Studies of Potential Intelligent Transportation Systems Benefits Using Traffic Simulation Modeling

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MTR 96W0000054

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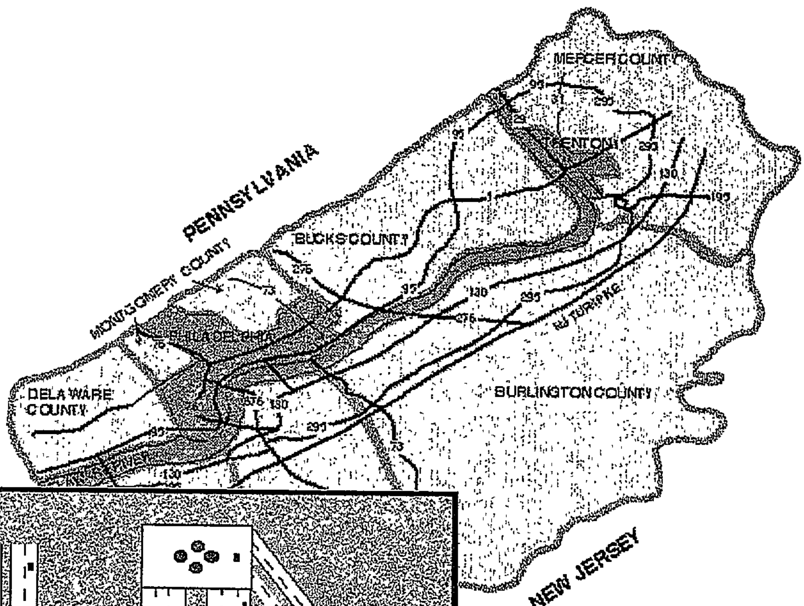

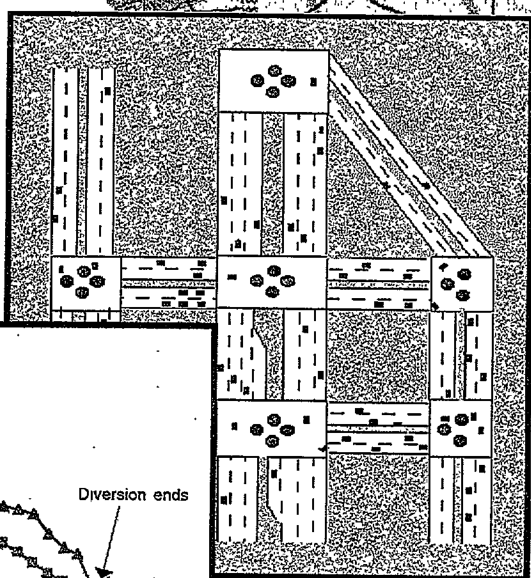

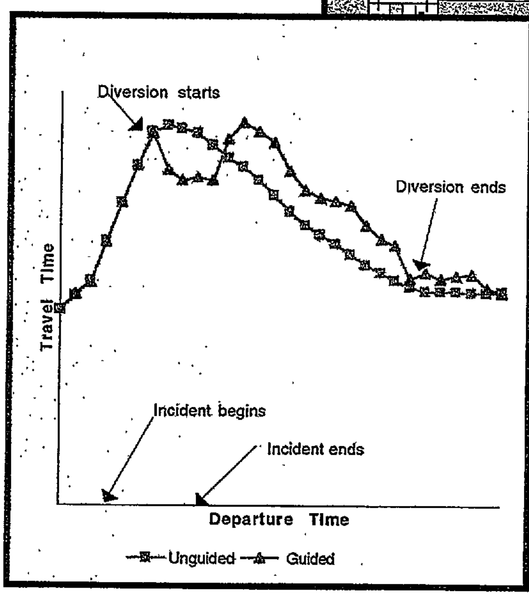

MITRETEK SYSTEMS
Center for Telecommunications and Advanced Technology
McLean, Virginia

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McLean, Virginia

Abstract

This report documents five studies performed by Mitretek Systems, Inc. to analyze potential benefits of Intelligent Transportation Systems (ITS) deployment, in support of the ITS Architecture Development Program. The studies explore the operation and benefits of four ITS user services: En-Route Driver Information, Route Guidance, Pre-Trip Travel Information, and Traffic Control. The studies use traffic simulation models to quantify the benefits of ITS deployment in typical urban and inter-urban scenarios and to study key sensitivities. The results illustrate potential benefits and address critical issues affecting the realization of ITS benefits.

KEYWORDS: Intelligent Transportation Systems, Federal Highway Administration, benefits, modeling, simulation, Advanced Traffic Management Systems, Advanced Traveler Information Systems

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Executive Summary

Mitretek Systems conducted a series of five modeling studies in support of the U.S. Department of Transportation (DOT) Joint Program Office (JPO) on Intelligent Transportation Systems (ITS). The studies originated as part of the JPO's ITS Architecture Development project, but evolved to become independent studies of ITS benefits. This report presents the study findings and documents study scenarios and methodologies.

