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USING DYNAMIC TRAFFIC ASSIGNMENT IN THE DEVELOPMENT OF A CONGESTION MANAGEMENT SYSTEM

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16. Abstract

This report discusses the use of a dynamic traffic assignment (DTA) model as an analytical tool for a congestion management system (CMS). State agencies and metropolitan planning organizations have expressed a growing need for improved analytical tools to evaluate congestion mitigation strategies as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The static assignment models used today are not capable of satisfactorily addressing the CMS requirements. The difficulties associated with the traditional static approaches provide an opportunity to evaluate the feasibility of using DTA for transportation planning in the context of congestion management. This research examines the capabilities introduced by dynamic traffic assignment and its potential to play a valuable role in congestion management. Experiments include the evaluation of several congestion management strategies with static and dynamic traffic assignment models to stress the strengths and weaknesses of both approaches. Finally, the CMS functional requirements are reviewed in connection with the static and dynamic modeling capabilities.

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Chapter 1

INTRODUCTION

1.1 Background

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) required all states to develop and implement a congestion management system (CMS) [1]. ISTEA defines a congestion management system as a process of data collection and analysis. This process includes monitoring existing transportation system performance and evaluating strategies with the potential to reduce traffic congestion and improve mobility. The CMS, once implemented, will serve as a decision-support tool and an integral part of the transportation planning process. However, new analytical tools are needed to model and evaluate the potential benefits of congestion management as part of the CMS program. Under ISTEA, states and other government agencies began to recognize the positive benefits of congestion management in the planning process. As these benefits continue to be realized, a more thorough understanding of congestion and the need for better approaches to mitigate congestion will be achieved.

The National Highway System Designation Act of 1995 repealed the ISTEA mandate giving states the option to develop a CMS (although it remains a requirement in transportation management areas). Regardless of the repeal, however, many states continue the development of fully operational congestion management systems in consideration of the need for a systematic program to encourage more efficient use of the existing network and infrastructure.

Although single occupant vehicle (SOV) travel is becoming increasingly more prevalent in this society, rising construction costs and environmental impacts limit the amount of additional roadway capacity that can be provided. Recent legislation, such as the 1990 Clean Air Act Amendments, included environmental regulations that restricted building SOV capacity to reduce congestion [2]. ISTEA shifts the focus away from construction and towards effective management of the existing infrastructure. The intent of a CMS, and ISTEA in general, is to introduce multi-modal and nontraditional alternatives to mitigate congestion through the integration of new and existing approaches. Another goal of the ISTEA legislation involves developing a framework to address deficiencies in the transportation planning process, particularly the lack of analytical tools for evaluating alternatives to reduce the severity of congestion. Some states, such as Washington, have previously enacted growth management legislation that advocates a similar philosophy [2, 3, 4].

1.2 Motivation and Problem Definition

State agencies and metropolitan planning organizations have a strong desire for improved analytical tools to evaluate the benefits of potential congestion mitigation strategies. This need exists because the traditional static assignment models have limited capabilities when it comes to fulfilling the requirements of an operational congestion management system. Furthermore, the necessity for these tools existed long before the congestion management system came about. It is only recently that the need for such analytical tools has intensified. New and better tools play an important role in designing a functional and effective congestion management system. Through an operational CMS, areas with the potential for recurring congestion can be identified prior to undesirable increases in vehicular demand and delay occurring.

As state agencies and metropolitan planning organizations work toward the development of a functional congestion management system, shortcomings of the existing planning process make this task more difficult. The static travel forecasting models used in practice today were developed with evaluation of long-term transportation planning applications in mind, and, therefore, are not suitable for assessing the benefits of congestion mitigation alternatives as dictated by a CMS [5]. Nevertheless, the state-of-the-practice in congestion management continues to rely exclusively on static approaches for transportation planning and traffic assignment.

Static traffic assignment assumes that travel demands remain constant over time. However, this assumption does not always hold, particularly during peak periods in urban areas. Another disadvantage of this approach is the potential to ignore or misrepresent dynamic effects such as congestion and incidents [6]. Additionally, the use of static assignment for short-term conditions such as traffic maintenance has been questioned due to its inability to model the effects of traffic control devices in the network. These are critical issues when it comes to accurately modeling and predicting real world traffic conditions.

The role of static traffic assignment has been accepted for a long time, although new methods, such as dynamic traffic assignment (DTA), present a unique opportunity to evaluate the potential benefits of state-of-the-art modeling techniques for use in congestion management and transportation system planning. A dynamic model captures daily traffic variations with a level of detail that is far greater than a static model is capable of providing. With respect to congestion management, this detail is essential for identification of the precise locations and severity of traffic congestion. The application of DTA advocates a transition from state-of-the-practice to state-of-the-art in transportation planning.

This research explores the feasibility of the dynamic traffic assignment model to satisfy the functional requirements of a congestion management system. A primary objective is to determine whether DTA can better fulfill the CMS functional requirements compared with traditional static models. The findings are generalized to examine the applicability of DTA in widespread transportation planning applications.

1.3 Research Contributions

Several reasons exist for undertaking this research subject. Congestion management is at the core of transportation planning. By exploring new approaches, in this case dynamic traffic assignment, new analytic tools may be discovered to provide a clearer understanding of present and future traffic conditions. To move forward, the strengths and weaknesses of the static approach must be fully understood in order to accept a shift toward embracing new modeling techniques for congestion management. With these ideas in mind, the primary contributions of this work are as follows:

1. Provide a better understanding of what is expected from a congestion management system including the need for new analytical procedures.
2. Identify the limitations of static models in fulfilling the functional requirements of a congestion management system.
3. Demonstrate the feasibility of dynamic assignment for transportation planning purposes.
4. Outline the assumptions and data requirements associated with using dynamic traffic assignment for the modeling component of a congestion management system.

1.4 Overview of the Report

The chapters are organized as follows. Chapter 2 describes the state-of-the-practice in congestion management and assignment modeling as determined from a comprehensive literature review.

Chapter 3 describes the simulation-based dynamic traffic assignment model employed in this research. Discussions of the input data requirements, algorithm methodology and output results are included.

Chapter 4 identifies the functional requirements of a congestion management system as established by ISTEA.

Chapter 5 contains the experimental design and results of the research. We introduce an approach to evaluate congestion mitigation alternatives using DTA as a planning model. The scenarios evaluated using DTA are defined along with the modeling assumptions and compared to the results obtained from a static assignment model. Both dynamic and static traffic assignment approaches are reviewed in terms of each model's ability to evaluate the potential congestion mitigation strategies outlined in ISTEA.

Chapter 6 summarizes the results of the experiments and contains concluding comments on the thesis. Additional thoughts on the application of dynamic models for planning purposes and congestion management are included.

The Appendix includes a pre-print of a paper based on this research that was accepted for publication the American Society of Civil Engineers.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

A literature review was conducted to better understand the status and development of congestion management systems at the state and metropolitan levels. Static traffic assignment was examined in terms of its current role in transportation planning and potential use in congestion management applications. An overview of various dynamic traffic assignment models was performed with an emphasis on the applicability of each approach to transportation planning and congestion management.

2.2 Congestion Management Systems

Urban congestion has increasingly become more of a problem in recent years giving rise to excessive fuel consumption and increased vehicular emissions. In response to these and other growing concerns, the interest in congestion management has intensified to support the tasks of identifying and addressing congestion and its causes. Since the solution to reducing congestion can no longer rely solely on capital improvement projects to provide additional highway capacity, the most recent approach, which complies with ISTEA, is to make better use of the existing infrastructure. This can be accomplished by developing a methodology to assist decision-makers with problem identification and solution evaluation procedures, namely a congestion management system. Several states and metropolitan areas have developed preliminary CMS frameworks; however, most states remain far away from implementing an operational CMS.

In order to understand where the state-of-the-practice of congestion management stands, an extensive review of the congestion management plans under development in several states and metropolitan areas was conducted. Most of the published literature emphasizes the need for a systematic framework and identification of performance measures to quantify congestion levels on freeways and arterial streets. Other areas of concern include data collection and the application of Intelligent Transportation System (ITS) technologies. Unfortunately, the published information does not address the modeling aspects of a congestion management system in any detail. At this point, most states are still trying to identify the components and methodology necessary to move forward with the development of an operational CMS.

As for the need and availability of data, many agencies maintain databases containing information on roadway inventories, origin-destination surveys and historical travel patterns. A recent study in Ohio determined that traffic data are readily available from the Ohio Department of Transportation for both operational and planning activities [7]. Additionally, a traffic monitoring system is in place, which supplies traffic data to state agencies, metropolitan planning organizations and the Federal Highway Administration [7]. Data from the monitoring system include average daily traffic (ADT) volumes, vehicle classifications and intersection turning movement volumes.

In the Washington, D.C., metropolitan area, the emphasis of congestion management is on data management and the identification of performance measures [2]. Travel time has been selected as an appropriate congestion indicator for the CMS. Many issues have yet to be resolved so the CMS remains in the conceptual stages of development.

In Albany, New York, the regional planning commission revised its ten-year mobility plan upon passage of ISTEA [3]. At this point, the CMS work plan calls for expanding the data collection effort to obtain intersection volumes and conduct household travel surveys. The CMS performance measures consist of travel time and excess vehicle hours of delay. No details have been finalized regarding the implementation of a congestion management system.

The Washington State Department of Transportation (WSDOT) and the Puget Sound region have been working on a plan to monitor urban congestion [3, 8, 9]. In the Puget Sound region, the plan, in the past, has been to accept a high level of congestion in hopes that it will discourage SOV travel and encourage the use of public transportation [3]. Now the use of ITS technologies is being explored. One possibility is to place transponders on public buses to collect data on travel times and vehicle performance. Congestion monitoring is being studied by WSDOT as a potential alternative to congestion management [8, 9]. The argument is that transportation models are not capable of accurately predicting the impacts of congestion mitigation strategies. A monitoring system supported with ITS technology, on the other hand, can provide accurate, up-to-date information. However, the problem with evaluating future traffic conditions remains if a traffic monitoring system is implemented without any capabilities for modeling future traffic conditions. Although congestion monitoring may address operational issues, it is not suited for long-term planning applications or evaluation of measures to relieve congestion. Both WSDOT and Puget Sound have decided to use travel time as the primary indicator of congestion.

The only information found on the use of transportation models was a single study stating that the use of models is preferred since fairly reliable results, including travel time estimates, can be obtained [2]. At this point, most states have not yet narrowed the focus to modeling issues.

In summary, the current work involves identifying measures that can be used to quantify congestion. The majority of the states seem to agree that travel time is a good indicator of congestion since it is a good link-level and corridor-wide measure, and sensitive to changes in the network. The use of ITS technologies was also mentioned as another method to collect traffic data, which can be used for operational and planning purposes. The literature did not, however, contain any detailed information on current congestion management modeling approaches. Many states and local agencies are still attempting to define the scope and functional requirements of a congestion management system.

2.3 Static Traffic Assignment and Congestion Management

Transportation planning employs static traffic assignment as part of the Urban Transportation Model System (UTMS). The UTMS includes four steps: trip generation, trip distribution, modal split and traffic assignment. All four components are important, but the traffic assignment step is most relevant to this research. Static traffic assignment is an iterative procedure that determines the amount of traffic that travels on each link in the network based on a fixed origin-destination trip table.

The Ohio Department of Transportation modified its static traffic assignment approach to produce statistics that can be used to approximate the location and severity of congestion on an aggregate level [10]. This process splits the twenty four-hour link volumes into hourly flows for each hour of the day. This is typically done as a post-processor to the travel demand model. The twenty four-hour origin-destination trip table is factored to obtain a three or four hour peak period trip table for the assignment step. The link hourly volumes are adjusted with factors that account for daily and seasonal effects, auto equivalency and the percentage of the daily traffic. These volumes are broken down to obtain the directional distribution and percentage of traffic during peak periods. The static traffic assignment model outputs are aggregate measures for the entire analysis period, which include link travel time and average speed. This procedure can be extended to congestion management by calculating link hourly delays when the post-processed speed is less than the free flow speed, which provides a quantitative estimate of congestion on each link. However, this method assumes that the link flows and travel times do not vary during the analysis period, although this is not always true. This assumption may be acceptable for off-peak periods, but it fails to hold during peak hours when a dramatic increase in demand takes place. Application of different demands for the morning and evening peak periods still does not enable the model to capture or accurately predict traffic flows, incidents or other events that vary over time.

2.4 Dynamic Traffic Assignment Models

Research on dynamic traffic assignment is advancing at a rapid pace. DTA models were originally intended for short-term, real-time (operational) purposes. Therefore, much of the early work on dynamic traffic assignment was directed toward real-time traffic applications. Now these same models are being evaluated for use in transportation planning applications such as congestion management. Dynamic models have the capability to predict the time-dependent variations in traffic flow, whether the effect of recurring congestion, road construction or an accident. These models can capture traffic variations with a level of detail and accuracy that cannot be achieved by the traditional static models. This is the type of information that is useful to a congestion management system. The CMS requires link level data that is specific enough to identify the location, duration and severity of congestion. Due to the formulation of dynamic models, they can provide a more realistic representation of traffic flow and network conditions, which is desirable for congestion management where decisions are based on analytical results. Different approaches have been taken to solve the dynamic assignment problem, although limitations are associated with each formulation. These DTA modeling approaches are presented below.

The early work on dynamic assignment began with Merchant and Nemhauser who developed a mathematical program for the dynamic assignment problem [11, 12]. The analytical approach formulates the problem as a mathematical program with an objective function. Desirable properties exist with this method because optimality can be guaranteed. However, this problem is typically difficult to formulate and cannot be solved for multiple destinations. In order for the model to be useful in congestion management it must be able to handle networks of realistic size. Analytic formulations, including mathematical programming, are limited in their ability to realistically represent traffic networks and may violate the first-in, first-out property (FIFO). The FIFO property guarantees that a vehicle cannot "jump" over another vehicle that departed at an earlier time. Essentially, a vehicle can not leave later and arrive at its destination earlier without violating FIFO. Carey [13, 14] and Janson

[15, 16] have also developed mathematical programming approaches that encounter the same restrictions.

Ziliaskopoulos recently introduced a linear programming formulation of the system optimum dynamic traffic assignment problem [17]. This formulation is based on Daganzo's cell transmission model [18, 19], which may capture flow variations within the cell (i.e., link). The linear program minimizes the total network travel time, subject to a set of constraints, for the single destination problem. Although the approach does provide valuable insight into DTA, it is not practical for networks of realistic size.

Other approaches by Friesz et al. [20] and Ran et al. [21] apply optimal control theory. Like the analytical formulation, drawbacks exist with the optimal control theory approach. For example, a different formulation is required for the system optimum and user equilibrium dynamic traffic assignments, and the FIFO property is not always guaranteed.

Mahmassani and Jayakrishnan developed a simulation-based dynamic traffic assignment model [22, 23]. The model computes time-dependent directional flows from time-dependent origin-destination trip tables. The built-in traffic simulator moves all vehicles on a link while keeping track of their individual positions. The drawback to the simulation-based approach is that it lacks the analytical properties found in the mathematical programming and optimal control theory approaches such as guaranteed convergence. The simulation approach is heuristic in nature so optimality can not be guaranteed. The capabilities include modeling the effects of ramp metering, variable message signs, traffic control, incidents and bus operations [24]. Since computational time is not an issue with planning applications, the simulation-based DTA model can be used to evaluate various improvement strategies on large-scale networks that are associated with a congestion management system (e.g., incident management, ITS technologies and operational improvements).

