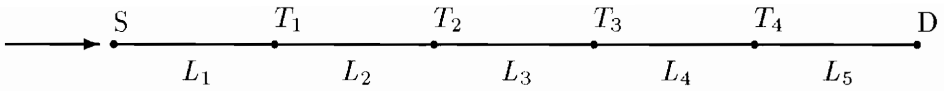


Figure 5.1: Scenario 1 — a Single Highway

5.1 Simulation Experimentation

After the model has been conceptualized, coded, and tested, it is ready to provide information through experimentation.

The seeds used in random-number generation should not affect the final conclusion. Thus, the model should produce similar results for different seed values. It may be verified by running the simulation with different seed values. There are general guidelines for seed selection such as *avoid even values, use nonoverlapping streams,* and *reuse seeds in successive replications* [Law and Kelton 1991].

We design three typical scenarios to conduct the experiments to compare EDS and MTDS. Any real traffic system can be divided into a set of subsystems, each being one of these three typical situations. The programs are written in the C language. The execution times of the experiments are measured for one run on a DECstation 5000/133. The physical data for each link is selected to represent various traffic conditions. For present experiments, we set the headway-threshold as 1 second (see equation 3.1) at each source, that is, there is no headway less than 1 second. Both EDS and MTDS use the same link physical data. We also assume that all lanes of a link have the same arrival pattern. All steady-state performances in the following experiments are obtained by using the *replication/deletion approach* described in Section 2.5.

5.1.1 Scenario 1: A Single Highway

Figure 5.1 shows the network situation, a single freeway with one low-capacity link (L_4). The physical features for each link are given in Table 5.1.

Table 5.1: Physical Link Data in Scenario 1

LinkID	L_1	L_2	L_3	L_4	L_5
Length (mile)	1	1	1	1	1
JamDensity (veh/lane/mile)	170	180	200	120	185
FreeFlowSpeed (miles/hr)	55	60	65	45	55
MinSpeed (miles/hr)	6	6	6	6	6
SD_Parameter	1.2	1.2	1.2	1.2	1.2
NumLanes	2	2	2	2	2

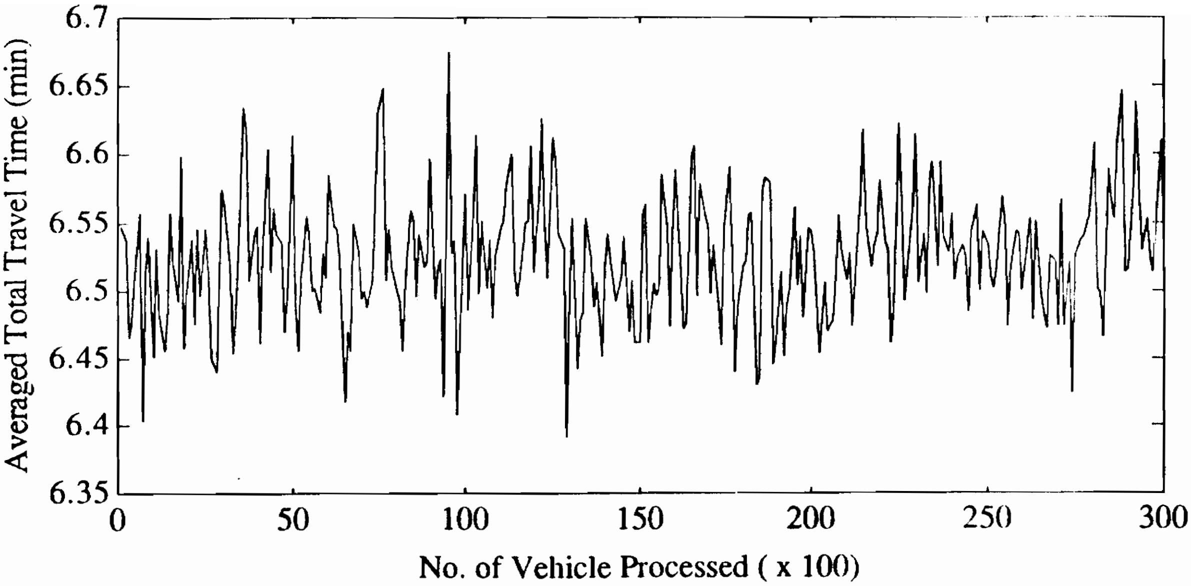
5.1.2 Warmup Periods

In order to perform a steady-state input, it is necessary to detect and eliminate warmup period. We made 20 independent replications of each simulation with length $m = 300 \times 100$ vehicles. Both EDS and MTDS use the same physical features for each link are given in Table 5.1. Figure 5.2a and Figure 5.2b plot the averaged trajectories of the total travel time from EDS and MTDS-1, respectively. The other runs for each model have similar trajectories to Figure 5.2. It is clear that further smoothing of the plot is necessary. Figure 5.3 plots the moving average trajectories of each model by Welch's procedure with 50×100 window size . Here, $q(S) = .3$ vehicles per second as the arrival rate. The result shows that the warmup period is about 20,000 vehicles for both EDS and MTDS. Figure 5.4 analyzes the sensitivity of the warmup period to the traffic arrival rate, where the data comes from EDS. The result shows that the warmup periods for all arrival rates are almost the same, and thus needn't be reset as the model simulates traffic flow dynamically.