Background

ITS deployment cannot be justified until there is credible evidence of significant benefits from ITS user services. Mitretek is currently engaged in projects evaluating the benefits of ITS from three approaches. First, Mitretek has been active in the collection of real-world, empirical ITS benefits. A review of empirical benefits appears in ITS Benefits: Early Results (Roberts and Shank, 1995), assembling measured benefits from ITS deployments.

Second, Mitretek is conducting quantitative studies of ITS benefits using statistical analysis of accident data These meta-evaluation studies (Evanco, 1996) examine the safety impacts of improved incident detection, rural mayday, and automated commercial vehicle inspection.

The simulation studies documented in this report are the third approach, providing estimates of ITS benefits to complement and go beyond findings that can be obtained solely from operational tests or analysis of statistics. Simulation enables controlled experiments and parametric analyses featuring alternative lTS deployments and varying traffic demand patterns. The studies can supplement empirical data on ITS benefits by examining the dependence of potential ITS benefits on critical parameters and sensitivities affecting the realization of those benefits.

Overview of the Modeling Studies

The five studies are named:

1. Benefits of Dynamic Route Guidance in Congested Urban Networks
2. Dynamic Route Guidance Compared to Advisory Messages
3. Impact of Network Surveillance on Dynamic Route Guidance Benefits
4. Pre-Trip Mode Shift Benefits Assessment
5. Adaptive Signal Control

The studies predicted benefits related to four ITS user services defined by the ITS Architecture:

1. En Route Driver Information
2. Route Guidance
3. Pre-Trip Travel Information
4. Traffic Control

The first three user services are aspects of Advanced Traveler Information Systems (ATIS), while Traffic Control is an aspect of Advanced Traffic Management Systems (ATMS).

Mitretek used the INTEGRATION and THOREAU traffic simulation models for the studies. Both models were developed for the purpose of providing trip-based statistics resulting from running thousands of vehicles on variable paths from origins to destinations in urban or interurban networks. THOREAU is a microscopic simulation of vehicle movement, modeling the details of vehicle car-following, acceleration and deceleration, lane-changing, turning movements, incident avoidance, and queue formation and dissipation. INTEGRATION is a mesoscopic model, tracking individual vehicles, but using flow equations and a simpler queuing model to model the travel time on each link. THOREAU has strengths in the area of modeling signal control, while INTEGRATION has many good features for modeling dynamic route guidance and en route information.

Wherever possible, Mitretek incorporated real-world data into the simulation scenarios. For example, the urban scenario was developed using traffic information from the Southeast Michigan Council of Governments and data on signals from the City of Detroit. The interurban scenario used traffic data from the Delaware Valley Regional Planning Council. Other scenario parameters came from research and empirical results, such as ATIS market penetrations from the ITS Architecture program, diversion percentages from the INFORMS operational test, mode shift percentages from a survey of Seattle commuters, and capacity reduction under weather conditions and rush hour peaking patterns from the Highway Capacity Manual.

Table ES-l summarizes the characteristics of the roadway networks employed in the five studies. Table ES-2 summarizes the scenarios and presents the major results. The table includes references to sections in the full report providing more information. Each page following the summary presents a short description of one study, some of the major study results, and a representative graphic. Finally, some over-arching conclusions and recommendations are presented.

Table ES-l. Summary of Evaluation Scenarios

Study Number	Scenario Name	Network Represented	Network Type	Simulation Model	Links	Total Vehicles
1	Urbansville (Urban Scenario)	Subarea of Metro Detroit (90 sq. miles)	Urban/Suburban Freeway and Major Arterial	INTEGRATION	2,000	250,000
2	Thruville (Inter-urban Scenario)	Wilmington, DE - Trenton, NJ (600 sq. miles)	Inter-City Freeway Corridor	INTEGRATION	1,000	135,000
2,3	Thruville Subset	I-295/NJ Turnpike Corridor, Cherry Hill, NJ (50 sq. miles)	Freeway and Major Arterial	INTEGRATION	250	40,000
4	Modal Test Network	Hypothetical Network	Mixed Rail and Roadway	Smart-Shift Framework	100	8,000
5	Urbansville CBD	Detroit CBD (5 sq. miles)	urban surface Sheet	THOREAU	850	15,000
5	Grid Test Network	Hypothetical Network	surface street	INTEGRATION, THOREAU		505,000