DTA provides the capability to predict temporal fluctuations associated with demand, construction or the occurrence of an incident on the network. Link specific output measures provide detailed information on travel conditions as a function of time to detect changes during the peak hours of the day. These qualifications suggest that DTA, particularly the simulation-based approach, could be a valuable tool in the area of congestion management. Using a dynamic model as part of a CMS will permit evaluation of various strategies to quantify the benefit of specific improvements in mitigating congestion. Chapter 4 describes the simulation-based dynamic assignment model developed by Mahmassani and Jayakrishnan, which is employed in this research, in greater detail.

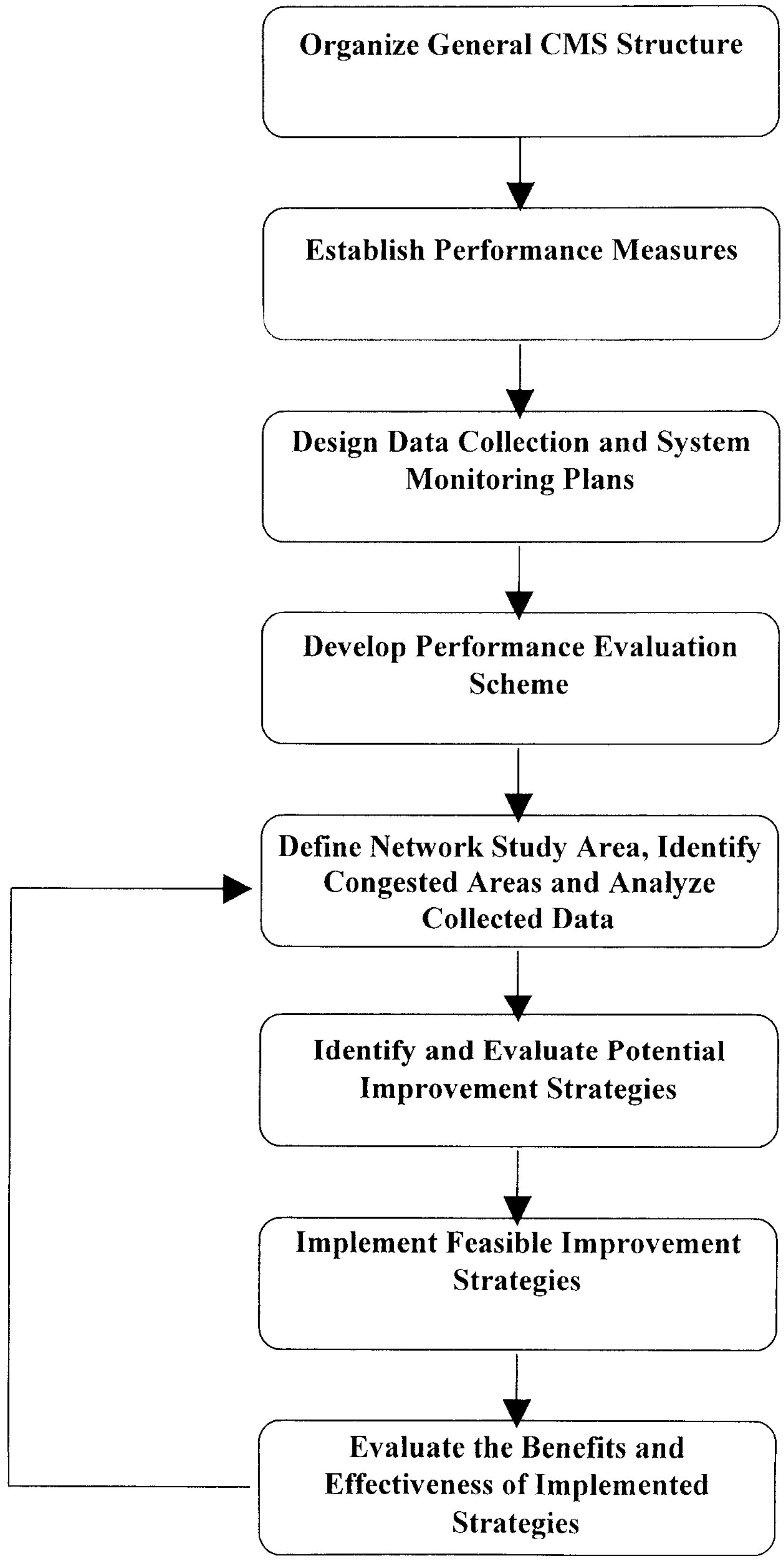
Chapter 3

CONGESTION MANAGEMENT SYSTEM FUNCTIONAL REQUIREMENTS

3.1 Congestion Management System Components

The ISTEA legislation calls for the development and implementation of a traffic congestion management system (CMS). The CMS is optional at the state level, but mandatory in all transportation management areas (population over 200,000). A congestion management system monitors and evaluates transportation system performance, identifies and carries out cost-effective congestion mitigation strategies and evaluates the effectiveness of implemented improvements [1]. Essentially, a congestion management system is a tool to assist state and local agencies in the decision-making process for transportation improvement and congestion mitigation projects. The CMS is partially an iterative process since new alternatives are continually being evaluated and the transportation network is constantly monitored and updated to reduce or eliminate recurring congestion. Figure 3.1 shows the functional requirements associated with CMS development.

Figure 3.1 Congestion Management System Conceptual Framework [1, 2]



ISTEA contains several requirements for a congestion management system. First of all, a thorough understanding of the purpose, scope and requirements of a CMS must be achieved to develop a useful management system. The structure of the CMS should be organized such that it can incorporate new approaches and technologies as they become available. The CMS should also be able to address alternative modes of transportation such as buses and light rail.

The next step involves establishing a set of performance measures. Emphasis should be placed on selecting indicators that are easy to comprehend and capable of capturing the extent and severity of the congestion. Performance measures such as travel time, average speed and vehicular delay can play an important part in quantifying the level of congestion on a link, corridor or network. The performance measures must address the needs of a CMS as stated in ISTEA and those of the particular state or local agency executing the operational congestion management system.

The usefulness of a CMS depends on the types and quality of data collected in relation to the performance measures and modeling process used. Therefore, after establishing a set of performance measures, a program should be organized to collect (new and existing) data and monitor transportation system performance. When designing this program, the data collection and modeling issues should be considered jointly. Accurate data are necessary to support the modeling process and produce analytical results that are consistent with the previously identified performance measures. The modeling process consists of using an analytical tool, such as a traffic assignment model, to evaluate the performance of the transportation system with respect to congestion management. The model employed for performance evaluation plays an important role in providing the information needed to select a feasible and cost-effective mitigation strategy for implementation.

As part of the data collection and modeling step, limits of the transportation network must be established to define the study area. The study area is the region to be monitored for the location and occurrence of congestion. Analysis of data gathered as part of the data collection program will assist in identifying congested areas for further evaluation. The network requires periodic updates and modifications to account for factors such as urban growth and changing travel patterns.

ISTEA lists several strategies to consider as possible solutions for congested areas. State and local agencies may also identify additional strategies for consideration. Section 3.2 contains a discussion of the potential mitigation strategies outlined in ISTEA. After identifying potential strategies, the feasible improvements should be evaluated to determine the benefits and effectiveness of each action in reducing congestion. The objective is to implement the most efficient and cost-effective solution to reduce delay and improve mobility.

The final product from a CMS is information supporting a particular recommendation for congestion mitigation on a specific link or corridor. This information can be used by decision-makers to select projects for construction and implementation as part of the metropolitan or statewide transportation improvement programs.

3.2 Congestion Management System Mitigation Strategies

ISTEA lists several congestion mitigation strategies to consider as part of a congestion management system. The strategies range from simple capacity improvements to implementation of ITS technologies. Table 3.1 lists several congestion mitigation strategies.

TABLE 3.1 Proposed Congestion Management Strategies Outlined in ISTEA [1]

Proposed CMS Strategies
Traffic Operational Improvements
Incident Management
Congestion Pricing
ITS Technology
Access Management
General Purpose Lane Additions
Public Transit Operational Improvements
Transportation Demand Management

Traffic operational improvements include widening roadways, installing traffic control systems and ramp metering. Controlling the flow of traffic entering a freeway with a ramp meter, for example, enables the flow on the mainline freeway to continue uninterrupted while delaying vehicles on the ramp, therefore reducing freeway congestion.

Incident management includes methods to facilitate response to accidents or disabled vehicles on a roadway. Incidents and special events (e.g., road construction/maintenance, sporting events) produce nonrecurring congestion. Recurring congestion occurs at the same location on a daily basis whereas nonrecurring congestion is a periodic, unexpected occurrence. However, nonrecurring congestion does produce a significant amount of delay and requires attention from a congestion management system when appropriate.

Congestion pricing is a policy where fees or tolls are imposed on users of certain highways or lanes. This strategy is used to encourage high occupancy vehicle use, which reduces the total traffic on a given facility.

Intelligent Transportation System (ITS) technologies include in-vehicle navigation and information systems. The objective of this strategy is to alert motorists of congestion and provide route guidance to avoid an affected area. Variable message signs and highway advisory radio are frequently used to provide drivers with similar information.

Access management encompasses techniques such as the spacing between driveways, elimination of left turns or construction of a center median on an arterial street. These strategies protect the flow on the arterial by restricting disturbances from turning vehicles.

Adding new lanes is not always a desirable solution since they encourage single occupant vehicle (SOV) travel, although when multi-modal alternatives are not feasible, general-purpose lane additions merit consideration. Constructing new SOV lanes increases roadway capacity thereby reducing delay and improving flow.

Public transit improvements introduce multi-modal alternatives such as park-and-ride lots and exclusive rights-of-way for buses and light rail. Improving the access to and operation of public transit facilities reduces the demand for SOV travel.

Transportation demand management reduces SOV travel by introducing flexible scheduling for employee work hours, telecommuting and carpooling. The goal is to lessen the burden on the roadway network during peak hours of congestion by decreasing the demand.

Chapter 4

SIMULATION-BASED DYNAMIC TRAFFIC ASSIGNMENT

4.1 Introduction

This chapter describes the simulation-based dynamic traffic assignment model employed in this research. The simulation-based DTA was originally developed for real-time applications to provide drivers with information through Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS) [24]. A central controller would use the information to provide route guidance to motorists on a real-time basis. In order to communicate this information in real-time, more advanced algorithms and methodologies were needed. The conceptual, algorithmic and mathematical frameworks have been established to produce an operational simulation-based dynamic traffic assignment model. This research takes the operational DTA model and applies it as an analytical tool for congestion management.

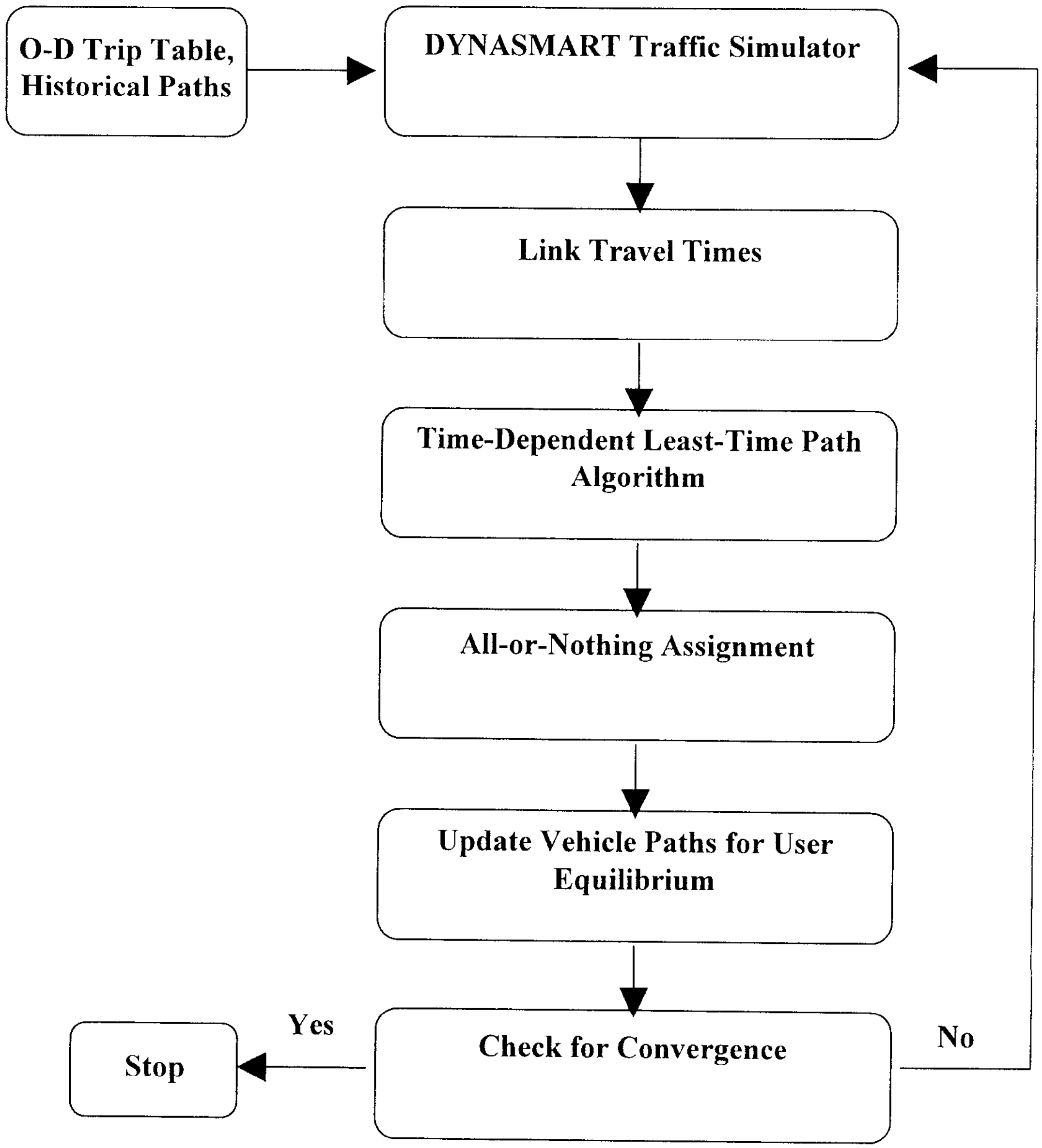
4.2 Algorithm Methodology

A simulation-assignment algorithm has been developed to solve the user equilibrium (UE) dynamic traffic assignment problem and the system optimum (SO) dynamic traffic assignment problem [24]. The SO formulation seeks to determine the minimum total network travel time. Not all users are assigned to their least-time or least-cost paths since the objective is to benefit the entire system as a whole and not individual users. The UE DTA formulation is believed to be the way drivers actually behave. Every user attempts to minimize his/her travel time without consideration of other users on the network, as would be the case when severely congested conditions exist. The UE approach is used in this research because it most accurately represents true driver behavior. The solution methodology for the UE dynamic traffic assignment problem is presented below. A flow chart illustrating the user equilibrium DTA solution procedure is provided in Figure 4.1.

The algorithmic steps, as stated by Mahmassani et al. [24], are as follows:

1. Set the iteration counter I = 0. Obtain the time-dependent historical paths (paths obtained from database) for each assignment time step over the entire duration for which assignment is sought.
2. Assign the O-D desires (which are known a priori for the entire peak period) for the entire duration to the given paths and simulate the traffic patterns that result from the assignment using DYNASMART.
3. Compute the link travel times using time-dependent experienced or estimated link travel times and the number of vehicles on links obtained as post-simulation data (from step 2).