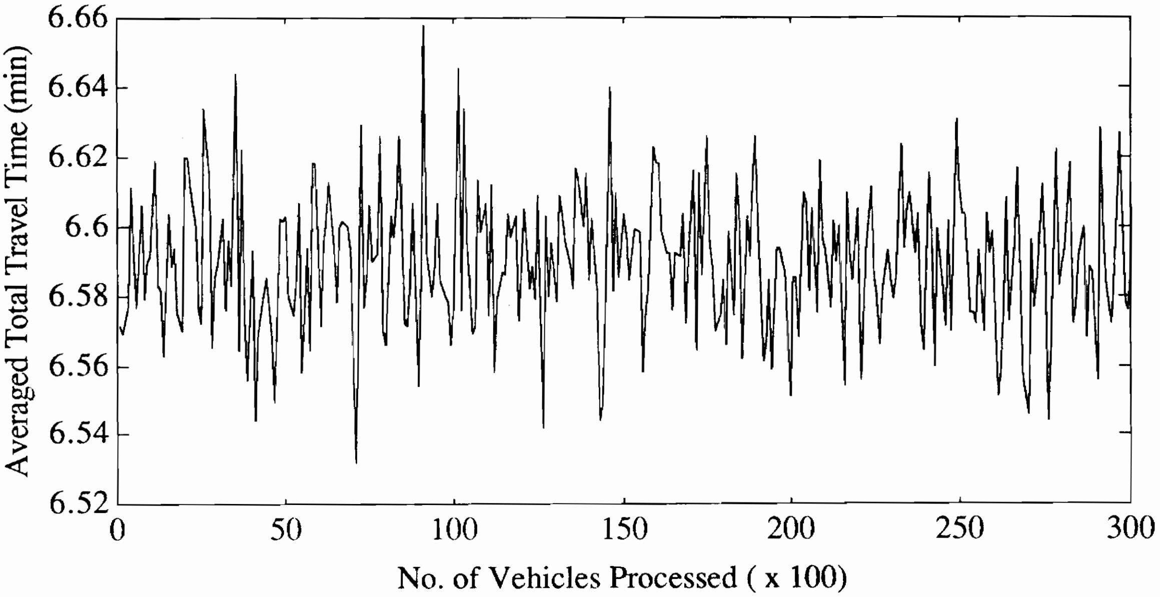
Based on these experiments, we have the following results related to the warmup period:

1. The warmup period is about 20,000 vehicles for both EDS and MTDS.
2. The traffic arrival rate hardly affects the warmup period of the model.

In the following two scenarios, we conduct the similar experiments to analyze the warmup period. Those experiments also demonstrates the above two results. In the following experiments, therefore, we always set the warmup period to be 20,000 vehicles, and