Table ES-2. Condensed Summary of Modeling Study Results

Study	**Benefits of Dynamic Route Guidance in Congested Urban Networks**
Scenarios	Morning peaking rush hour in Urbansville: 1997, 2002, 2012 demand
Goals	Quantify trip time savings for vehicles with dynamic route guidance under varying congestion
Results	- Benefits are greatest in moderate congestion, increase with trip length [§2.5.1, 2.5.2] - Trip-time reduction up to 13% when compared to experienced commuter traffic [§2.4]
Study	**Dynamic Route Guidance Compared to Advisory Messages**
Scenarios	High functionality ATIS (Dynamic Route Guidance) and low functionality ATIS (Advisory Messages implemented by Changeable Message Signs), Thruville and Thruville subset
Goal	Compare travel time reduction benefits of dynamic route guidance to advisory messages in incident scenarios with different levels of market penetration
Results	- 13-16% reduction in travel time for vehicles with dynamic route guidance [§3.3.4] - 8-11% reduction in travel time for vehicles responding to advisory message [§3.3.5] - Higher market penetration decreases user benefit, increases system benefit [§3.3.4, 3.3.5]
Study	**Impact of Network Surveillance on Dynamic Route Guidance Benefits**
Scenarios	Thruville subset, reduced percentage of probe vehicles providing surveillance information and reduced link reporting opportunities during incident conditions
Goals	Quantify percentage of probe vehicles required to support dynamic route guidance service
Results	- All benefits of route guidance can be provided with as few as 20% probe vehicles [§4.2.3] - Most (over 50%) benefits of route guidance realized with as few as 1% probe vehicles [§4.2.3] - Effectiveness of small probe populations can be augmented by more frequent updates [§4.3.2] - Reporting travel times only for congested links provides 90% of benefit at lower cost [§4.7.2]
Study	**Pre-Trip Mode Shift Benefits Assessment**
Scenarios	Rush hour on two mode (roadway vs. rail) sample network, various types of congestion (local and global, predictable and unpredictable)
Goals	Quantify user and system benefit of mode shifts enabled by pre-trip planning information
Results	- Under various non-recurrent delays, 15% market penetration induces 3-4% mode shift [§5.5.3-5] - Mode shifters cut travel time 11-35%; system travel time drops 2-7% [§5.5.3-5] - System-level benefits of pre-trip planning and route guidance are additive [§5.5.5]
Study	**Adaptive Signal Control Strategies**
Scenarios	Urbansville Commercial Business District rush hour with and without changes to traffic volume and direction, and a simple grid network
Goals	Compare average trip times for different adaptive signal control strategies compared to fixed signal timing plans
Results	- Less than 10% improvement over fixed signals when traffic follows expectations [§6.5, 6.6] - Dynamic corridor synchronization reduces average travel time 2 to 15% in other cases [§6.5, 6.6] - Actuated signals reduce average travel time 3 to 25% in other cases [§6.5.6.6]

NOTE: The reference following each result indicates the section providing context and explanation.

Benefits of Dynamic Route Guidance in Congested Urban Networks

This study quantifies the relationship between network congestion and travel-time reduction benefits of a dynamic route guidance user service. It employs the INTEGRATION traffic simulation model and the Urbansville test network, based on Detroit, Michigan. The value of route guidance is evaluated over three demand levels resulting from projected steady increases in annual travel demand under the assumption that the Urbansville roadway capacity is not increased from the 1997 baseline. Measures of congestion in the simulated Urbansville network under the lightest demand scenario (base year 1997) match most current empirical national average data, while the heaviest scenario demand (base year 2012) is roughly comparable with recent Tokyo conditions.

A near-term route guidance user service is defined for Urbansville under the assumption of a uniform five percent market share. Route guided vehicles receive accurate reports of current link travel time conditions every ten minutes. The performance of the guided vehicles is compared with vehicles modeling the behavior of experienced commuters, who are assumed to know the fastest routes according to average conditions during the peak period. Two representative cases with non-recurrent congestion are studied in each scenario: an incident case and a case with 10% heavier than normal demand. In these cases, the route guided vehicles have the opportunity to identify faster routes than the non-guided experienced commuters.

Figure ES-l illustrates trip time reduction for vehicles with dynamic route guidance compared with non-guided experienced commuters. Route guided vehicles experience a trip time reduction of up to 13% when compared to the experienced commuter subpopulation under incident or heavier than normal demand conditions. The benefit from dynamic route guidance increases as trip length increases. Trip time and &lay reduction for guided vehicles are observed to be highest under moderate-to-heavy levels of congestion.

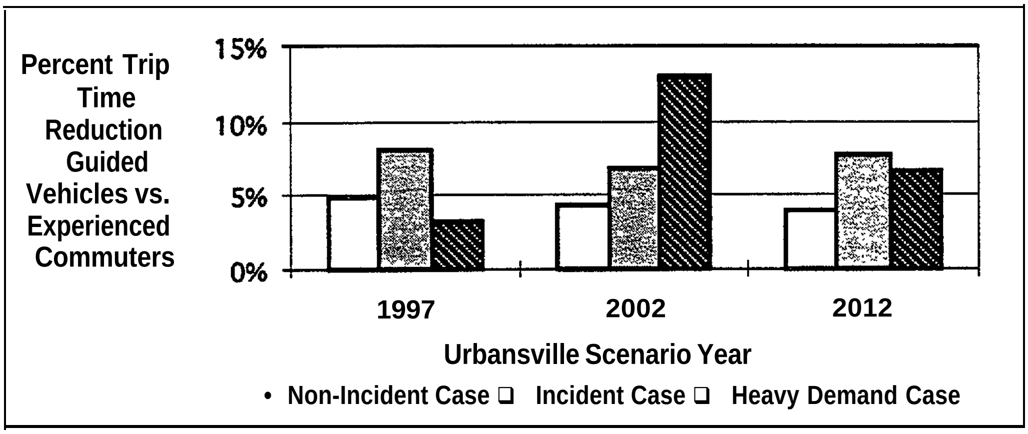

Figure ES-l. Dynamic Route Guidance Trip Time Reduction

Dynamic Route Guidance Compared to Advisory Messages

This study compares the travel time benefits realized from two levels of traveler information services. Dynamic route guidance directs equipped vehicles onto alternate paths when travel times on original paths exceed travel times for the alternates. Advisory messages warn vehicles to avoid certain congested links, but only a specified percentage of vehicles respond to the messages and take alternate routes.