FIGURE 4.1 Dynamic Traffic Assignment Model: User Equilibrium Solution Algorithm [24]



4. Using a time-dependent least-time path algorithm, compute the shortest average time paths for each O-D pair for each assignment time step based on the travel times obtained in step 3.
5. Perform an all-or-nothing assignment of O-D desires to the shortest average travel time paths computed in the previous step. The result is a set of auxiliary path vehicle numbers for each O-D pair for each assignment time step t =1,..., T.
6. Update paths and the number of users assigned to those paths. Update of paths is done by checking if the path identified in step 4 already exists (i.e., has carried vehicles in at least one prior iteration) for that O-D pair and including it if it does not. The update of the number of vehicles (assignment of vehicles to the various paths currently defined between the O-D pair after the path update) is performed using the Method of Successive Averages (MSA), which takes a convex combination of the current path and correspondingly auxiliary path numbers of vehicles, for each O-D pair and each time step. This is based on the scheme developed by Sheffi and Powell. Note that other convex combination schemes could equally be used.
7. Check for convergence using an ϵ–convergence criterion (in terms of the difference between iterations in number of users on each path).
8. If convergence criterion is satisfied, stop the program. Otherwise, update the iteration counter I = I + 1 and go to step 2 with the updated data on paths and the number of vehicles assigned to each of those paths.

4.3 Traffic Simulator

The user equilibrium (UE) single user class dynamic traffic assignment model is applied as a planning level model in this research. The UE method solves for the time-dependent vehicle assignment to travel paths between every O-D pair so that no user can unilaterally switch paths to improve his/her travel time for a given time of departure. The DYNASMART traffic simulator assigns the time-varying travel demands and models the travel patterns that result from this demand by moving vehicles between links in the network. DYNASMART is an analytical tool within the DTA model that permits evaluation of various traffic control strategies, capacity improvements and other management strategies. The simulation component of this DTA model provides the capability to evaluate various improvement strategies, which is essential to a congestion management system.

The functional requirements of a simulation model include capabilities to simulate both freeways and arterial streets as an integrated network. This is necessary to accurately model and evaluate the performance of a given transportation system. Additional functional requirements are summarized in Table 4.1.

TABLE 4.1 Functional Requirements of DYNASMART [24]

Functional Requirements of Simulator to Represent Surface Streets
• Realistic representation of traffic control devices
• Modeling capability of various link geometric configurations
• Accurate measurement of system effectiveness on link-specific and network-wide basis
• Ability to simulate trip generation and destinations
• Model bus operations
Functional Requirements of Simulator to Represent Freeways
• Realistic representation of geometric configurations and traffic attributes
• Simulation of traffic control devices and freeway ramp flows
• Provide measures of effectiveness for link-specific and network-wide analysis

DYNASMART was originally designed for ATMS and ATIS purposes, but it is flexible enough that new and emerging applications can be easily added. The capabilities of DYNASMART are listed below.

1. Simulates traffic characteristics at the individual or packet level
2. Models multiple user classes according to driver behavior, vehicle classification (car, truck, bus) and information supply
3. Records the travel path and location of vehicles at the individual or packet level
4. Incorporates various traffic signal control strategies for freeways and arterial streets
5. Models traffic disturbances due to the occurrence of incidents
6. Produces output at the system, link and vehicle levels

The purpose of a traffic simulator is to replicate traffic dynamics based on vehicle path assignments. In order for DYNASMART to produce a realistic representation, it was designed with traffic flow, path processing, driver behavior and information supply strategies in mind. All of these components were integrated into the simulation-assignment model. The simulator's heuristic iterative solution procedure models network traffic interactions and evaluates the system performance for given conditions. DYNASMART is based on macroscopic traffic flow relations and moves vehicles in packets (representing a single vehicle) according to speed-density relations. Therefore, the simulator can keep track of every vehicle in the network. DYNASMART monitors the location of vehicles at every time step. Since this is not a microscopic approach, not every detail for individual vehicles is recorded. Vehicles are moved from link to link at every time step in the simulation run within the constraints of the link capacity and traffic control strategies in operation.

The drawback to DTA and DYNASMART is the extensive data requirements. The DYNASMART simulator has the following inputs:

1. Time-dependent O-D matrices
2. Network characteristics (links, nodes)
3. Traffic control devices (signals, stop signs, yield signs)
4. Incident information (location, duration, severity)
5. Freeway ramp control (ramp metering)
6. Additional information on growth factors and vehicle movements

The time-dependent O-D table is a difficult piece of data to collect. Therefore, a profile can be applied to a given O-D table to represent time-varying demands. The profile will generate vehicles according to a typical peak period pattern with a gradual build-up of traffic followed by a period of decline, similar to a bell-shaped curve.

There are a number of traffic control strategies that DYNASMART can accommodate. Freeways and arterial streets are represented by the strategies listed in Table 4.2.

DYNASMART simulates signal control although the user must input the offsets and cycle times since this will not optimize signal control. Traffic is modeled by considering the vehicle travel time and queue time.

TABLE 4.2 Traffic Control Elements Represented in DYNASMART [24]

Intersection and Link Geometry	
Surface Streets	***Freeways***
Saturation flow rate	Link capacity
Number of lanes	Number of lanes
Number of approaches	HOV lanes
Types of Control	
Surface Streets	***Freeways***
No Control	Ramp metering
Yield Sign Control	Variable Message Signs
Stop Sign Control	
Traffic signals (pretimed, actuated; cycle length, phasing)	
Measures of Effectiveness	
Surface Streets	***Freeways***
Average Speed	Average Speed
Average Delay	Average Density
Average Travel Time	Average Ramp Queue Length

Incidents are defined as accidents, road construction or traffic maintenance such as temporary or permanent lane closures and other special events. The time of occurrence, duration, severity and location of incidents can be specified in DYNASMART. Incidents are modeled as reductions in available lane capacity on a given link. The severity of an incident is modeled by imposing partial or complete closure of a link during the predetermined time period.

DYNASMART addresses freeway management through ramp metering, HOV lanes and variable message signs. Ramp metering restricts the rate of vehicles entering the freeway to ensure proper performance on the freeway. HOV lanes are used to reduce the travel demand by promoting carpooling and bus usage. Separate links are used to carry only HOV vehicles in the network.

DYNASMART is capable of modeling multiple user classes. Multiple user classes are defined by the driver behavior or information availability from in-vehicle equipment. Variable message signs are used to provide drivers with advisory information on traffic conditions. This action includes route advisory and warning messages. Route advisory supplies drivers with information on alternative paths to avoid congestion. The warning messages include providing a message to alert drivers when congestion exists downstream.

Bus operations are modeled by assuming that a bus is equivalent to two passenger cars. The input information includes the dwell time at stops, specified bus route and other activities associated with bus operations such as mid-block stops. Bus stops cause temporary lane closures that are accounted for within DYNASMART. Stops at intersections are considered lane closures and mid-block stops are simulated as incidents. Buses are integrated with passenger cars in the vehicle mix. In addition to buses, other vehicle types may be modeled as long as a predefined path and fixed departure time are provided.

The output information consists of various statistics to represent average and overall performance measures of the system. The primary output measures are as follows:

1. Average and total travel time
2. Average and total stop time
3. Average and total trip distance
4. Average travel speed

Additional results are produced for vehicle queues, density and the travel path of each vehicle.

These output measures are used to describe the traffic behavior and other characteristics for a given network. The average and total measures provided by DYNASMART allow the user to make comparisons between different loading patterns and observe any trends that may exist between models.

Chapter 3 suggested several congestion mitigation strategies to consider as part of the evaluation process. DYNASMART provides the capability to model CMS strategies that are themselves dynamic. Incident management, for example, requires special treatment due to the dynamics involved. DTA can capture time-varying changes in flow and, therefore, more realistically model real world conditions using the simulator.

Chapter 5

EXPERIMENTAL TESTING AND RESULTS

5.1 Introduction

Experiments will be investigated to demonstrate and evaluate the feasibility and usefulness of dynamic traffic assignment as a CMS tool. Whether DTA can satisfy the CMS functional requirements better than static traffic assignment will be addressed through evaluation of the ISTEA congestion mitigation strategies from Chapter 3.

The DTA model is employed according to user equilibrium criterion. This method is chosen as opposed to a system optimum approach because it is generally accepted that drivers follow user equilibrium routes. For comparative purposes, a static traffic assignment model based on the Frank-Wolfe algorithm is used to solve for the user equilibrium link flows. This approach, also known as the convex combinations algorithm, is based on the minimization of a linear program [25]. The

Frank-Wolfe approach is an efficient method for solving static traffic assignment problems.

5.2 Experiments

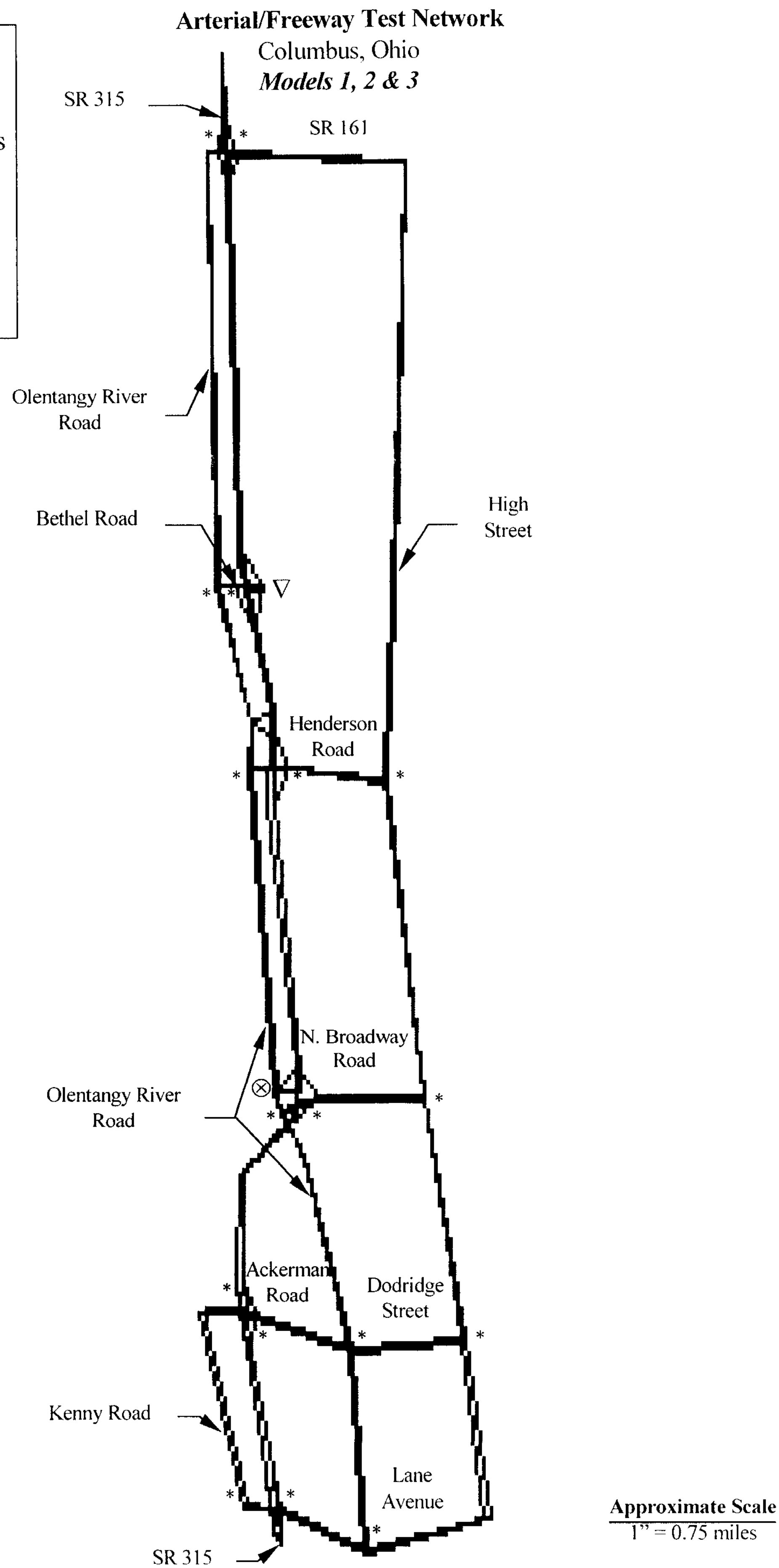
The study area consists of a small arterial/freeway network of Columbus, Ohio. The test network is modeled to represent the actual network, although some geometric and traffic control simplifications were made for analytical purposes. It includes a multi-lane freeway (SR 315) surrounded by an arterial street network. The test network contains 50 nodes, 108 links and 18 origin and destination nodes. Arterial streets contain 2 lanes per direction and freeways have 3 lanes. Entrance and exit freeway ramps are represented as directed arcs with a single lane. There are 12 on-ramps and off-ramps connecting the freeway with the arterial street system. 17 intersections have pretimed signal control while the remaining intersections either have stop or yield signs, or no traffic control devices at all. No ramp or variable message sign control has been used. This information is summarized in Table 5.1 and illustrated in Figure 5.1.

TABLE 5.1 Network Topology

Network Data	Traffic Control Node Data	Ramp Data
50 Nodes	31 No Control Device	No Ramp Control
108 Links	17 Pretimed Signal Control	No Variable Message Signs
18 Origins	1 Stop Sign Control	
18 Destinations	1 Yield Sign Control	

Figure 5.1
Test Network
Existing traffic control devices are indicated as follows:

* - *Traffic Signal (17)*
⊗ - *Stop Sign (1)*
∇ - *Yield Sign (1)*



An origin-destination matrix for this network was extracted from a static origin-destination table of the Columbus metropolitan area. Using the scaled down O-D matrix, 17,097 vehicles are generated for each experiment. This is enough demand to result in the formation of queues and moderate congestion for a period of time during which the peak analysis was performed. This study assumes all vehicles are passenger cars, although the capability exists to include buses and commercial trucks in the vehicle mix. Since a time-dependent O-D table was not available, a profile based on peak period demands was used in its place. Additional analyses using DTA were preformed with a uniform demand (static O-D) to detect the sensitivity of the model to variations in demand.

The simulation consists of a five-minute start-up phase followed by a thirty-minute period divided into six five-minute intervals. The start-up time generates background traffic in the network. Approximately 12% of the traffic is generated during the start-up phase. Statistics are only computed for vehicles generated after the start-up phase. During the thirty-minute period, successive five-minute intervals generate 14%, 18%, 24%, 18% and 14% of the vehicles (for a total of 17097 vehicles) according to the peak period profile. DTA experiments conducted with the static O-D generate about 17% of the traffic in each five-minute interval, including the start-up period. Therefore, some models will generate statistics based on more vehicles than other models.

Using the 50-node network, three principal scenarios are investigated. They are traffic control strategies, increased roadway capacity and incident management. Each scenario addresses a particular CMS strategy described in Chapter 3.

Figure 5.2 shows the existing network evaluated in Experiment #1. Models were evaluated using dynamic traffic assignment, with the static and time-dependent origin-destination matrices, and static traffic assignment based on the Frank-Wolfe algorithm.

Experiment #2, shown in Figure 5.3, investigates the potential for improved arterial flow due to progression and traffic control modifications. The improvements evaluated in this experiment are the coordination of traffic signals on Olentangy River Road and replacement of the existing stop sign with signal control at the SR 315 off-ramp near North Broadway Road. Coordinating traffic signals facilitates progression along a section of roadway. By coordinating several intersections, delay and congestion may be decreased at the link and network levels. This scenario is a simple operational improvement that can save money and reduce congestion without investing large amounts of capital for large-scale improvement projects.