(a) Averaged Total Travel Time from EDS



(b) Averaged Total Travel Time from MTDS-1

Figure 5.2: Comparison of Averaged Travel Time across Replications

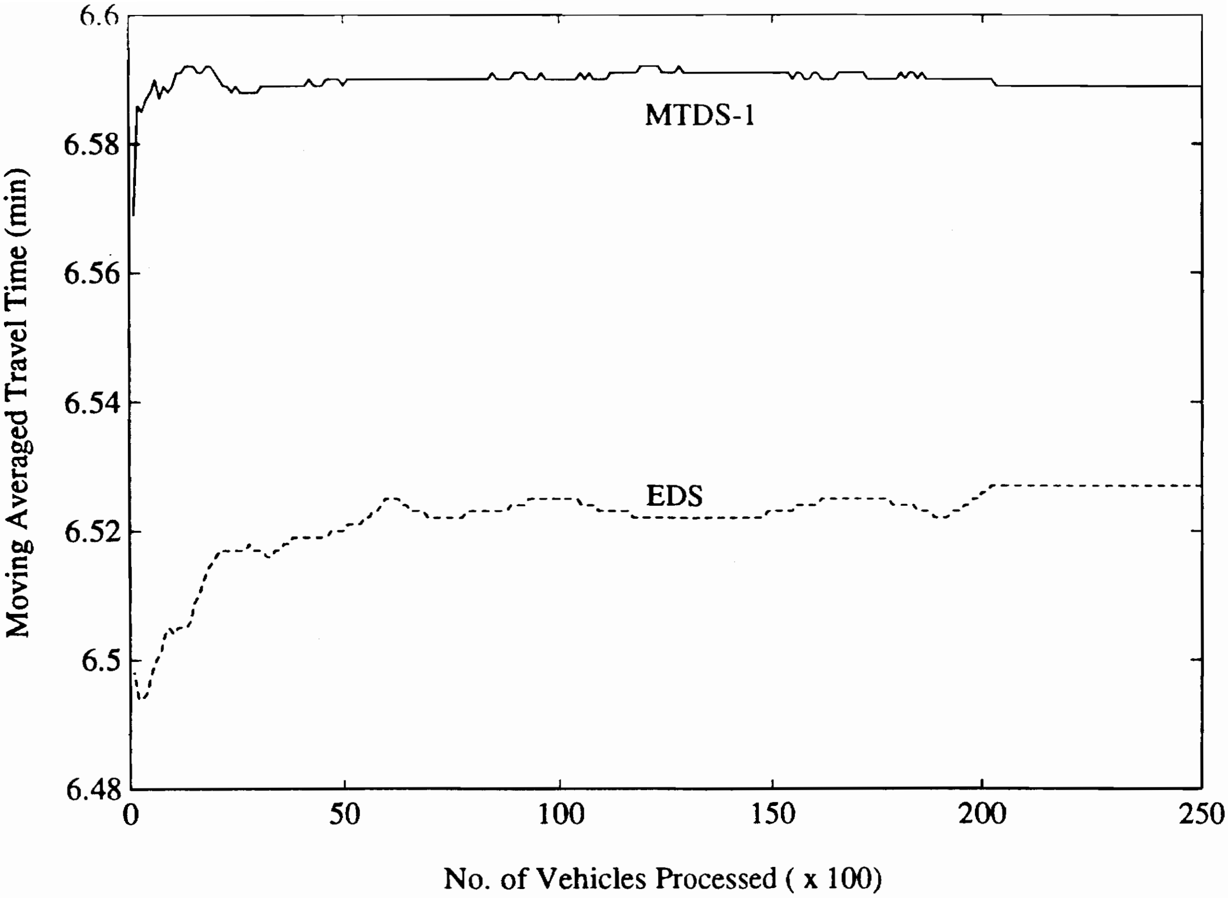


Figure 5.3: Comparison of Warmup Period for Total Travel Time

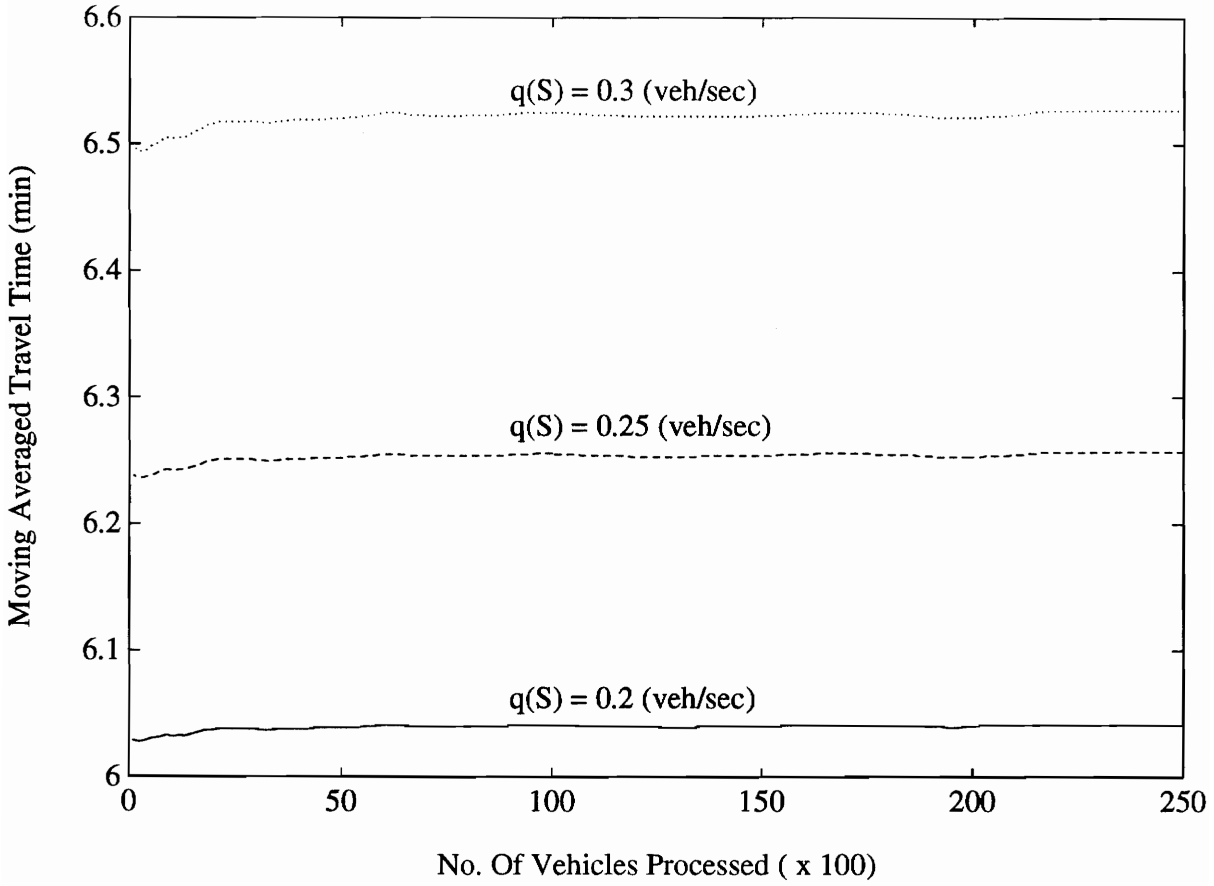


Figure 5.4: Effect of Arrival Rate on Warmup Period

collected statistics for the next 200,000 vehicles.

We must claim that the warmup period will increase as the size of network becomes quite large. Generally, we set ϵ in equation 3.3 as 0.04, but may be slightly modified with different arrival rates.