The study uses the INTEGRATION model to simulate the Thruville inter-urban network, based on the Delaware Valley corridor. Three scenarios represent incident-caused delays of various severity. In each scenario, the ability of dynamic route guidance (5% or 20% market penetration) and advisory messages (5% or 20% response rate) to reduce delay is measured.

In all scenarios, the incident-caused delay for vehicles equipped with dynamic route guidance is cut more than 50%, reducing average trip times by 13-16%. Vehicles responding to advisory messages receive somewhat less benefit (8-11% reduction in average trip time). Unequipped and non-responding vehicles experience a slight (1-2%) reduction in average trip time as guided or responding vehicles reduce congestion by avoiding the incident.

If the advisory messages are presented by localized devices such as changeable message signs (CMS), however, the size of delay reduction is highly sensitive to the placement of the signs. When the signs were located at places where the travel time for an alternate route was high compared to the delay caused by an incident, the information did more harm than good for those who responded to it. Figure ES-2 illustrates these results.

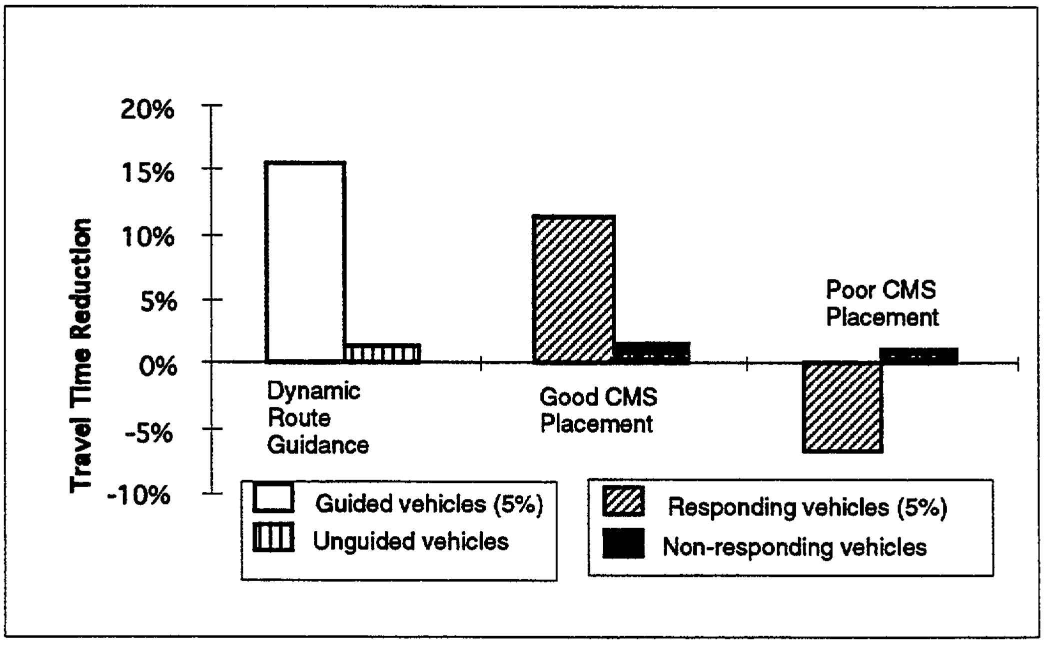

Figure ES-2. Travel Time Reduction for Dynamic Route Guidance and Advisory Messages

Impact of Network Surveillance on Dynamic Route Guidance Benefits

This study uses the INTEGRATION model to simulate incident-caused congestion on a subset of the Thruville network. Probe vehicles provide network surveillance information by reporting travel times for each link they traverse. The study varies the number of probe vehicles, thus varying the amount of surveillance information provided to the route guidance system, and measures the average travel time of vehicles with dynamic route guidance as compared to unguided vehicles.

If unguided vehicles serve as probes, study results indicate there is effectively no degradation in the value of dynamic route guidance when the probe population decreases from 100% to as low as 20%. An unguided probe population as low as 1% can still provide over 50% of the benefit of full surveillance. These results are illustrated in figure ES-3. The maximum time savings for guided vehicles is about 10% of trip time. At very low probe percentages, the value of dynamic route guidance can be increased by updating travel times more frequently than every ten minutes.