Increased arterial capacity is studied in Experiments #3 and #4. Capacity changes will be investigated through general-purpose lane additions. Experiment #3 increases the capacity on Olentangy River Road from two lanes to three lanes in each direction. The limits of the lane widening improvements are illustrated in Figure 5.4.

Figure 5.2
Base Case
Experiment #1 - *Existing Test Network*

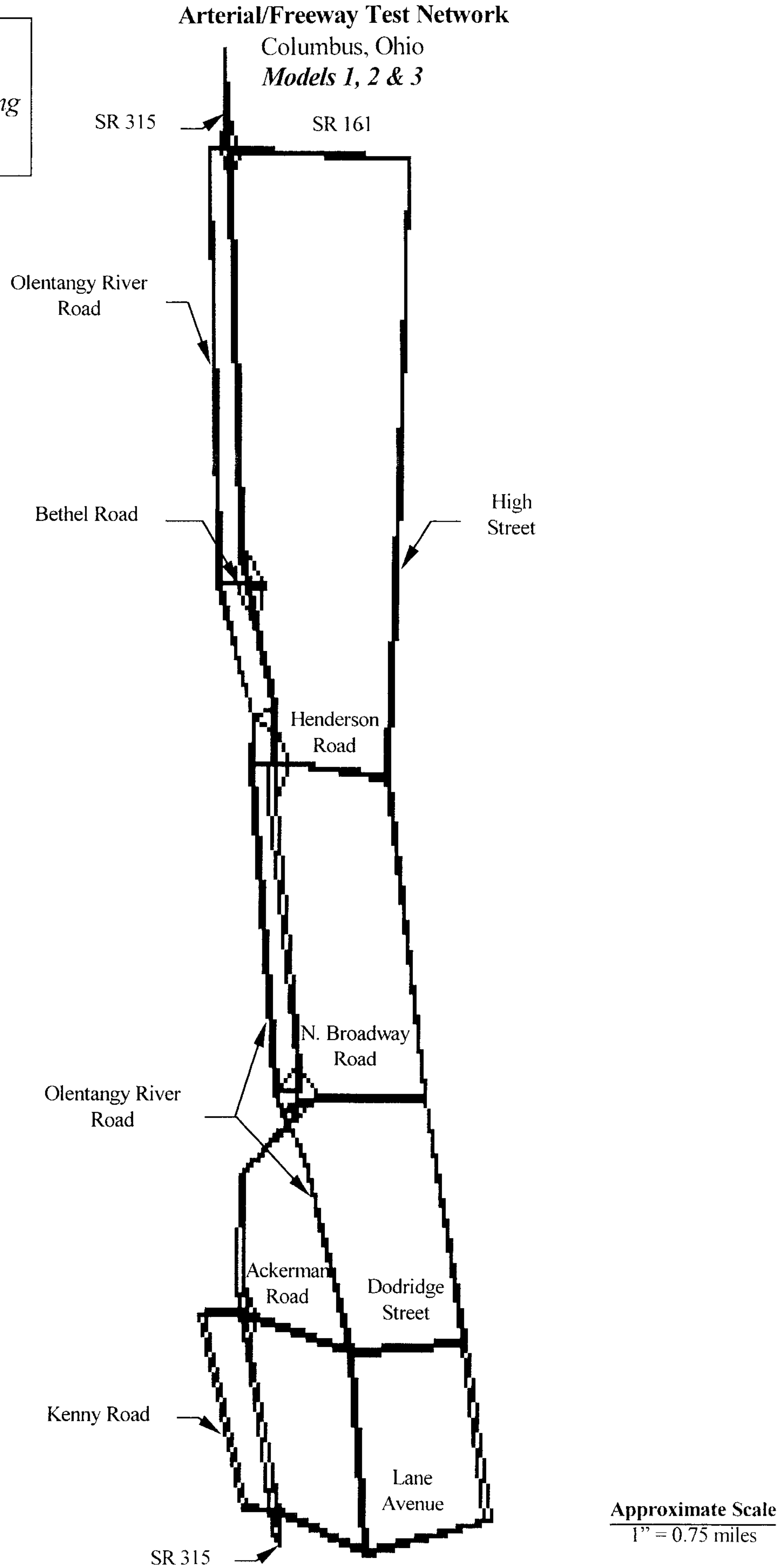
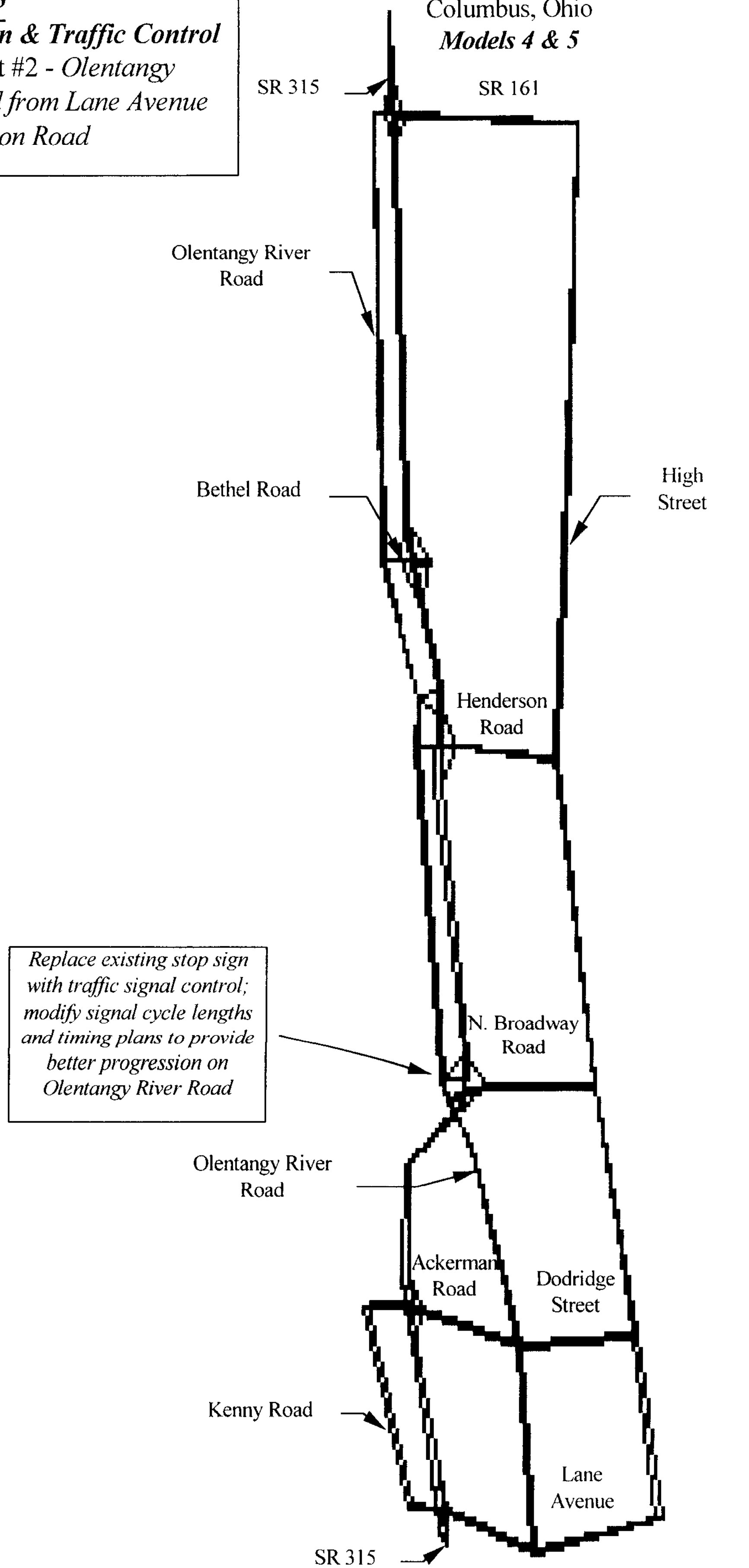


Figure 5.3
Progression & Traffic Control
Experiment #2 - *Olentangy River Road from Lane Avenue to Henderson Road*

Arterial/Freeway Test Network
Columbus, Ohio
Models 4 & 5

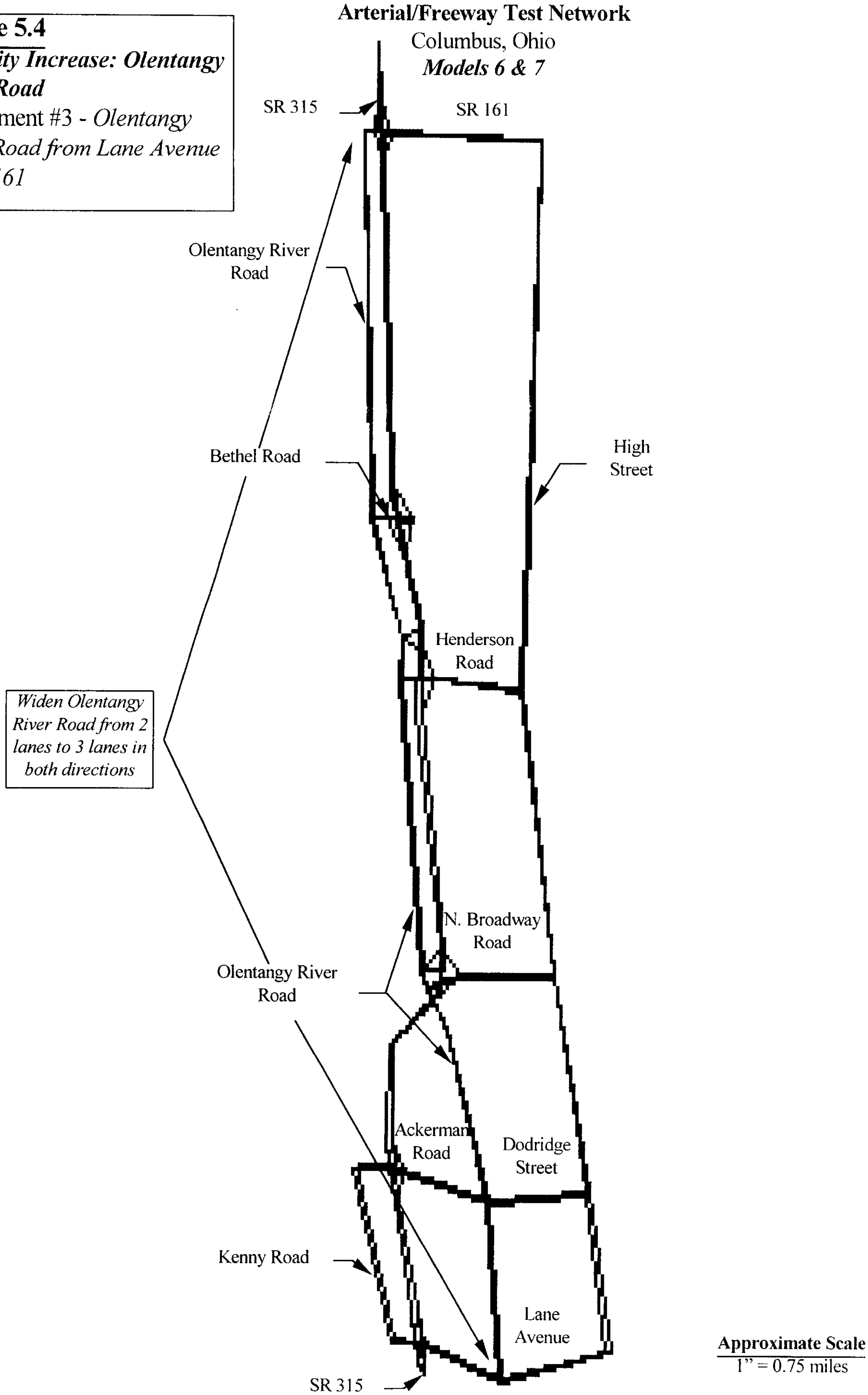


Approximate Scale
1" = 0.75 miles

Figure 5.4

Capacity Increase: Olentangy River Road

Experiment #3 - *Olentangy River Road from Lane Avenue to SR 161*



High Street is widened from two lanes to three lanes in both directions for Experiment #4. Figure 5.5 shows the improvements associated with this scenario.

Experiments #5 and #6 investigate the incident management strategy proposed in ISTEA. The network representation of a freeway incident is shown in Figure 5.6. An incident is created on SR 315 southbound between Bethel Road and Henderson Road imposing a 90% reduction in capacity for a ten-minute period directly after completion of the start-up phase. Experiment #5 assumes all users are provided with full information on the incident and can take a route that avoids the lane closure. This type of incident is similar to road construction where it is common knowledge that a particular link or lane will be closed during certain time periods. This situation looks at the incident as part of the infrastructure to observe how traffic will reroute according to user equilibrium criterion. Experiment #6 models the traffic as though no information is supplied to any motorists. This represents the occurrence of an automobile accident where drivers have no prior knowledge of the event and cannot change their travel paths. The travel paths are simulated to identify how the flow is impeded without computing new paths that account for the incident.