5.1.3 Simulation Results

Table 5.2 and Table 5.3 give the comparisons of mean travel times and mean traffic densities, respectively. They demonstrate that (1) MTDS-ΔT converges to MTDS-1 when ΔT approaches to 1 second; (2) MTDS-0.2 has the similar results to MTDS-1; (3) EDS produces results similar to MTDS-1; and (4) the differences between MTDS-1, MTDS-10 and MTDS-30 becomes larger when the arrival rate gets bigger. Why is 1 second so important? The reason is that we took 1 second as the headway-threshold in vehicle generation. That is, MTDS can process at most one vehicle during each 1 second period. From Table 5.3, we also notice that the big difference of traffic density lies in the first link. This is due to **Assumption 1** which assumes link state is constant and not affected by new arrivals during each time-slice.

Little's Law in Section 2.6 is useful to test the validity of the simulation model. In Table 5.4, *theoretical volume* = *arrival rate* × *an hour*, where the arrival rate is assumed *constant* during the hour. The *simulated volume* is computed by using the fundamental equation 2.2 of traffic characteristics, where float is truncated into the next lower integer. Table 5.4 shows that EDS produces the same volume to the theoretical one. The error of MTDS-ΔT results from **Assumption 1** and thus, the bigger ΔT results in the bigger error. In this sense, the EDS model is more accurate than the MTDS model, and MTDS-ΔT gets more accurate when ΔT approaches to zero. Table 5.4 also shows that when traffic flow is greater than 0.35 veh/lane/sec, there happens the serious traffic jam in the highway. This is caused by the low capacity of L_4. Table 5.5 shows that the speedup of EDS is about 4 times to MTDS-1.

Table 5.2: Comparison of Mean Travel Times (min) of Scenario 1

LINK	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
ID	$q(S) = 0.15$ (veh/lane/sec)				
L_1	1.174	1.174	1.174	1.174	1.173
L_2	1.065	1.066	1.066	1.065	1.064
L_3	0.972	0.973	0.973	0.973	0.972
L_4	1.525	1.522	1.522	1.521	1.519
L_5	1.165	1.166	1.166	1.165	1.164
Total	5.901	5.901	5.901	5.898	5.892
	$q(S) = 0.25$ (veh/lane/sec)				
L_1	1.239	1.239	1.239	1.238	1.238
L_2	1.113	1.115	1.115	1.114	1.113
L_3	1.008	1.009	1.009	1.008	1.007
L_4	1.722	1.719	1.718	1.717	1.714
L_5	1.222	1.223	1.223	1.222	1.221
Total	6.304	6.305	6.304	6.299	6.293
	$q(S) = 0.3$ (veh/lane/sec)				
L_1	1.277	1.277	1.277	1.277	1.276
L_2	1.142	1.143	1.143	1.142	1.142
L_3	1.028	1.029	1.029	1.028	1.027
L_4	1.881	1.879	1.878	1.875	1.870
L_5	1.255	1.257	1.257	1.256	1.254
Total	6.583	6.585	6.584	6.578	6.569

Table 5.3: Comparison of Mean Densities (veh/lane/mile) of Scenario 1

LINK	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
ID	$q(S) = 0.15$ (veh/lane/sec)				
L_1	10.571	10.541	10.410	9.059	6.059
L_2	9.588	9.587	9.587	9.582	9.576
L_3	8.751	8.754	8.754	8.750	8.338
L_4	13.737	13.696	13.694	13.682	13.672
L_5	10.493	10.492	10.491	10.483	10.474
Total	10.628	10.590	10.587	10.311	9.703
	$q(S) = 0.25$ (veh/lane/sec)				
L_1	18.584	18.535	18.324	16.072	11.059
L_2	16.707	16.715	16.715	16.706	16.694
L_3	15.112	15.125	15.125	15.118	15.108
L_4	25.836	25.778	25.776	25.749	25.703
L_5	18.335	18.334	18.334	18.330	18.302
Total	18.915	18.882	18.857	18.395	17.373
	$q(S) = 0.3$ (veh/lane/sec)				
L_1	22.999	22.887	22.686	19.983	13.969
L_2	20.558	20.569	20.567	20.559	20.542
L_3	18.493	18.510	18.509	18.506	18.499
L_4	33.875	33.789	33.789	33.736	33.640
L_5	22.601	22.615	22.615	22.595	22.587
Total	23.705	23.660	23.634	23.076	21.848

Table 5.4: Comparison of Effect of Arrival Rate on Major Performances of Scenario 1

ARRIVAL RATE	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
(veh/lane/sec)	TOTAL TRAVEL TIME (min)				
0.15	5.901	5.901	5.901	5.898	5.892
0.20	6.084	6.085	6.085	6.082	6.075
0.25	6.304	6.305	6.304	6.299	6.293
0.30	6.583	6.585	6.584	6.578	6.569
0.36	Jam	Jam	Jam	Jam	Jam
	TRAFFIC DENSITY (veh/lane/mile)				
0.15	10.628	10.590	10.587	10.311	9.703
0.20	14.575	14.568	14.557	14.191	13.375
0.25	18.915	18.882	18.857	18.395	17.373
0.30	23.705	23.660	23.634	23.076	21.848
THEORETICAL VOLUME (veh/lane/hr)	SIMULATED VOLUME (veh/lane/hr)				
540	540	539	538	524	494
720	720	719	717	699	660
900	900	899	897	876	828
1080	1080	1079	1076	1052	997