If the only source of network surveillance is guided vehicles acting as probes, those guided vehicles may experience longer travel times than unguided vehicles. This can happen after congestion caused by an incident has dissipated. The route guidance system does not learn that congestion has dissipated, however, because all the guided probes arc still being routed to a longer alternate path.

The study also shows that if probe vehicles report only travel times for links that deviate from historical norms, 90% of the potential benefit to guided vehicles can be obtained. Exception reporting can reduce the load on the communications network significantly, but it requires maintenance of an in-vehicle database of historical travel times.

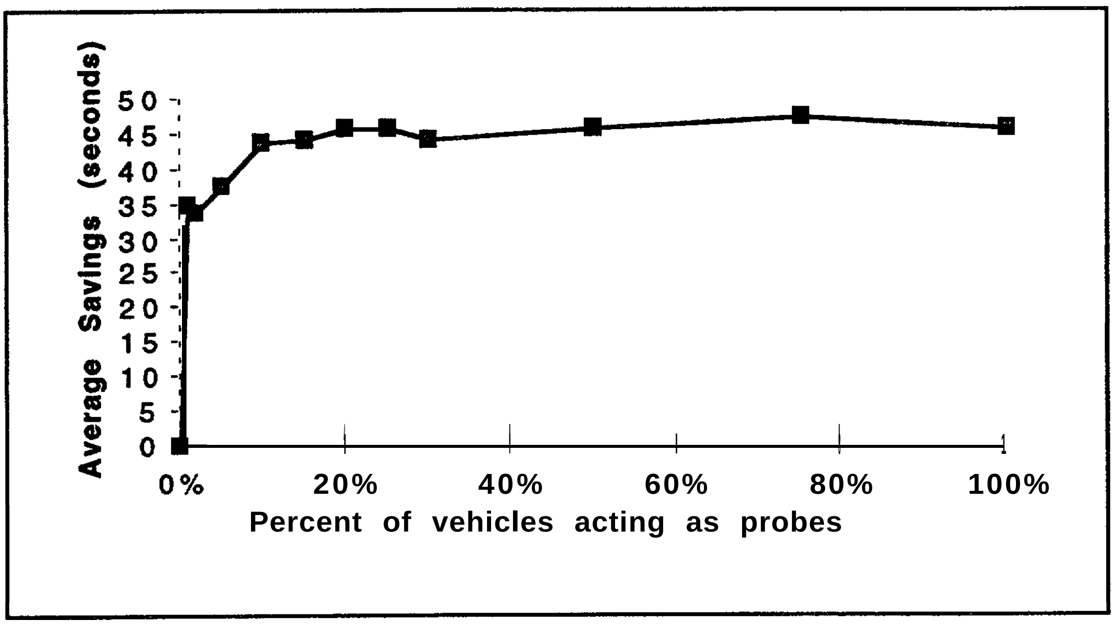

Figure ES-3. Time Savings Benefit to Guided Vehicles vs. Probe Percent

Pre-Trip Mode Shift Benefits Assessment

This study compares the benefit of a pre-trip planning service enabling single-day changes in mode choice to other congestion reduction strategies, including route guidance and lane construction. The test network includes two-modes: on-roadway and off-roadway (such as rail). The "Rainstorm" scenario features a network-wide reduction of 25% in roadway capacity. The "Construction" scenario features a predictable, localized reduction in roadway capacity. An "Incident" scenario features an unpredictable, localized reduction in roadway capacity. Off-roadway capacity and travel times are not affected in any scenario.

The evaluation framework is composed of a mode choice model and the INTEGRATION simulation model. For each scenario, the effects of roadway capacity reduction are simulated, and the resulting link travel times are input to the mode choice model, causing some drivers to change modes. The simulation is run again with the new on and off-roadway demands.

The results indicate a significant benefit to mode shifters and to the overall system in the test network. At low (3%) and medium (15%) market penetrations, 0.6-4% of the travelers shift modes. Shifters experience 11-37% travel time savings when compared with non-shifters with the same origins, destinations and trip start times. Total system travel time is reduced by 1-7% in these cases. At high (70%) market penetrations, mode shifters represent 15-21% of all trips in the network, and system travel time reduction is much higher: 12-21% . User benefits are smaller, however, as the information is more widely distributed. Figure ES-4 illustrates the reductions in travel time for the Rainstorm scenario.