Figure 5.5
Capacity Increase: High Street
Experiment #4 - *High Street from Lane Avenue to SR 161*

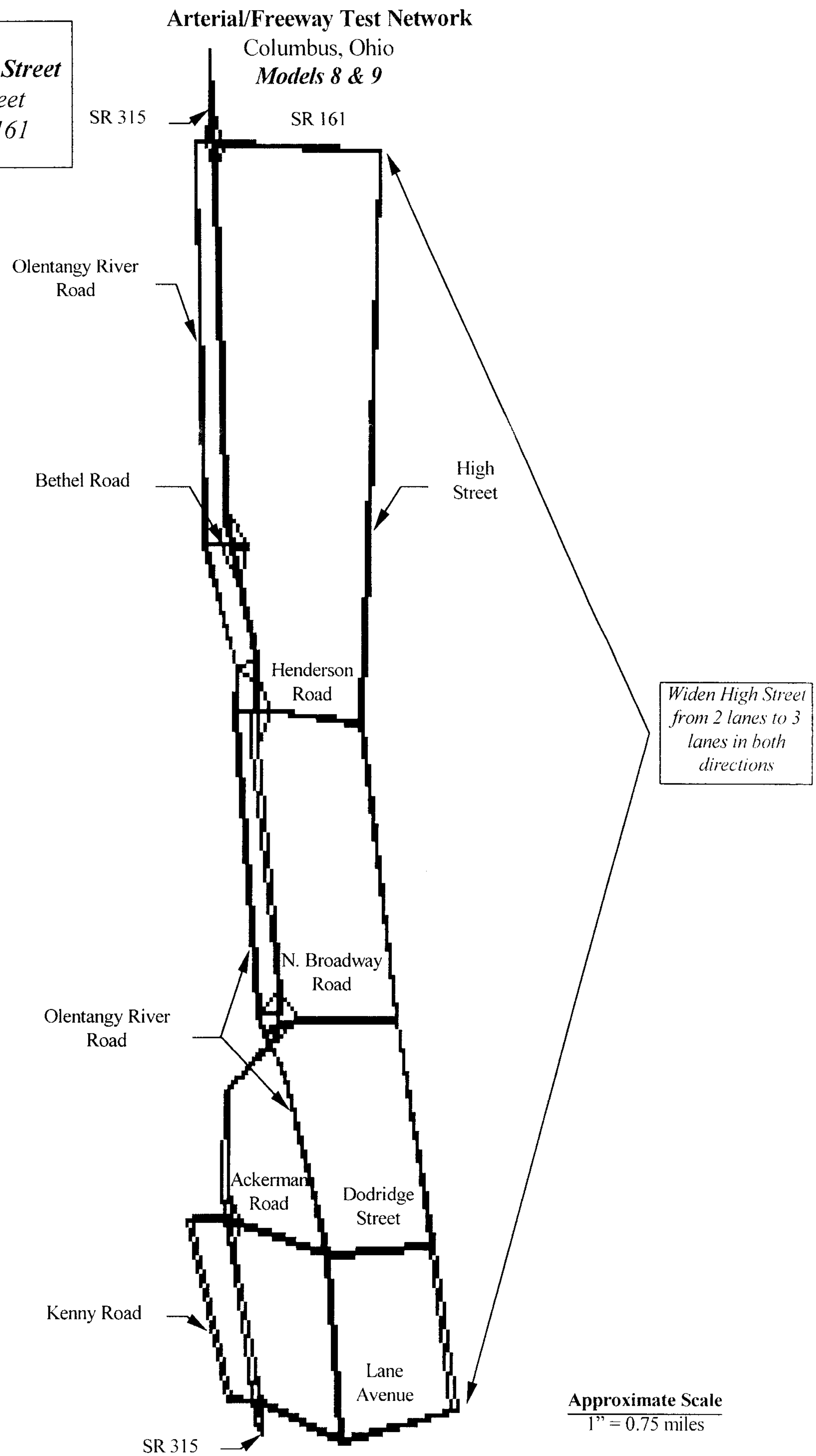
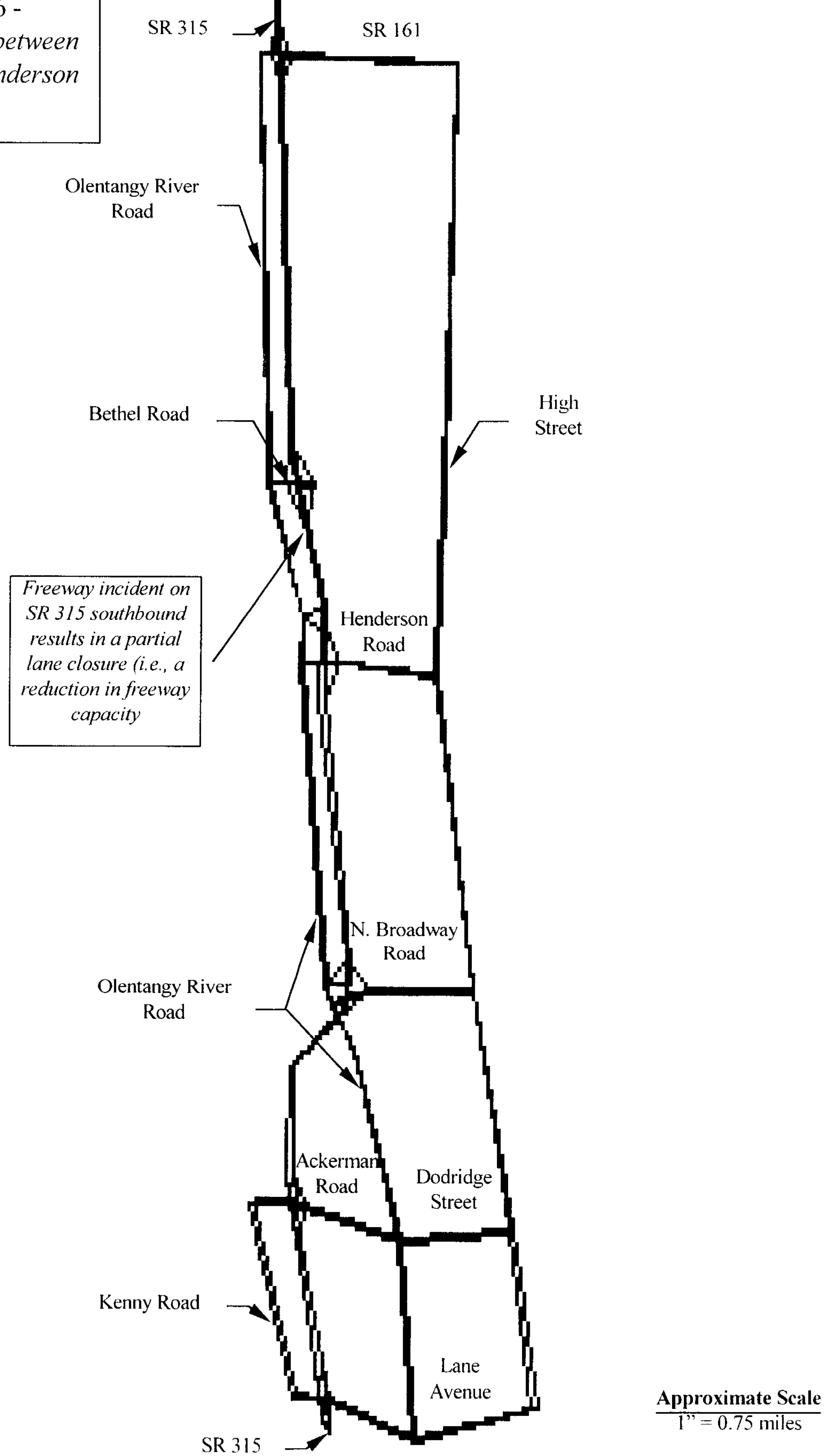


Figure 5.6
Incident Management
Experiments #5 & #6 -
SR 315 southbound between Bethel Road and Henderson Road

Arterial/Freeway Test Network
Columbus, Ohio
Models 10, 11 & 12



5.3 Computational Results

The results from each of the experiments are presented in this section. Statistics are reported for travel time, stop time, trip distance and average speed. The results of the experiments do not represent optimal solution strategies and should be treated simply as representations of modeling capabilities in connection to CMS strategy evaluation.

Experiment #1 – Base Case (Models 1, 2, and 3)

Three models were evaluated as part of the base case. Two models used the dynamic traffic assignment and the other model employed the static traffic assignment approach. Both the time-dependent and fixed (static) origin-destination tables were used in the DTA scenarios. The results of these models are presented in Table 5.2. In comparing the base case models, it is apparent that the static assignment results are significantly different from those of the DTA approach. The average speed for the static model (model 3), for example, is 2.5 and 2.6 times greater than models 2 (fixed O-D) and 1 (time-dependent O-D), respectively. It seems unrealistic that the average speed in this network would exceed forty miles per hour as suggested by the static model. This simple example illustrates how results are influenced by congestion, time-varying demands and traffic control devices. Since the static model cannot model the effects of traffic signals or other control devices, the average speed is much higher than if vehicles have to stop for control devices as in the DTA simulation model. Figure 5.7 illustrates this point by showing the variation in travel time on Henderson Road from models 1 and 3 during the thirty-minute peak period.

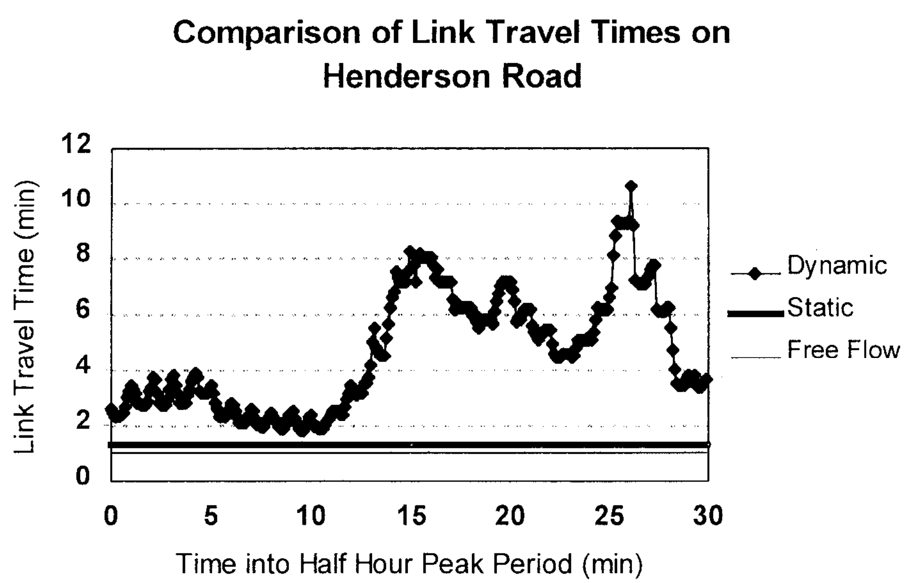
TABLE 5.2 Comparative Results for Experiments #1 - #4

	Experiments								
	Base Case - Experiment #1 *(Existing Test Network)*			**Progression & Traffic Control - Experiment #2** *(Olentangy River Road)*		**Capacity Increase - Experiment #3** *(Olentangy River Road)*		**Capacity Increase - Experiment #4** *(High Street)*	
Model No.	①	②	③	④	⑤	⑥	⑦	⑧	⑨
Statistics	**DTA**	**DTA***	**STA**	**DTA**	**DTA***	**DTA**	**STA**	**DTA**	**STA**
Total Trip Time (hr)	3403.5	2964.1	1586.1	3260.8	2907.7	3115.7	1584.7	3105.4	1584.3
Average Trip Time (min)	13.540	12.458	5.566	12.972	12.221	12.394	5.561	12.364	5.560
Total Stop Time (hr)	976.8	861.4	--	923.7	734.5	910.7	--	845.2	--
Average Stop Time (min)	3.886	3.621	--	3.675	3.087	3.623	--	3.365	--
Total Trip Distance (mi)	55607.1	52096.3	66615.8	55255.9	52294.6	55221.3	66573.8	55677.5	66413.7
Average Trip Distance (mi)	3.687	3.649	3.896	3.664	3.663	3.661	3.894	3.695	3.885
Average Speed (mph)	16.338	17.576	43.021	16.945	17.985	17.724	43.060	17.929	42.996

DTA = Dynamic Traffic Assignment results
STA = Static Traffic Assignment results
* Denotes DTA results based on a *static*, as opposed to time-dependent, origin-destination table

The travel time remains constant for the static model, but the effect of increasing demand during the peak period is rather pronounced in the dynamic formulation with the time-dependent O-D trip table. The static model not only underestimates the average link travel time, but it completely ignores any variation which is influenced through changes in demand and the effect of traffic signals on the link.

FIGURE 5.7 Plot of Arterial Link Travel Times



Comparing models 1 and 2 shows that the time-dependent O-D table does have a dramatic impact on the network performance measures. The analysis with the fixed O-D table produces a higher average speed with decreases in both the trip time and stop time. These results are logical since less congestion is present in the network when a uniform demand is applied over the simulation period.

Experiment #2 – Progression and Traffic Control (Models 4 and 5)

Two DTA models were executed to study the effect of traffic control modifications. Model 4 employed the time-dependent trip table and model 5 used the fixed O-D matrix. Since static traffic assignment cannot evaluate such strategies, no results are available for the static model. The statistical results for Experiment #2 are presented in Table 5.2. The results suggest that a small improvement was produced compared with the base case. The increase in average speed ranged from 2% (model 5) to 4% (model 4) when compared to the respective base case models. In addition, the control strategies reduced the trip time and stop time by about 6% on average. Overall, the traffic control experiment yielded an enhancement in system-wide performance. This implies that the DTA is capable of evaluating traffic control strategies and producing reasonable results for congestion management applications.

Experiment #3 – Capacity Increase: Olentangy River Road (Models 6 and 7)

Increased capacity on Olentangy River Road was modeled using the dynamic and static approaches. Model 6 employed the time-dependent O-D matrix for the DTA model and model 7 used static traffic assignment. The results for Experiment #3 are included in Table 5.2. Each model was compared with the base case to determine the effect of the lane additions. Model 6 yielded an increase in average speed of about 8% compared with model 1. Moreover, the trip time and stop time were reduced by 8% and 7%, respectively. These results seem logical based on the magnitude of the imporovements involved. The static model, on the other hand, did not create any changes of more than 1% in the trip time, stop time or average speed.

This is another situation where the sensitivity of the static model to changes in the network topology appears to be nonexistent.

Experiment #4 – Capacity Increase: High Street (Models 8 and 9)

The High Street lane additions were evaluated with dynamic and static traffic assignment. The DTA model was investigated in model 8. Model 9 utilized the static traffic assignment procedure. The results of the Experiment #4 analyses are listed in Table 5.2. In comparing model 8 with the DTA base case, the results appear to be consistent with the findings for model 6 in Experiment #3. An increase in average speed (10%) and decreases in trip time (9%) and stop time (13%) were produced. The results from the static assignment model failed to detect any significant benefit from the additional capacity. The average speed actually decreased slightly (0.1%) in model 9, compared with the results from model 3. This suggests that static assignment may produce contradictory results under certain conditions as seen here.

Experiment #5 – Incident Management: Full Information (Models 10 and 11)

Two DTA models were investigated using the incident management strategy under full information conditions. Model 10 utilized a time-dependent trip table. A fixed O-D matrix was applied in model 11. The statistical results for this experiment are summarized in Table 5.3. Compared with the base case, models 10 and 11 both react to the incident in a logical manner. The average speed decreases as vehicles are rerouted away from the freeway onto arterial streets with lower free flow speeds. Additionally, the trip time decreases, as does the stop time. Further evaluation of the

TABLE 5.3 Comparative Results for Incident Management Experiments

	Experiments				
	Base Case - Experiment #1 *(Existing Test Network)*		Incident Management - Experiment #5 *(Full Information)*		Incident Management - Experiment #6 *(No Information)*
Model No.	①	②	⑩	⑪	⑫
Statistics	**DTA**	**DTA***	**DTA**	**DTA***	**DTA**
Total Trip Time (hr)	3403.5	2964.1	3436.8	3138.2	3482.1
Average Trip Time (min)	13.540	12.458	13.672	13.190	13.853
Total Stop Time (hr)	976.8	861.4	1143.5	1056.2	943.9
Average Stop Time (min)	3.886	3.621	4.549	4.439	3.755
Total Trip Distance (mi)	55607.1	52096.3	55492.9	52348.2	55607.1
Average Trip Distance (mi)	3.687	3.649	3.679	3.667	3.687
Average Speed (mph)	16.338	17.576	16.147	16.681	15.970

DTA = Dynamic Traffic Assignment results
STA = Static Traffic Assignment results
* Denotes DTA results based on a *static*, as opposed to time-dependent, origin-destination table

incident management models reveals that model 11 has a higher average speed (3%) and lower trip time (4%) and stop time (2%) than model 10. These are reasonable conclusions since the demand in model 11 is uniform throughout the simulation period. Model 10 experiences more congestion due to the variable demand in the peak period.

Experiment #6 – Incident Management: No Information (Model 12)

A DTA model using time varying demands was evaluated to study the no information incident management scenario. The results for model 12 are included in Table 5.3. Compared to the base case, the average speed dropped and the trip time increased as expected. The trip distance did not change from the base case indicating that no vehicles changed travel paths as required under the no information condition. Compared with model 10, the average speed declined by 1% and the trip time increased by 1%. These changes are small in magnitude, but do suggest that providing motorists with information on incidents is beneficial. Furthermore, 12% of the traffic was present on the network when the incident occurred and only 44% of the demand had been generated by the time the incident was cleared. Therefore, the effects of the incident may have diminished by the time the remaining 56% of the traffic entered the network.