Table 5.5: Comparison of Execution Times of Scenario 1

MODEL	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
Execution Time (sec)	85	1770	350	50	22

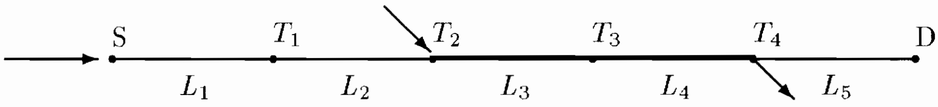


Figure 5.5: Scenario 2 — a Freeway with two Ramp Junctions

Table 5.6: Physical Link Data in Scenario 2

LinkID	L_1	L_2	L_3	L_4	L_5
Length (mile)	1	1	1	1	1
JamDensity (veh/lane/mile)	190	180	210	200	190
FreeFlowSpeed (miles/hr)	50	65	60	55	65
MinSpeed (miles/hr)	6	6	6	6	6
SD_Parameter	1.2	1.2	1.2	1.2	1.2
NumLanes	2	2	2	2	2

5.2 Scenario 2: A Merging Highway

Figure 5.5 shows the network situation that consists of a source (S), an on-ramp point (T_3), an off-ramp point (T_4), a destination (D) and five links L_1, L_2, L_3, L_4 and L_5. Table 5.6 shows the physical features for each link. An on-ramp provides for the merging of the entering vehicles with a shoulder lane of through traffic on the freeway. An off-ramp allows vehicles to diverge from a freeway lane onto an existing roadway. Ramp junctions are those short segments of freeway where vehicles are permitted to enter or leave the freeway.

Table 5.7 compares the major performances between EDS, MTDS-0.2, MTDS-1, MTDS-10, and MTDS-30. Like the first scenario, the results show that (1) MTDS-ΔT converges to MTDS-1 when ΔT approaches to 1 second; (2) there is little difference between MTDS-0.2 and MTDS-1; (3) for MTDS-ΔT, the major error of volume that lies in the first link gets smaller when ΔT approaches to zero; and (4) EDS produces results similar to MTDS-0.2 and MTDS-1. However, EDS speeds up about 4 times to MTDS-1, as shown in Table 5.8.

Table 5.7: Comparison of Major Performances of Scenario 2

$q(S)$	$q(T_3)$	$q(T_4)$	LINK	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
(veh/sec)			ID	MEAN TRAVEL TIME (min)				
0.4	0.2	0.1	L_1	1.32	1.32	1.32	1.32	1.319
			L_2	0.997	0.999	0.999	0.999	0.998
			L_3	1.118	1.118	1.118	1.117	1.116
			L_4	1.243	1.241	1.241	1.240	1.239
			L_5	1.013	1.014	1.014	1.013	1.012
			TOTAL	5.691	5.692	5.692	5.689	5.684
				MEAN TRAFFIC DENSITY (veh/lane/mile)				
			L_1	15.84	15.82	15.65	13.83	9.82
			L_2	11.97	11.99	11.99	11.97	11.95
			L_3	20.14	20.12	20.11	20.09	20.07
			L_4	22.38	22.34	22.34	22.31	22.26
			L_5	15.20	15.20	15.20	15.19	15.17
THEORETICAL VOLUME (veh/lane/hr)				SIMULATED VOLUME (veh/lane/hr)				
720			L_1	720	719	711	628	446
720			L_2	720	720	720	718	718
1080			L_3	1080	1079	1079	1079	1079
1080			L_4	1080	1080	1080	1079	1077
900			L_5	900	899	899	899	899
0.6	0.2	0.1		MEAN TRAVEL TIME (min)				
			L_1	1.397	1.397	1.397	1.396	1.395
			L_2	1.042	1.044	1.044	1.043	1.042
			L_3	1.170	1.169	1.169	1.168	1.167
			L_4	1.313	1.311	1.311	1.310	1.308
			L_5	1.058	1.059	1.059	1.058	1.057
			Total	5.980	5.980	5.980	5.975	5.969
				MEAN TRAFFIC DENSITY (veh/lane/mile)				
			L_1	25.16	25.10	24.85	22.13	16.11
			L_2	18.77	18.79	18.79	18.77	18.75
			L_3	28.08	28.04	28.04	28.02	28.00
			L_4	31.52	31.46	31.44	31.41	31.37
			L_5	22.23	22.25	22.25	22.22	22.20
THEORETICAL VOLUME (veh/lane/hr)				SIMULATED VOLUME (veh/lane/hr)				
1080			L_1	1080	1077	1067	951	692
1080			L_2	1080	1079	1079	1079	1079
1440			L_3	1440	1439	1439	1439	1439
1440			L_4	1440	1439	1438	1438	1438
1260			L_5	1260	1260	1260	1260	1260

Table 5.8: Comparison of Execution Times of Scenario 2

MODEL	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
Execution Time (sec)	64	1360	258	43	19