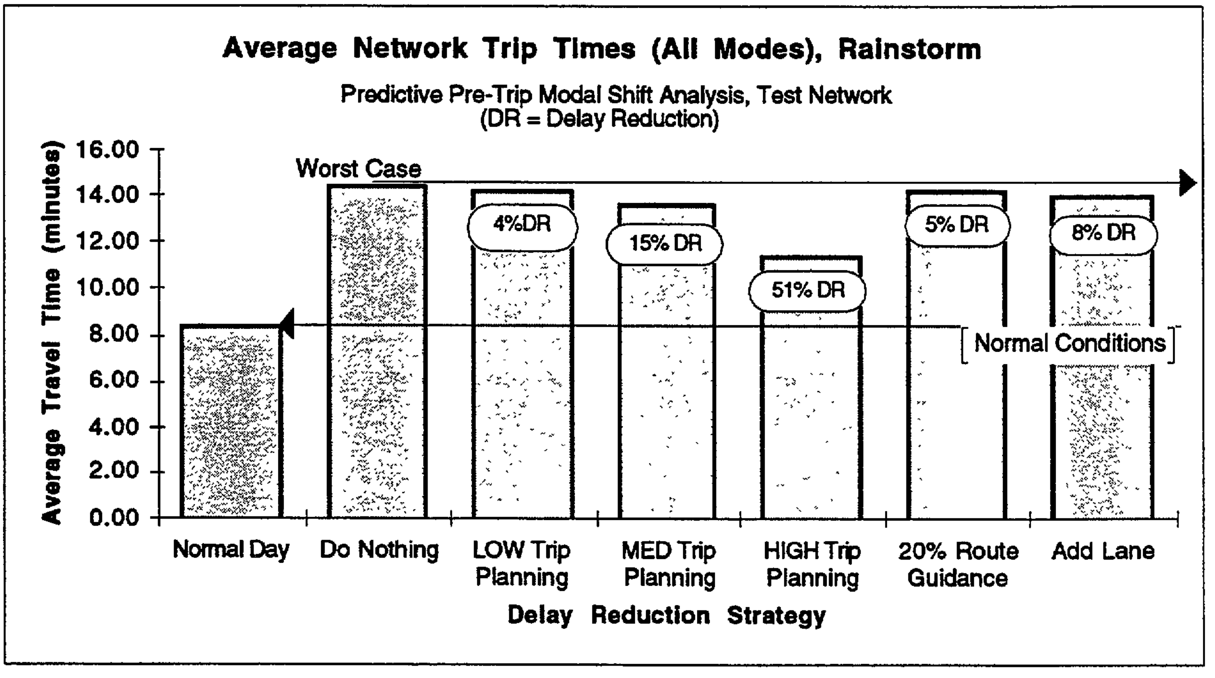

Figure ES-4. Travel Time for Various Congestion Reduction Strategies

Adaptive Signal Control Strategies

This study uses the THOREAU traffic simulation model for a network representing the Detroit commercial business district Three schemes for adaptive signal control were modeled: (1) isolated signal optimization, determining optimal cycle lengths and phase splits, (2) corridor optimization, synchronizing signals along dynamically selected corridors, and (3) signal actuation, extending green phases using real-time traffic counts and queue lengths. The study identifies conditions under which each adaptive strategy is most effective and quantifies impacts in terms of travel time savings and delay reduction. The study also shows that results from THOREAU match results from INTEGRATION on a simple grid network.

The base scenario represents the morning rush hour. A set of fixed signal timing plans was developed to provide synchronization on the major corridors. 47% of the base scenario traffic follows these corridors. The performance of the fixed signals and the three adaptive signal plans was compared for 20 scenarios: the product of four levels of traffic volume (60%, l00%, 110%, 120% of the base scenario volume) and five percentages of traffic following corridors with synchronization provided by the fixed plan (53%, 47% ,41%, 35%, and 29%).

Figure ES-5 shows the percent savings in average trip time for the best adaptive signal plan for each scenario. When traffic follows an expected pattern (region l), a good fixed plan might as well be used, since adaptive signals provide little benefit (0-5%). If traffic is heavier than expected, (region 2) isolated signal optimization provides the most benefit (3-7%). In region 3, all adaptive signal plans provided 5-15% savings; dynamic corridor optimization was the best by a small margin. If traffic is less than expected or the direction of traffic changes significantly (region 4), actuated signals provide the greatest benefit (15-25%).