In summary, both modeling approaches produced interesting results for the evaluation of congestion mitigation strategies. The DTA model was able to produce reasonable results for each of the experiments, although the same cannot be said for the static approach. The differences in the O-D tables using DTA suggest that fluctuations in demand do influence the performance of the transportation system, but to what degree cannot be concluded based on this study alone. Dynamic traffic assignment appears to be a feasible alternative to static assignment for the purposes of evaluating some of the CMS strategies. Additional discussion on this subject is presented in the Section 5.4.

5.4 Comparison Between Dynamic and Static Assignment Models

In Chapter 3, several congestion mitigation strategies were proposed for consideration. This section describes the differences of the two modeling techniques with respect to evaluating the CMS strategies. Now that the dynamic and static traffic assignment models have been tested, the capabilities of both approaches in evaluating the congestion mitigation strategies are reviewed.

The dynamic traffic assignment model used in this research contains the built-in DYNASMART traffic simulator. This component of DTA provides the capability to evaluate numerous traffic control and ITS strategies. Furthermore, the model captures time varying changes in demand and network performance to better represent the flow during peak hours.

Static models have traditionally been used for all operational and planning applications. However, dynamic traffic assignment is capable of modeling the effects of congestion reduction strategies to a greater extent than static models. A static model is not capable of directly addressing issues much beyond general-purpose lane additions. Many of the strategies cannot be evaluated at all with the static approach. Those that can be investigated require extensive changes to be made to the modeling procedure including the use of external software such as a traffic simulator [10]. Table 5.4 presents the CMS strategies along with the evaluation capabilities of both dynamic and static traffic assignment.

TABLE 5.4 Comparison of Congestion Management Strategy Evaluation Capabilities [1, 10, 24]

Proposed CMS Strategies (ISTEA)	Static Evaluation Capabilities	DTA Evaluation Capabilities
Traffic Operational Improvements	Some traffic operational improvements indirectly with capacity or other network modifications	Traffic control strategies, e.g., ramp metering, signalization, network wide control applications
Incident Management	None	Model traffic disruptions due to incidents
Congestion Pricing	None	Flexibility to incorporate pricing schemes for user response rules
ITS Technology	None	ITS applications, e.g., variable message signs
Access Management	Access management indirectly, e.g., incorporate external traffic simulator into modeling process	Simulate various access and approach configurations using built-in traffic simulator
General Purpose Lane Additions	Addition of lanes	Incorporate various geometric configurations, e.g., lane additions
Public Transit Operational Improvements	Modifications to mode split step	Model buses, routing, stop locations and dwell times
Transportation Demand Management	Limited demand management strategies, e.g., HOV lanes (after extensive modeling modifications)	Most demand management actions, e.g., HOV lanes

There are some strategies, particularly those that are multi-modal in nature, that DTA is not able to address. Nontraditional modes such as bicycle and pedestrian facilities or ferry service are not part of the current DTA modeling process. DTA can evaluate strategies that the static model is not able to address. The strategies that both models can address are evaluated more extensively using the dynamic model as shown in Section 5.3. The three proposed strategies that a static model cannot consider are incident management, congestion pricing and ITS technology. This is a severe limitation because all three play an important and growing role in transportation planning.

In summary, ISTEA outlines several strategies that should be evaluated in order to select the appropriate congestion mitigation action for implementation. Evaluation of these alternatives is one area DTA can make a significant contribution with respect to congestion management.

Chapter 6

SUMMARY AND CONCLUDING REMARKS

This research presented a modeling approach that evaluated congestion mitigation alternatives using dynamic traffic assignment as a planning tool. The capabilities of the simulation-based dynamic traffic assignment model were investigated in connection to fulfilling the functional requirements of a congestion management system. This study demonstrated the feasibility of dynamic traffic assignment to evaluate various congestion mitigation strategies proposed in ISTEA. DTA appears capable of evaluating multiple CMS strategies individually, or in combinations, to prove useful as an analytical planning and evaluation tool.

The findings of this research indicate that dynamic traffic assignment provides different and more detailed traffic flow information than static traffic assignment. Furthermore, the DTA results are so different from the static findings that the validity of the static assignment models should be questioned. However, it remains difficult to generalize the findings of this study to widespread planning applications without additional research. The results of this study are not conclusive due to the small test network, but they are encouraging and do suggest that further consideration should be given to utilizing DTA as a planning tool. One drawback to the dynamic model is the time-dependent O-D table, although the experimental results suggest that using a fixed trip table with the DTA model will produce more reasonable results than static assignment. This suggests that DTA can be a useful tool even without a time-dependent O-D table because incidents and traffic control strategies can still be accurately modeled.

Some areas for future research include sensitivity analysis, calibration to real world conditions and stochastic effects or uncertainty in the modeling process. These issues should be examined to validate the results of the simulation-based assignment model. Other considerations include exploring larger transportation networks and variations in the demand. Dynamic traffic assignment may also be tested in areas other than congestion management, such as air quality analysis, to determine its effectiveness in other transportation planning applications.

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APPENDIX

Large Scale Dynamic Traffic Assignment: Implementation Issues and Computational Analysis

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LARGE-SCALE DYNAMIC TRAFFIC ASSIGNMENT: IMPLEMENTATION ISSUES AND COMPUTATIONAL ANALYSIS

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ABSTRACT: *This paper is concerned with implementation challenges related to using DTA on actual large urban networks. Such challenges include the manipulation of network and demand data, the modeling of turning movements, the efficient computation of link travel times, and the handling of complex path data. The basic simulation-assignment based approach introduced by Mahmassani et al. (1993) was enhanced to address the challenges outlined above. The model is used on applications presently performed by agencies with static models, such as infrastructure improvements, demand management, and congestion pricing. In addition, various applications difficult to be performed with static models are explored, such as the evaluation of Intelligent Transportation Systems technologies. Computational tests are performed on the Columbus, OH urban network and the results are analyzed.*

1. INTRODUCTION

Dynamic Traffic Assignment (DTA) has substantially evolved in the last two decades and has reached a sufficient level of maturity to be used in a number of planning and operational applications. In planning, off-line DTA models can be used to replace existing static models for many traditional applications. The shortcomings of static assignment models have occasionally been discussed in the literature but in the absence of reliable alternative models this discussion has not attracted much interest. Currently, agencies use static assignment models for an array of planning applications: from infrastructure improvement evaluation, air quality impact to congestion management systems and traffic maintenance. While DTA was originally developed to meet operational Intelligent Transportation Systems (ITS) needs, in principle, it can be used as a planning tool replacing static assignment models. In spite of the numerous issues that must be resolved before using DTA on actual applications, steps need to be taken in that direction due to the limitations of static modeling. Traditional static tools can be used reasonably well to evaluate planning applications, such as infrastructure improvements; they are, however, unable to account for traffic control, information provision, traffic dynamics and temporal elements of users' behavior, which makes their suitability for certain applications, such as evaluating ITS technologies, questionable. Most DTA models reported in the literature deal with relatively small networks, which may be sufficient to demonstrate algorithm design issues or properties, but fall short from addressing the challenges associated with real-world networks and applications. Thus, it is unclear precisely how DTA models will behave on such networks or in what ways the system performance will vary when certain assumptions are being made with regard to the supply and demand data.

The objective of this paper is to address issues key to the application of DTA on actual large data sets, similar to the ones currently used by State DOTs and Metropolitan Planning Organizations. Major contributions of this paper include a time-dependent shortest path algorithm that accounts for intersection movement delays, an efficient scheme for the computation of link travel times, a methodology for handling complex path data, and the use of a cell transmission based traffic simulator that allows fast computation of very large networks. In addition, several types of typical analyses are performed on the Columbus, OH data set, currently used by the Ohio DOT and MORPC. Network infrastructure improvements, congestion pricing, demand management, and the evaluation of information provision are discussed. Furthermore, the impact of trip demand assumptions is explored through the evaluation of various peak period profiles.

A brief summary of DTA systems is given in Section 2, along with an overview of the model implemented in this paper. Section 3 discusses the implementation issues of the assignment-based simulation critical to actual applications. Section 4 describes the actual network and demand data and the assumptions made. Section 5 presents the computational experiments performed as well as some analysis. Section 6 summarizes the findings of this paper and identifies future research.

2. BACKGROUND AND MODEL OVERVIEW

DTA models are typically classified into two broad categories: analytical and simulation based heuristic ones. Extensive work has been reported for both types of approaches and an overview of this literature can be found in Peeta (1994) and Mahmassani *et al.* (1993). Analytical methods have advanced greatly since the pioneering work of Merchant and Nemhauser (1978a,b) and Carey (1986, 1987, 1992). Efforts in this area include mathematical programming approaches by Janson (1991) and Ziliaskopoulos (1998), optimal control theory based formulations by Friesz et al. (1989), and variational inequality approaches introduced by Friesz et al. (1993), Smith (1993), Wie et al. (1995), Boyce et al. (1996), and Lee (1996).

Most analytical formulations are extensions of their equivalent static formulations and seem to have two main disadvantages: (i) they cannot adequately capture all realities of street networks due to simplifications, and (ii) they tend to be intractable for realistic size networks. Heuristic approaches, especially those that are simulation-based, overcome these disadvantages, but fail to guarantee optimality and often even convergence. Moreover, unlike closed-form analytical formulations, they lack the potential to obtain insights into the problem. While further research into these analytical models is vital to the understanding and future applicability of DTA, the remainder of this paper will deal solely with simulation-based models, which appear to be the only ones currently applicable to actual large networks.

Currently, there are two main simulation-based approaches in the literature: DYNASMART-X (Mahmassani et al., 1997) and DYNAMIT (Ben-Akiva et al. 1997). The approach implemented in this paper is based on DYNASMART-X. The main differences between the models is the replacement of the traffic simulator DYNASMART Mahmassani *et al.* (1993) with RouteSim (Ziliaskopoulos and Lee 1996). RouteSim is a traffic simulator based on the Cell Transmission model (Daganzo 1994, 1995). In addition, the path assignment module and time-dependent shortest path module were re-engineered into an efficient module that can handle large data sets, intersection movements delays and link travel times. Finally, database support was added to handle critical data communication issues involving the link flows, travel times, and path storage, based on a key/data pairing database system.

3. DTA SOLUTION ALGORITHM IMPLEMENTATION DETAILS

The DTA system implemented in this paper can be broken into three general modules: the traffic flow simulator, the time-dependent shortest path algorithm, and the path assignment module. Each module has singularities that must be addressed when applying the system on large-scale realistic networks.

3.1 The Traffic Simulator--RouteSim

RouteSim (Ziliaskopoulos and Lee, 1996) is a path-based simulator that propagates traffic according to the Cell Transmission Model (Daganzo 1994, 1995). In a preprocessing step, it divides the network links into a number of cells based on their length and free-flow speed and transmits vehicles between cells according to the cell's density, the downstream cell's density and jam density, and the saturation flow rate. Since this involves only simple comparisons and not complex floating-point calculations, RouteSim can handle networks of thousands of links while maintaining acceptable CPU time and memory requirements. In addition, the simulator has been designed to update the vehicle movements at varying time intervals, depending on how frequently the queue evolution need to be monitored. Close to intersections, incidents, construction zones and other problematic points the simulator updates the queues every two seconds, while for long uniform freeway segments at multiples of that time period, up to twenty seconds. This results in enormous CPU saving without substantially sacrificing accuracy of computations.

Another issue encountered in simulating traffic for assignment applications is the calculation of the link travel times. If this calculation is CPU expensive, it can be the computational bottleneck for the overall approach; in the implementation adopted in this paper, the calculation of travel time is similar to an efficient approach proposed by Lawson *et al.* (1996). As the simulation progresses, it begins by recording the cumulative flow into and out of each link. Furthermore, this method must also be able to calculate movement delays. Therefore, when a vehicle enters a link, its next desired link is examined; the vehicle is then recorded as an inflow for the link-movement combination it intends to perform. When a vehicle departs from a link, it is recorded as an outflow for the intersection movement performed. This effectively creates two vectors: INFLOW and OUTFLOW for each link-movement combination indexed over time. In a post-processing stage, these cumulative flows are examined to calculate the travel time for every link and movement performed.

Specifically, the travel time $\tau_{ijk}(t)$ of a link (i,j) including the movement into link (j,k) at time t is computed as

$$\tau_{ijk}(t)=min\{(s-t), \text{ subject to: } OUTFLOW(i,j,k,s) \geq INFLOW(i,j,k,t)\text{ , } s \geq t+\tau_{ijk}(0)\}$$

where $\tau_{ijk}(0)$ is the free flow travel time.

This approach allows the simulation to continue indefinitely, since no output data is stored in memory. As the simulator iteratively progresses, it stores density and flow data into a file, without maintaining any additional past information. If necessary, the computation of the travel times can be performed in parallel with the simulation; in addition, if the flow file grows too large, it can be erased or aggregated without affecting future simulation steps. Currently, RouteSim can continuously simulate networks of the size of Columbus, OH in faster than real-time computational times.

3.2 Path Assignment and Data Handling

The path assignment and time-dependent shortest (TDSP) path modules were combined into a single software entity, which eliminates the need to record the labels generated by the TDSP algorithm between successive iterations. Furthermore, since the TDSP and assignment modules are both able to execute by destination, only the labels for a single destination must be stored in memory at any time.

The assignment module is responsible for handling most of the complex data manipulations. It reads the TDSP labels, the OD demand information, and maintains a set of used paths for each OD pair. This set of paths, however, could become prohibitively large as the network size increases, and it may not be possible to cache all paths in the memory. To deal with this problem, a data/key pairing database system is employed that is capable of handling binary-tree and hashed data storage and retrieval as well as data caching. One such system is BerkeleyDB (Olson et al. 1999), which is the database adopted in this implementation.

Three key data elements are stored in the database, in every iteration: the link flows, the travel times, and the path sets. The flows and travel times are stored as typical vectors indexed over time. This provides a convenient structure for computing the travel times, since this calculation is performed on a link basis rather than on a time interval basis; thus, efficient database searches can be used to retrieve only information by link instead of by time. The path set is stored as a dynamic vector with a key containing the destination, assignment time and iteration. Each record consists of the optimal path calculated during the iteration for each origin to that destination, in the specified time period. Since an efficient Binary-Tree search is performed to store and retrieve this information, this allows all computations within the TDSP and assignment modules to only require data for the needed destination, thus consuming considerably less memory.

3.3 Accounting for Intersection Turning Movements, Entry and Exit Delay

An approach typically used to compute shortest paths with turning movements is to expand each intersection into a more detailed sub-network (Ziliaskopoulos and Mahmassani, 1996). In the sub-network, each incoming or outgoing approach in the original network is represented by a node and each movement is represented by an arc connecting these nodes. With such an expanded network, movement delays at intersections can be modeled by the travel times on the arcs, and any shortest path algorithm can be used to handle the problem. The disadvantage with this approach is that the size of the network after expansion is usually much larger than the size of the original network, thus causing a significant increase in memory requirements and computational time.

The time-dependent shortest path algorithm used with the simulator takes into consideration optional movement delays at intersections and entry/exit delays at origin/destinations. This algorithm is an important modification to the original one because it can capture the impact of turning movement delays on the routing decision of travelers. Such impact is evident on real street networks, and the ability to account for it addresses the underlying theme of implementing DTA on such networks.