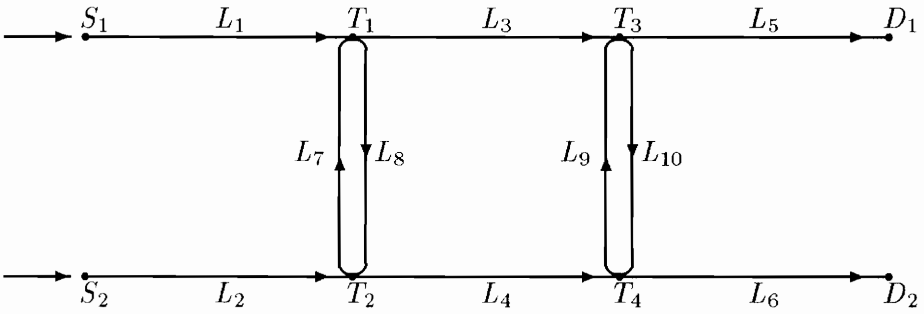


Figure 5.6: Scenario 3 — a Sample Network

5.3 Scenario 3: A Sample Network

The sample network is illustrated in Figure 5.6, with link data given in Table 5.9. There are eight different routes, as shown in Table 5.10. For simplicity, we assume that each vehicle enters the network with a predetermined route. We associate one random generator with one route to generate the arrival pattern of that route.

Table 5.9: Physical Link Data in Scenario 3

LinkID	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}
Length (mile)	1	1	1	1	1	1	1	1	1	1
JamDensity (veh/lane/mile)	180	180	200	200	180	180	180	180	180	180
FreeFlowSpeed (mile/hr)	45	65	65	65	55	55	45	55	65	45
MinSpeed (mile/hr)	6	6	6	6	6	6	6	6	6	6
SD_Parameter	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
NumLanes	2	2	2	2	2	2	2	2	2	2

Table 5.10: Eight Routes in Scenario 3

ROUTE NO.	ROUTE
1	$S_1 \to T_1 \to T_3 \to D_1$
2	$S_1 \to T_1 \to T_2 \to T_4 \to T_3 \to D_1$
3	$S_1 \to T_1 \to T_2 \to T_4 \to D_2$
4	$S_1 \to T_1 \to T_3 \to T_4 \to D_2$
5	$S_2 \to T_2 \to T_4 \to D_2$
6	$S_2 \to T_2 \to T_1 \to T_3 \to T_4 \to D_2$
7	$S_2 \to T_2 \to T_1 \to T_3 \to D_1$
8	$S_2 \to T_2 \to T_4 \to T_3 \to D_1$

Table 5.11 assumes that all arrival rates $q(R_i)$ of route R_i $(i = 1, 2, ..., 8)$ are 0.1 veh/lane/sec. The results agree to these in the first two scenarios. EDS produces results similar to MTDS-0.2 and MTDS-1. Since the arrival rate for each route is quite low (i.e., 1 vehicle per 10 seconds), the difference between MTDS-1, MTDS-10 and MTDS-30 is little. Table 5.13 shows that EDS speeds up 2.6 times to MTDS-1. Compared the first scenario, the speedups of EDS to MTDS-1 and MTDS-0.2 are decreased. The reason for this is that the size of the global event queue in EDS is increased, but the size of each route queue in MTDS keeps small due to optimally allocating vehicles into eight different queues associated with their routes. However, we can also speedup EDS for large network applications by using some optimal event-set algorithms such as *calendar queues* [Brown 1988].

5.4 Conclusions

We conduct three experiments to compare the event-driven traffic simulation model versus the time-driven traffic simulation model in both accuracy and efficiency. Both EDS and MTDS are general-purpose freeway simulation models, not limited the above three situations. These models can be further developed into on-line application software packages to inform the driver about current and near-future traffic conditions based on the dynamics

Table 5.11: Comparison of Major Performances of Scenario 3

LINK	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
ID	MEAN TRAVEL TIME (min) ON EACH LINK				
L_1	1.772	1.77	1.77	1.764	1.76
L_2	1.104	1.102	1.102	1.10	1.10
L_3	1.078	1.078	1.078	1.078	1.076
L_4	1.078	1.078	1.078	1.066	1.06
L_5	1.356	1.358	1.358	1.356	1.352
L_6	1.356	1.358	1.358	1.354	1.35
L_7	1.492	1.492	1.492	1.49	1.49
L_8	1.20	1.20	1.20	1.20	1.20
L_9	0.998	1.00	1.00	1.00	0.998
L_{10}	1.49	1.49	1.49	1.49	1.49
	MEAN DENSITY (veh/lane/mile) ON EACH LINK				
L_1	42.54	42.54	42.54	42.42	42.40
L_2	26.50	26.50	26.50	26.48	26.48
L_3	25.86	25.86	25.86	25.84	25.84
L_4	25.86	25.86	25.86	25.54	25.42
L_5	32.56	32.56	32.56	32.52	32.36
L_6	32.56	32.56	32.56	32.52	32.36
L_7	17.92	17.90	17.88	17.86	17.86
L_8	14.40	14.40	14.40	14.40	14.34
L_9	11.98	12.04	12.04	12.04	11.96
L_{10}	17.88	17.88	17.88	17.86	17.84
ROUTE	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
NO.	MEAN TRAVEL TIME (min) ON EACH ROUTE				
1	4.206	4.206	4.206	4.198	4.188
2	6.404	6.406	6.406	6.398	6.386
3	5.406	5.406	5.406	5.384	5.37
4	5.696	5.696	5.696	5.686	5.676
5	3.538	3.538	3.538	3.52	3.51
6	6.52	6.52	6.52	6.512	6.506
7	5.03	5.03	5.03	5.024	5.018
8	4.536	4.538	4.538	4.522	4.51