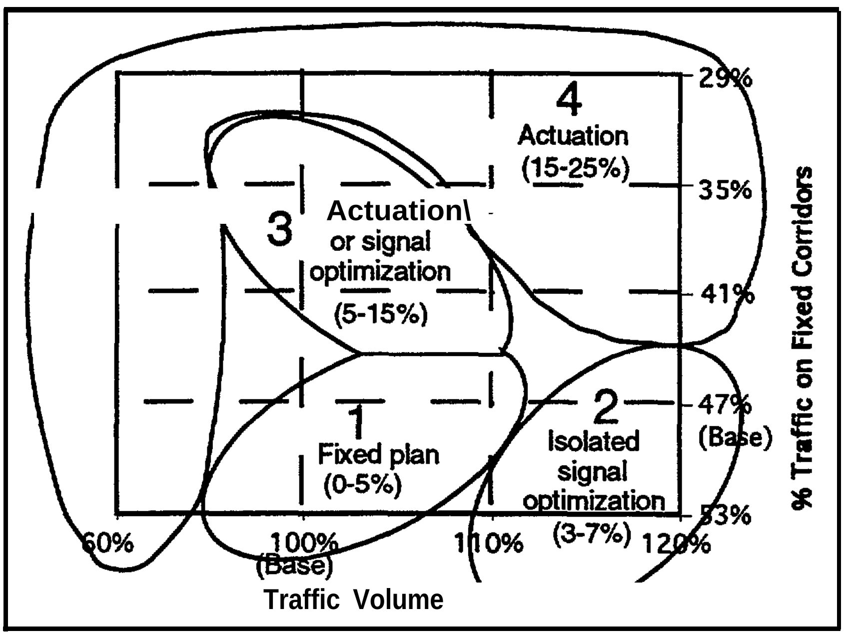

Figure ES-5 Best Signal Strategy and Percent Savings in Average Trip Time

Conclusions Regarding ITS Benefits Assessment

Adaptive control strategies and traveler information services can have positive impacts on system and individual efficiency (reduction in travel time, reduction in system &lay) in both the recurrent and non-recurrent traffic congestion cases. The Mitretek modeling studies, however, focus on the value of ITS user services in terms of impact on non-recurrent delay.

Mitretek consistently measures ITS benefits from the baseline of an efficient and optimized but non-adaptive system. Since many current non-adaptive systems are not optimal, the potential ITS benefits quantified in these studies may be conservative estimates of benefits that could be realized in those actual systems.

Key findings common to several of the studies include:

- Non-recurrent perturbations to the transportation system and the resultant delays can be significantly reduced by lTS user services like traveler information and real-time signal control. For example, the adaptive signal control study demonstrates a 2-25% reduction in trip time under perturbations to demand intensity and directionality. Vehicles that bypass incidents in an inter-city corridor network because of low or high functionality route guidance systems can reduce travel delays by 50% or more in some cases.

- The ITS user services examined have higher benefit in terms of travel time and delay reduction when the network experiences a greater deviation from expected conditions. A highly variable system is likely to be a good candidate for these ITS user services. Conversely, a highly predictable system may not be a good candidate for deployment of these services, unless there are significant underlying inefficiencies in steady-state control or assignment. In a highly predictable system, congestion occurs day after day in the same locations with similar magnitudes, so traffic control systems and experienced travelers' plans develop over time taking the anticipated congestion into account.

- The impact of ITS may be most strongly perceived by the traveler not in average delay avoided, but in the reduction of delay on outlier days, that is, days with significantly higher than expected delay. This also implies a reduction in variability in trip duration and better predictability of travel.

Key findings in the area of value of traveler information include:

- The value of information to the ITS user decreases as the proportion of the population receiving that information increases. The value of information to the overall system, however, generally increases as the proportion of the population receiving that information increases.

- One exception to this proposition, however, occurs when such a large population reacts to the information that the system may actually have worse performance (as in the mode shift study). In these cases, however, predictive forecasting techniques that anticipate traveler behavior can be employed to blunt this effect The simple techniques employed for prediction in the mode shift study indicate the value of such approaches. However, significant work remains to be done in determining both how such approaches might be implemented and the effectiveness of these techniques in a real-world environment.

- The value of traveler information is proportional to the value of the alternative opportunities available. When the time required to follow an alternate route or to shift mode is high, then the timeliness and accuracy of travel time prediction is more critical.

- Accurate surveillance information provided by limited probe vehicle populations can support effective ATIS user services. These services depend on the assumption that current information on traffic conditions (e.g., link travel tunes) are known throughout the network Such extensive and accurate information does not currently exist in any metropolitan or interurban network today. Perhaps one of the most positive results of these studies for ATIS user services is the relatively small number of probe vehicles needed to support adequate network surveillance.

Current and Future ITS Benefits Assessment Activities

The modeling studies presented in this document are components of the on-going ITS benefits assessment effort. Figure Es-6 depicts the three primary ITS benefits analysis activities at Mitretek and some related activities performed by other organizations. The other two activities at Mitretek are a review of empirical benefits and meta-evaluation of safety statistics. Key parameters and assumptions from those real world deployments have been employed in the modeling studies.

Having obtained the results presented in this report, Mitretek is now looking ahead to new studies to build on this information and these modeling capabilities. Mitretek recommends the following near-term modeling studies to address important aspects of integrated ITS user services. They represent the highest potential payoff studies that can be conducted within the near-term time frame, and involve only modest extensions of current capability.

- **Pre-Trip Travel Information:** The Smart-Shift evaluation framework should be employed on other realistic, large-scale networks such as Urbansville. Smart-Shift should also be augmented to add pre-trip route selection and trip-start timing to the current capabilities for pre-trip mode shifting. The framework could then be used to investigate potential conflicts or synergies among these three aspects of a pre-trip planning user service.

- **Hierarchical Traffic Control:** Hierarchical control systems combining components of both corridor optimization and advanced actuation may have significant merits. These potential benefits should be explored with some additional simulation-based research, including coordination with the RT-TRACS evaluation work sponsored by the Turner-Fairbank Highway Research Center.