This algorithm is an extension of the well-known label-correcting algorithm. The scan eligible list is maintained as a DEQUE structure. The algorithm works backwards from the destination and searches for the shortest path from all nodes to the destination node for all time intervals. In this algorithm, the link costs are considered to stay constant after the time horizon T, so that there are paths from every node to the destination at every departure time given that the node is connected to the destination.

To represent intersection movements, we build a backward star data structure of the movements from the backward star structure of the links. Note that this representation of movements is based on links rather than nodes introduced in Ziliaskopoulos and Mahmassani, 1996. For link j, the links k that are in the set $\Gamma_L^{-1}(j)$ satisfy the following condition:

$$from[j] = to[k], k \in \Gamma_L^{-1}(j)$$

Since the network is represented in backward star, it is computationally efficient to find the links that satisfy this condition. To construct the set $\Gamma_L^{-1}(j)$, a simple iteration from *backpointer[from[j]]* to *backpointer[from[j]+1]-1* suffices. For each node, we also keep the *indegree* at the node *I(i)*, and for each arc we keep its rank as an incoming arc to its head node.

Optimality condition

The labels at optimality must satisfy the following condition:

$$\lambda^t_{i,S(a)} = \min\left\{D^t_{backpointer\_link(b)+S(a)} + C_b^{t+D} + \lambda^{t+D+C}_{j,S(b)}, i \in \Gamma_N^{-1}(j), a \in \Gamma_L^{-1}(b), (i,j) = b\right\}$$

$$\lambda^t_{destination,k} = 0, k = 1, \cdots, I(destination)$$

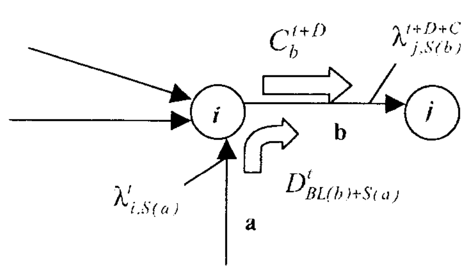

Figure 1 Movements within the TDSP Algorithm

The basic algorithm

We assume that travel time on a link after the time period of interest stays constant, *i.e.* $C_a^t = C_a^T, t > T$.

Step 1. Initialize the labels as follows:

$\lambda^t_{destination,k} = 0$, $P^t_{destination,k} = 0 \quad \forall t, \quad k = 1, \cdots, I(destination)$

$\lambda^t_{i,k} = \infty$, $P^t_{i,k} = 0 \quad \forall t, \quad \forall i \neq destination \quad k = 1, \cdots, I(i)$

$Flag[i] = 0 \quad \forall i \in N$

Create an empty SE list and put the destination node into the list, let $Flag[destination] = 1$.

Step 2. If the SE list is empty, go to Step 4; otherwise, select the first node in the SE list, call it *current node*, and delete it from the list, let $Flag[current\ node] = -1$.

Step 3. Scan every node in $\Gamma_N^{-1}(current\ \ node)$, call it *scan node*, let link b=*(current node, scan node)*. Check the labels on the incoming arcs of *scan node*, more specifically, for link a,

If $\lambda^t_{i,S(a)} > D^t_{backpo\text{int}er\_link(b)+S(a)} + C_b^{t+D} + \lambda^{t+D+C}_{j,S(b)}$

Then update $\lambda^t_{i,S(a)}$, $P^t_{i,S(a)}$:

$$\lambda^t_{i,S(a)} = D^t_{backpo\text{int}er\_link(b)+S(a)} + C_b^{t+D} + \lambda^{t+D+C}_{j,S(b)}$$

$$P^t_{i,S(a)} = current\ node$$

If any label on the incoming arcs to *scan node* is updated and $Flag[scan\ \ node] \neq 1$, insert *scan node* into the SE list:

If $Flag[scan\ \ node] = 0$, insert it at the end of the DEQUE;

If $Flag[scan\ \ node] = -1$, insert it at the beginning of the DEQUE.

And update $Flag[scan\ \ node] = 1$.

Step 4. Terminate the algorithm, the labels are optimal.

Consideration of entry delays at origin nodes

Entry delay of an origin node is viewed as the travel time on an additional link to the origin node as shown in Figure 2. At the termination of the algorithm, we only need to trace the path from the entry links of the origins to the destination.

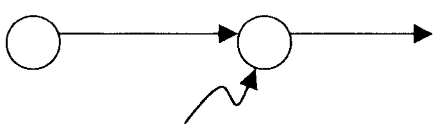

Figure 2 Example of an Entry Link

Algorithm for network with movement penalties at selected nodes

For the nodes that do not have significant turning flows or the turning delays are not an important portion of the link travel time and we choose to ignore them (e.g. intersections of residential streets), we keep the label $\lambda^t_{i,0}$ on the node and the sequence $S(a)$ for all incoming arcs a to the node is set to 0. Note that the overwhelming majority of intersections on actual networks experience negligible intersection delays and by not accounting for these delays, we significantly reduce the path computational time.

4. NETWORK AND DEMAND DATA

The simulation-based DTA system is implemented on the 1990 Mid-Ohio Regional Planning Commission (MORPC) Columbus, OH network currently in use by the Ohio Department of Transportation. This network consists of 12,658 arcs, 5,441 nodes and 978 centroids, resulting in the assignment of 2,889,278 trips over a period of 24 hours. Artificial arcs were not generated for the representation of movements, as these were handled by the optimum path algorithm as discussed in Section 3. A graphical representation of this network is shown in Figure 3.

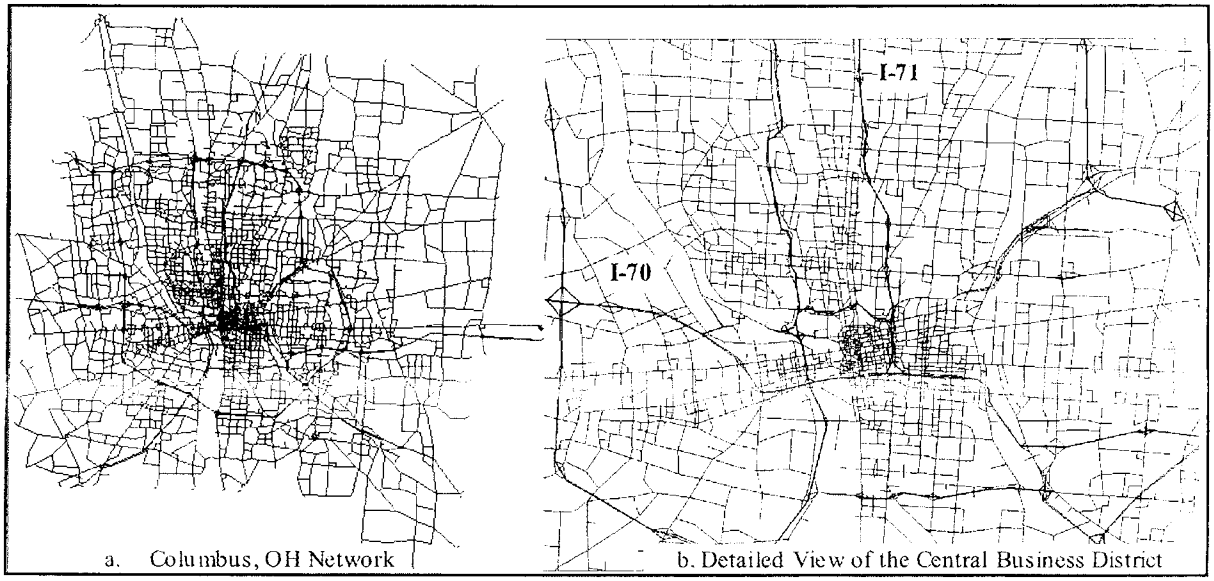

Figure 3 Columbus Network

The trip table was estimated based on the 4-step planning process for the entire 24-hour day. A peak hour factor is then applied on this daily trip table to convert it into the peak hour demand. Static traffic assignment, which is the final step of the widely used four-step process, is performed with the peak hour Origin-Destination (OD) demand, or with OD demand for different periods of the day (such as trip table for the morning peak, afternoon peak, and off-peak periods, respectively). However, as it has been observed, small disturbances on the demand side for a short time period can result in significantly different traffic conditions on the network; it is thus important to take into account the dynamics of the demand. While development of time-dependent trip information remains an active area of research, one means to gain insights and begin experimentation is to work with the existing static data currently maintained by traffic agencies. The development of demand data is presented in order to continue the exploratory analysis. Note, however, that were new methods to be developed, they could be implemented without changing the underlying DTA model.

For the DTA implementation, a 45-minute assignment period during the morning peak is modeled. Therefore, the 24-hour static trip table has to be translated into a usable time-dependent version for the period of interest. Since this analysis is focused towards the morning peak, more emphasis is given to the representation of origins rather than destinations. This yields some model efficiencies since the TDSP algorithm computes paths from many origins and departure times to one destination.

The 45-minute assignment time is broken into nine 5-minute assignment periods each one consisting of 50, 6-second time intervals. It should be noted that while the demand is profiled between these 9 assignment periods, the simulator and TDSP algorithm function on the 6 second time interval for more than 450 time periods. The majority of the original OD pair demands, consist of relatively few trips (less than 4). Since these trips are those made during an entire 24-hour period, it is unclear how they will impact the peak-hour demand.

To develop a morning peak–hour demand from the static trip tables, it was assumed that the densest OD pairs would be the ones most likely present for the peak hour. Therefore, the densest of these OD pairs (approximately 30,000) were selected and used in the remaining calculations. When a peak factor of 0.2 was applied, 89,166 trips were generated among 23,082 OD pairs. While this generates static OD demand for the period of interest, this demand must be temporally distributed among the assignment periods. Three demand profiles were examined for this distribution (shown in Figure 4) and the results are analyzed in Section 5. Furthermore, it should be noted that the assignment of the OD demand to centroid connectors was performed according to the user-optimal route from that centroid calculated by the TDSP algorithm.

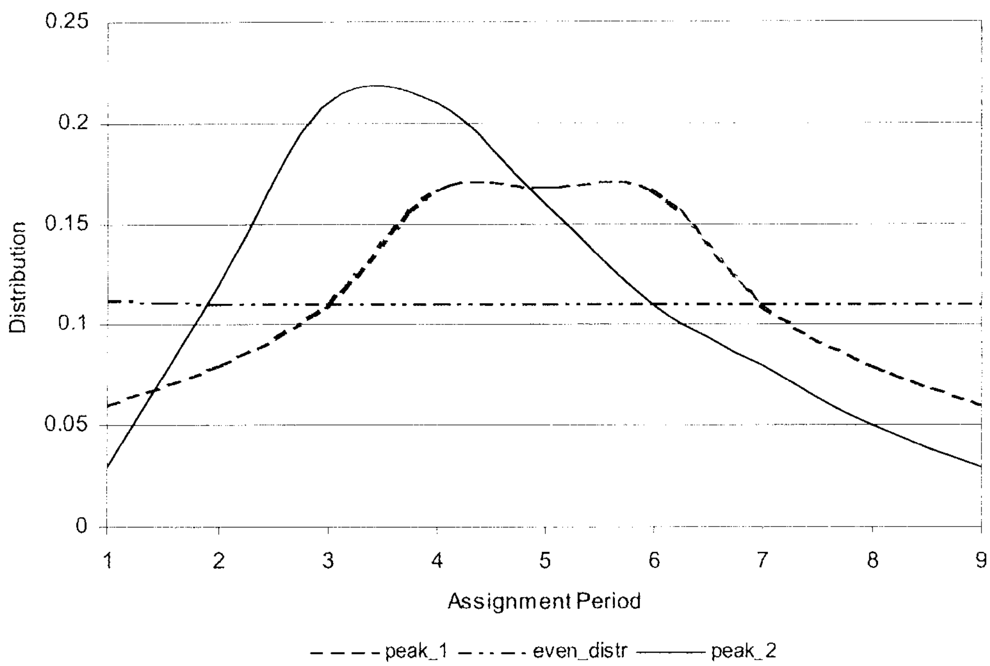

Figure 4 Profiles Applied to Demand

Finally, although a 45-minute time period is used for the assignment of demand to the network, a significant portion of this demand does not get to the destinations during this time. Therefore, the simulation of this traffic is carried out to 100 minutes, while statistics are only kept for the first hour of simulation. This allows the routing and interaction of these vehicles not to be influenced by to the effect of the simulation "cool down" period.

5. MODEL APPLICATION AND ANALYSIS

The main reason for applying DTA to this particular network is to explore possible means by which DTA can be used to help analyze existing problems and address those issues necessary for this implementation to take place. This is not intended to be a detailed comparative case study, but merely to obtain simple problem insights and demonstrate applicability on large actual networks.

While proving convergence properties for simulation-based models is beyond the scope of this paper, some insights into the performance of these systems for large networks can be attained. As the model iteratively progresses, topologically new optimal paths may be found for certain OD pairs. One test for equilibrium would be the generation of no additional new paths for any OD pair, while all used paths for each OD pair and departure time to have equal travel time. While this final state is not met, the system does appear to be approaching it. Figure 5 shows the number of new paths generated for each OD pair over the iterations. From this plot, the system appears to generate fewer new paths for each OD pair over the iterations. Furthermore, since the number of temporal OD pairs (207,738) significantly exceeds the demand total (89,166), many of the additional paths are being added for time periods where no demand is present and the actual number of rerouted vehicles is considerably less than what is shown in Figure 5.

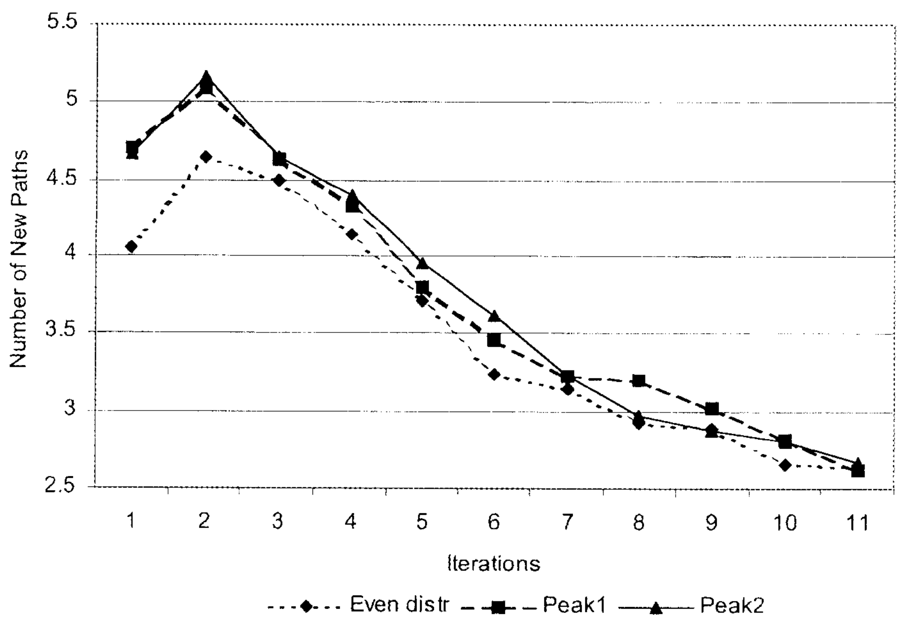

Figure 5 Number of New Paths by Iteration

Nonetheless, if the number of new paths found to be optimal diminishes, this might be one indication of approaching equilibrium. Figure 6 represents the average deviation of path travel times for all OD pairs and departure times. This plot does not appear to change significantly, and never increases beyond 40 seconds. Since the average path travel time exceeds 30 minutes, this indicates that OD pairs tend to be in equilibrium for the used paths. This is not intended to be a justification of the model—that is being dealt with elsewhere—but simply to explore how these models perform on actual networks.