Table 5.12: Comparison of Traffic Volume of Scenario 3

LINK ID	THEORETICAL VOLUME (veh/lane/hr)	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
		SIMULATED VOLUME (veh/lane/hr)				
L_1	1440	1440	1442	1442	1442	1445
L_2	1440	1440	1442	1442	1444	1444
L_3	1440	1439	1439	1439	1439	1338
L_4	1440	1439	1439	1439	1442	1338
L_5	1440	1440	1438	1438	1438	1436
L_6	1440	1440	1438	1438	1441	1438
L_7	720	720	720	719	719	719
L_8	720	719	719	719	719	716
L_9	720	720	722	722	722	719
L_{10}	720	719	719	719	719	718

Table 5.13: Comparison of Execution Times of Scenario 3

MODEL	EDS	MTDS-0.2	MTDS-1	MTDS-10	MTDS-30
Execution Time (sec)	160	2080	420	55	26

of the traffic flow on entry to the network.

Generally, we conclude as follows:

1. MTDS-ΔT converges to MTDS-τ when ΔT approaches to τ, and MTDS-ΔT behaves roughly like MTDS-τ when ΔT gets smaller than τ, where τ is the headway-threshold.
2. EDS produces results similar to MTDS-τ, and is more efficient than MTDS-τ, where τ is the headway-threshold and usually less than 2 seconds [Young et al. 1989].
3. Compared to the theoretical volume, EDS is very accurate and MTDS-ΔT becomes more accurate when ΔT gets smaller.
4. The differences between MTDS-1, MTDS-10 and MTDS-30 depends on the arrival rates. When the arrival rate is quite small, we may choose ten seconds or even bigger as the time-slice for MTDS for the better trade-off between efficiency and accuracy.

We believe that the event-driven freeway simulation offers an efficient alternative to the traditional time-driven freeway simulation.

Chapter 6

CONCLUSIONS AND FUTURE WORK

Increasing levels of traffic congestion underscore the importance of the Advanced Traffic Management System (ATMS). One major goal of ATMS is to improve highway systems performance by providing real-time route guidance information to on-road drivers. This goal makes it necessary for traffic models to capture the dynamic nature of traffic flow through the network and to predict the travel time for each link and each route. This project has made some progress toward the goal. The project has addressed several key issues of the development of traffic simulation such as how to generate vehicle arrivals, how to represent a transportation network, how to investigate vehicle movement, how to test a traffic simulation model, and how to obtain the desired statistical analysis of the simulation outputs. A subjective review of the widely publicized traffic simulation models is considered. A presentation and analysis of the experimental results is included.

Although past research efforts have produced some freeway simulation models, this research accomplishes four major tasks not achieved by other efforts:

1. Presents a hybrid traffic modeling approach for the development of traffic flow simulations within a reasonable time-scale.
2. Develops a general-purpose traffic flow simulation model by using the event-driven

approach, which provides a new simulation tool for freeway traffic study.

3. Develops a time-driven traffic simulation model that supports random arrival patterns. An interesting result is that all MTDS-ΔT converges to MTDS-τ, where τ is the headway-threshold.

4. Conducts a comprehensive comparison between EDS and MTDS. The experimental results show that the event-driven simulation is competitive in efficiency and accuracy with traditional time-driven simulation using small time slices.

The hybrid modeling approach is a combination of microscopic and macroscopic simulation techniques with stochastic modeling. That is, the traffic stream is composed of individual vehicles, while the interactions in the traffic stream are modeled macroscopically using the average speed-density relation. For the future research, however, we need to model some details of signalized operation at junctions by suitably constraining the interlink transfers.

6.1 Areas of Future Research

The availability of parallel processing suggests that we develop parallel simulation models for large-scale traffic networks. The event-driven simulation offers an effective working environment to the development of parallel traffic simulation models.

We can usually partition the network into a set of physical processes. A physical process represents a source, a destination, or a group of nodes which consist of one intersection and some dummy nodes. Each physical process PP_i is simulated by a computer program called *logical process* LP_i, which maintains the *pool of pending local events* Π_i. All interactions between physical processes are modeled by the exchange of messages between the corresponding logical processes. Each LP_i is allocated by one processing element PE_i.

6.1.1 A Concurrent Simulation Algorithm

A **concurrent simulation** is a mapping of a simulation program to a multiprocessor which can communicate through shared memory. The idea is to use a host machine to distribute each LP_i ($i = 1, 2, ..., N$) to each processor, and take the host as global synchronizer to handle the concurrency problems. We present the following concurrent simulation algorithm based on the *Lubachevsky Bounded Lag* approach [Lubachevsky 1988].

Let $\tau(e)$ denote the time-stamp of event e. The *bounded lag restriction* with parameter B is: "If events e_1 and e_2 are processed concurrently then $|\tau(e_1) - \tau(e_2)| \leq B$." The selection of B affects both efficiency and accuracy of the algorithm, where B is any input non-negative constant. Usually $B \leq \min_i T^F_{i,1}$, where $T^F_{i,1}$ is the free travel time on $L_{i,1}$, the first segment of link L_i. To maintain the bounded lag restriction, the simulation *floor* is set to $\min_{e \in \cup_i \Pi_i} \tau(e)$. An event e is admitted for processing only if $\tau(e) \leq floor + B$. Let register t_i represent the local simulated time of each Π_i. Thus, for each i, any $e \in \Pi_i$ satisfies: $\tau(e) \geq t_i$. The concurrent simulation algorithm is described below:

While $floor \leq TerminationTime$ do:

1. Each processor sends a message to the host with the time-stamp of the next event on its pending event pool;
2. The host selects the minimum time among these event messages as (new) simulation *floor*, broadcasts this floor to all processors, and synchronizes;
3. Each processor executes the events that satisfy the bounded lag restriction within its pending local event pool, updates its local states, and sends the appropriate messages to its successors.
4. After a processor finishes executing all the actions at this floor, it sends a *completion* message to all its successors.
5. Perform the *synchronization* statement and let each processor go back to step 1 after it has received all completion messages from all its predecessors.