Furthermore, the steepest peak distribution resulted in considerably higher total travel time than the first peak distribution. This indicates that important network-wide conditions are closely tied with the dynamic properties of the OD demand, and special care should be taken in developing these values.

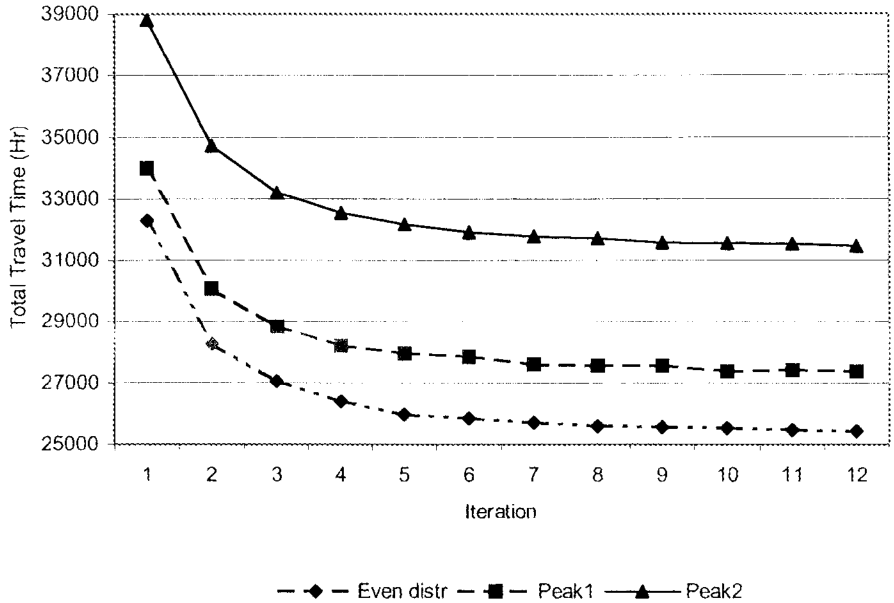

Figure 6 Average Deviation of Path Time

Three different demand profiles for the peak hour period were used to temporally distribute the OD demands among the assignment time periods. One obvious difference among these profiles can be seen in Figure 7: The evenly distributed profile resulted in considerably lower total travel time than either one of the peak profiles.

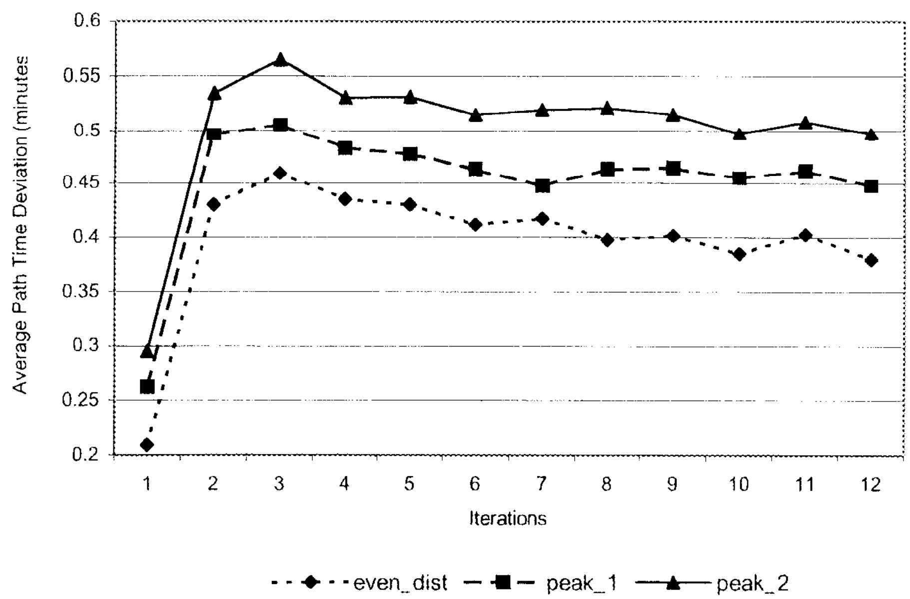

Figure 7 System Travel Time by Distribution

The network is pre-processed based on the principles presented in Ziliaskopoulos (2000). More specifically, based on the free-flow speed of a link and the length of time interval used, the link can be segmented in to cells so that each cell must be traversed by a vehicle even if traveling at free-flow speed. The resulting representation of the network has 57,533 cells. As is noted in Ziliaskopoulos and Lee (1996), cells of varying length might be employed for substantial improvements in computational times. While that is not attempted here, it would only improve the computational efficiency. The program runs on a Pentium III 500Mhz computer with 256 Megabytes of RAM. The computational time for this model for more than an hour of simulation time on the Columbus network is a total of 5 hours and 32 minutes, or approximately 30 minutes per iteration.

5.1 Evaluation of Infrastructure Improvements

The first analysis performed is the evaluation of simple infrastructure improvements. An one-lane addition is made to 23 consecutive links along I-71 extending from North Columbus down to the Central Business District (CBD), while using the evenly distributed demand data. Table 1 shows the total system travel time under each case, as well as the average travel time for those O-D pairs using this roadway before the improvement is made under each case. Before the addition, 564 O-D pairs routed flow to at least one of these links. Afterwards, 574 O-D pairs used at least one of these links. While the improvement does appear to lower the total travel time to benefit the directly affected vehicles and bring more traffic onto the expanded links, the total travel time differences are rather small.

Table 1 System Impact of Lane Addition

	Total System Travel Time (Hr)	Average Travel Time of Affected O-Ds (Min)
23 Link Base Case	25480	38.20
23 Link Lane Addition	25430	37.77
36 Link Base Case	25480	33.30
36 Link Lane Addition	25436	33.10

An additional expansion was tested, where the previous 23 links were again expanded with the improvement continuing for additional 13 consecutive links along the I-71/I-70 corridor running through the CBD. As before, slight improvements were observed, with 1000 O-D pairs using some segment of this roadway before the improvement, and 1017 using it afterwards. Again, it does not appear that the relatively small benefits gained by the improvements would justify this particular infrastructure improvement.

5.2 Evaluation of Congestion Pricing Policies

Developing congestion pricing policies is a complex problem and no attempt is being made in this paper to solve for optimal policies systematically; instead, we take a rather simplistic view of merely evaluating exogenously defined toll policies in the form of perceived delays by the drivers. No assumptions as to the value of time are made, but instead a penalty is applied to the "priced" links as additional time perceived by the drivers. Specifically, instead of specifying a dollar value for a toll on a given facility, we use the "time" corresponding to such an amount. For example, if a driver values his time at $10/hr, a 33-cent toll charge is equivalent to 2 minutes additional savings in trip delays. This delay obviously does not impact the actual time spent within the network, but it is simply considered within the TDSP algorithm—now a time-dependent least cost algorithm—for the vehicle routing. Furthermore, these results are presented as an example for the types of evaluation that can take place with DTA, and are not representative of optimal, or perhaps even beneficial, pricing policies. Finally, it should be noted that this analysis is made only with regard to the way in which drivers will re-route themselves as a result of the penalty, and does not represent any queueing effects caused by the physical toll area.

Table 2 depicts the results from applying this approach using the evenly distributed demand trip information. A 21-link segment of I-71 extending from Northern Columbus to the Central Business District is assumed to carry tolls equivalent to a total of 2 minutes. This penalty is spread proportionally through these links, based upon their length. The network is observed to perform somewhat worse (0.01%), with vehicles directly impacted by this toll experiencing an average of 33 seconds more travel time. Before this toll is placed, 564 O-D pairs used some portion of this roadway. Afterwards, only 445 O-D pairs drove some portion. Furthermore, the average travel time of these 445 O-D pairs comes to 39.3 minutes before and after the toll. Since the remaining OD pairs tend to have longer travel times both before and after the toll, this implies that the tolls tend to discourage drivers making shorter trips from using the toll facilities. When this toll is increased to 10 minutes, the total travel time and path travel time for directly affected OD pairs again increases. Furthermore, the number of OD pairs, which make use of some portion of this roadway, decreases to 231. In addition to the evenly distributed demand profile, the impact of the peak distribution is examined with the 10-min policy and is shown in Table 2. As expected, the increase resulting from the use of the peak distribution and the pricing policies is even larger.

One advantage for path-based simulation models is that these time penalties, or assumptions made with regard to the value of time, can be placed according to the vehicles' origin and/or destination. Therefore, if socio-economic data is known with respect to certain residential or business areas, different values of time can be used depending on where a vehicle is coming from or going to. One example of this possibility is examined: The toll is taken to be 10 minutes except for those drivers heading towards the Central Business District (CBD), where 5 minutes time value is assumed. This is done solely to see in what way the network will react to such differences and no further insights or analysis is attempted. As shown in Table 2, both the total and average travel time of directly affected ODs performed worse in this case.

Table 2 – System Impact of Congestion Pricing

	Profile	Total System Travel Time (Hr)	Average Travel Time of Affected O-Ds (Min)
Base Case	Even	25480	38.13
2 minute	Even	25493	38.45
10 minute	Even	25569	39.08
10/5 minute	Even	25729	42.00
Base Case	Peak2	31468	41.60
10 minute	Peak2	31563	42.83

It should be noted that OD pairs using some portion of the toll links and destined to downtown Columbus had their average travel time change from 31.48 minutes in the "no tolls" case to 33.28 in the toll case, a smaller but comparable change to the overall impact (from 38.13 to 42.00 minutes).

5.3 Evaluation of Demand Management

With DTA, it is possible to combine departure time/arrival time and route choice in one shell; that would not be possible with static assignment models. The problem of simultaneous choice of departure time and route choice has been address in Ziliaskopoulos and Rao, 1998 and Li *et al.*, 1999. In this section, we take a traditional view of demand management and use the approach that is commonly used in practice. Demand management has been the focus of extensive research. Any demand management measure has, though, two possible impacts on the network: (i) temporal shift of the demand that can result in "smoothing" the peak, and (ii) reduction of the demand during the peak hour.

The three profiles explored in Figure 4 demonstrate the potential benefits resulting from smoothing the peak. Examples of the second potential impact of demand management measures include shifting the demand to other transportation modes. For instance, if a light rail system is constructed, some portion of the demand currently using the roadway network will switch to this new transportation mode and thus reduce the number of trips between some OD pairs.

Three such demand reduction cases were examined by selecting an OD pair set and removing 10% of its present demand. The first case consists of only those OD pairs travelling from North Columbus along I-71 into the CBD, the second case consists of OD pairs moving between North Columbus along I-71 and the CBD (including shorter inner-city trips), the third consist of those pairs moving between the north suburbs of Columbus and Downtown (again including short trips). The demand reduction for these cases is 59, 1000, and 1646 vehicles respectively and the impact is shown in Table 3.

Table 3. Impact of Demand Reduction

	Total System Travel Time (Hr)	Average Experienced Time for the First Hour -- *All ODs* (Minutes)	Average Travel Time of *Reduced ODs* (Min)	Approximate Marginal Cost (Minutes)
Base Case	31468	21.18	33.04	
59 Demand	31427	21.16	32.20	8.64
Base Case	31468	21.18	22.05	
1000 Demand	31046	21.12	21.61	3.6
Base Case	31468	21.18	29.87	
1646 Demand	30386	20.83	28.66	9.6

An important inference from this analysis is the marginal cost for the demand, a measure typically hard to compute within a dynamic setting. The impact of a vehicle might have effects long after this vehicle has left the network. An approximation of the marginal cost can be obtained for the most critical time, the peak period, by only examining the data from this time period. This marginal cost can be computed from the difference between the first hour total system travel time and the direct contribution of the reduced demand (dividing by the number of vehicles for a per vehicle cost). While this only gives the impact of these vehicles made to that first hour, often it is this peak period that is of most concern. While it seems obvious that the largest demand reduction results in the lowest overall system travel time, the marginal cost for this demand is surprising. The marginal cost for demand is expected to decrease as the demand increases—this can be seen from the difference between the 59 and 1000 demand reduction cases. The fact that the demand from OD pairs selected for the third case result in much higher marginal costs suggests that demand from this region might have a greater impact on network performance and warrants further analysis.

5.4 Evaluation of Information Provision

Finally, we explored the potential of installing an ITS system that will provide information to drivers during a major freeway incident. An incident consisting of a 10-minute road closure along the I-70/I-71 roadway heading westbound through the Central Business District is modeled for demonstration purposes. Three cases are examined: (i) the base case with no incident, (ii) an incident scenario where no information is presented to drivers, where all drivers are expected to maintain their "no incident" paths, and (iii) a perfect information scenario, where it is assumed all drivers are aware of the incident and re-equilibrate their paths accordingly.

In Table 4, it can be seen that while both incident cases do perform worse as expected, the perfect information case appears to perform remarkably close to the no-incident case. This might suggest the potential for the deployment of various ITS information systems within this area. This result is quite significant since it outperforms all previous similar analyses on small networks. It demonstrates that on this particular network, there are enough alternatives for people to use in case of a major incident, so that the impact of the incident on the network is almost immaterial. The challenge is, however, to have the means to provide this information to all drivers, which is one of ITS' aims.

Table 4 System Impact of Ideal Information Provision

	Total System Travel Time (Hr)	Average Travel Time of Affected O-Ds (Min)
Base Case	25480	30.97
Incident w/ No Information	25516	44.47
Incident w/ Perfect Information	25495	31.57

This analysis is quite pertinent to the specific network, where an extensive freeway management system is currently deployed for the purpose of reducing the impact of recurring and non-recurring incidents. Although the results can hardly be generalized, they do point in the intuitive direction that on large networks there is enough temporal residual capacity, that if all drivers are aware of it and appropriately use it the impact of spatial reductions in supply could be substantially reduced.

6. CONCLUSION

This paper presented the implementation of a simulation-based DTA on large-scale realistic networks. To this aim, two primary issues were examined. First, implementation challenges were discussed and enhancements to the basic simulation-based DTA models were introduced, such as the modeling of turning movements within the time-dependent shortest path algorithm, the computation of travel times from link flows within the traffic simulation, and the handling of data necessary for the assignment of vehicles to paths. It was shown that if special consideration is given to the implementation issues, existing DTA models could be used for practical transportation applications. Second, the presented DTA model was applied to an actual urban network, currently in use by the Mid-Ohio Regional Planning Commission. Computational experiments were performed to demonstrate suitability of the model for applications such as infrastructure improvement evaluation, congestion pricing and effectiveness of information provision systems.

APPENDIX: NOTATION

$\tau_{ijk}(t)$	travel time of a link *(i,j)* including the movement into link *(j,k)* at time *t*
C_i^t	Travel cost for link *i* at time *t*
D_j^t	Turning delay for movement *j* at time *t*
T	Number of time intervals
$\Gamma_N^{-1}(i)$	Set of the predecessor nodes of node *I*
$\Gamma_L^{-1}(j)$	Set of the links that proceed link *j*
$I(i)$	Indegree of node *I*
$S(j)$	The rank of link *j* as an incoming link
$\lambda_{i,j}^k$	Label on the *j*th incoming arc of node *i* at time interval *k*
$P_{i,j}^k$	Successor node on the path from the *j*th incoming arc of node *i* at time interval *k*
Backpointer[i]	Pointer for node *i* in the backward star representation of the links
Backpointer_Link[j]	Pointer for link *j* in the backward star representation of the movements

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