The simulation starts with $floor = 0.0$, one vehicle in each source, and $t_i = 0.0$ for all i. The *synchronization* statement means that when a processor reaches it then the processor must wait until the other related processors have reached the same statement. A *successor* receives messages from an originating processor, also called its *predecessors*. The loop will not terminate until the local simulation time of each processor equals or exceeds the *termination time*.

Implementations and evaluation of this algorithm is required. However, the potential for a speed-up while using this strategy is limited because each local-event-pool processing bottlenecks a large-scale network. The challenge is to find massively parallel ways to operate on all states in the traffic network to accelerate the simulation [Greenberg et al. 1991].

6.1.2 An Optimistic Distributed Simulation Approach

A **distributed simulation** is a mapping of a simulation program to a set of processors which can communicate by passing massage. One distributed algorithm is based on the optimistic distributed approach that has achieved significant successes across a wide range of application by using the Time Warp mechanism [Jefferson 1985]. An *LP* can process every message as soon as it arrives; however, if a message with an earlier time-stamp subsequently arrives, the *LP* must roll back its state to the time of the earlier message and re-execute from that point. This may require the cancellation of message that the *LP* has sent, which can cause rollback at other *LPs*. The separation of events and states lends itself well to store the state information which is required for rollbacks and re-execution of some events. Since there exists a set of dummy nodes in some *PP*s, whose *LP*s must maintain enough events in their local pending pools as to reduce causality errors. Therefore, we may expect that there are few rollbacks in this distributed approach and thus great speed-up will be achieved.

6.1.3 A Visual Traffic Simulation Support Environment

Another important area is the development of a visual traffic simulation support environment (VTSSE). *Visual Simulation* is the process of building a model that permits a visual display of its input, internal behavior, and/or output, and experimenting with this model on a computer for a specific purpose [Bishop and Balci 1990]. The purpose of the development of VTSSE is to assist transport professionals to: (1) graphically design a traffic simulation model and its visualization, (2) interactively specify the model's logic, (3) automatically generate the executable version of the model in C programming language, and (4) support simulation-concurrent animation. Derrick [1992] has developed a prototype of the Visual Simulation Support Environment (VSSE) on a Sun workstation, which contains these five modules: Model Generator, Model Analyzer, Model Verifier, Model Translator, and Visual Simulator. VTSSE can be developed based on the logic of VSSE by restricting VSSE into network-oriented traffic applications and adding an intelligent module called *(Knowledge-based) Model Expert.* Model Expert is a very useful tool to assist the user to quickly build a valid model. For example, Model Expert should support the optimal selection of an event-set algorithm such that a simulation model in VTSSE is independent of the size of highway network. In an event-driven simulation, an event-set algorithm is required to ensure that the events occur in the proper order and at the proper time. There are two operations that are performed frequently on this set: one to insert new events in the set and one to find the next event and remove it from the set. The choice of the data structure used to maintain this set affects the processor time required for the two operations. Generally [Reeves 1984], (1) the simple linked list is the most efficient alternative if the number of events was small (less than 20 events); (2) the index linear list [Vaucher et al. 1975] is the best for event sets of sizes 20 to 120; and (3) the heap [Wyman 1975] and calendar queue [Brown 1988] are the most efficient for larger sets.

6.1.4 A Real-Time Traffic Simulation

ATMS needs to provide the real-time route guidance information to on-road drivers. This poses a challenge to developing a real-time traffic simulation. For a real-time simulation program, it is not sufficient for the program to be logically correct, the program must also satisfy specific timing requirements. *Timing requirements* include things such as the maximum allowable time delay between a specified input and the responding output action. However, it is very difficult to design and implement traffic simulations which will guarantee that the appropriate output will be generated at the appropriate times under all possible traffic conditions. This leads to the simulation termination problem [Abrams et al. 1991]:

Given a nonterminating simulation problem and a termination condition, specify how program may be terminated at the simulation time that satisfies the termination condition. It consists of three steps:

1. Find a value of simulation time t when the termination condition is satisfied,
2. Collect and report output measures at that time t, and
3. Stop execution of the simulation.

Anyway, real-time traffic models are non-trivial and expensive systems to develop. They usually require special hardware for monitoring and dynamic display. In these systems the computer is usually interfaced directly to the physical equipment in the real network and is dedicated to monitoring or controlling the operation of that equipment. An operator's console is required for manual intervention. The human operator is kept constantly informed of the state of the transportation system by displays of various types including graphical ones. Records of the system's state changes are also kept in an information base which can be interrogated by the operators at will, to support decision making in the day-to-day running of systems [Burns et al. 1990].

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