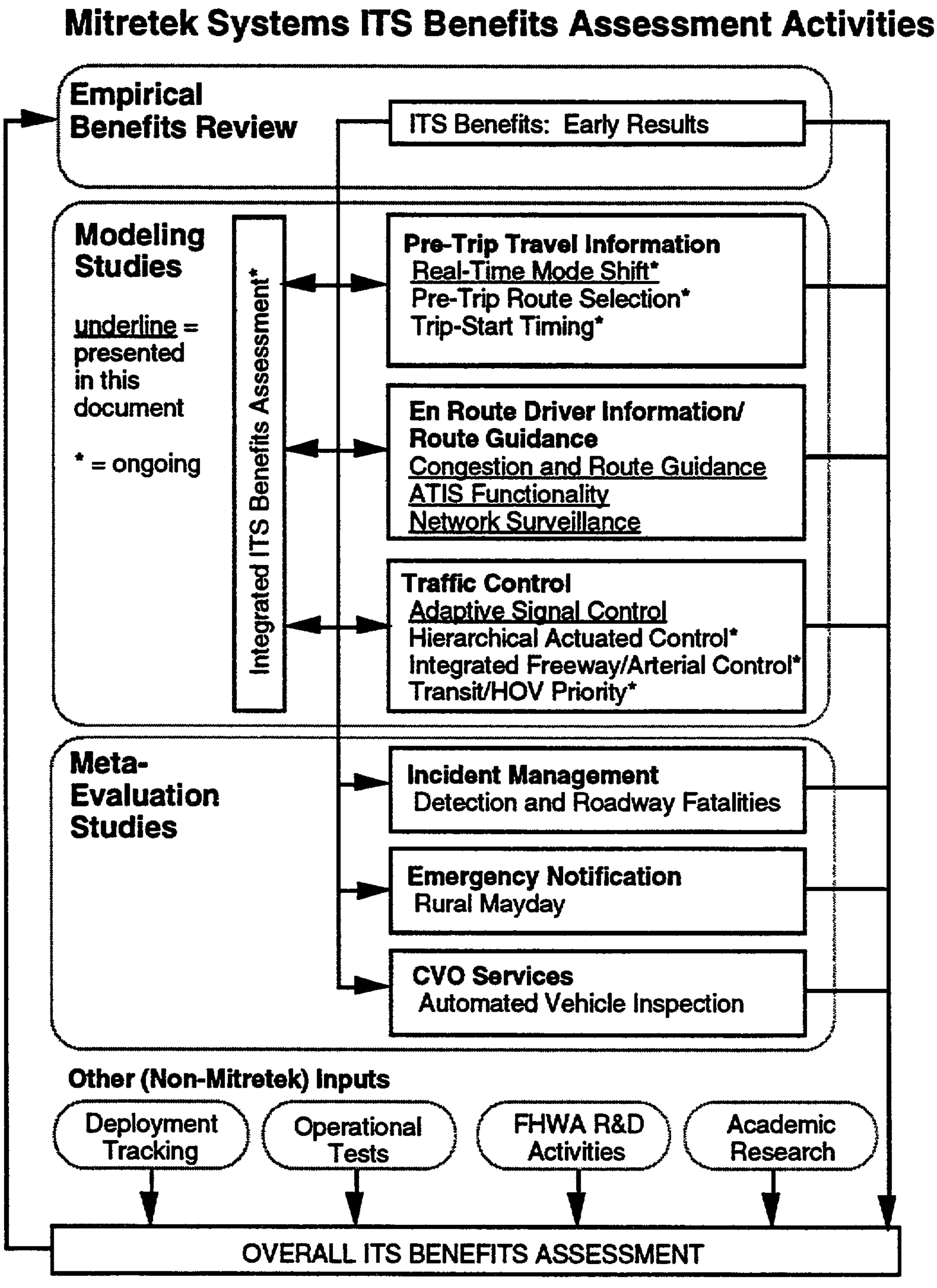

Figure ES-6. Mitretek ITS Benefits Assessment Effort

- **Integrated Traffic Control:** Integrated freeway/arterial control represents another area for near-term modeling evaluation. Mitretek is currently evaluating this aspect of traffic control in conjunction with MVA and Associates, examining potential synergies or conflicts between freeway ramp metering and adaptive arterial control. The study has a related component exploring the impact of providing transit or High Occupancy Vehicle (HOV) priority within the integrated freeway/arterial environment

- **Integrated ITS Benefits Assessment:** Integrated ATIS user services (both pre-trip and en route) and integrated ATIS and traffic control should be incorporated into the Smart-Shift evaluation framework This framework could then be employed in a near-term assessment of integrated user services.

Recommendations to Improve ITS Benefits Assessment

There are still many areas where existing tools are not able to address meaningful questions related to ITS benefits. Key needs for ITS benefits assessment identified in this study include:

- ***A research effort to develop a better understanding of underlying traveler behavior and traveler perception of ITS benefits. ITS*** has demonstrated potential for significant impact on non-recurrent congestion. Until underlying inefficiencies in traveler network assignment can be identified, however, the potential impacts of ITS on recurrent congestion cannot be accurately estimated. In addition, there is currently poor understanding of how travelers perceive the value of travel time reduction. An examination of traveler perceptions might also address factors other than travel tune reduction, such as cost, safety, comfort, and convenience.

- ***The development of better data and metrics describing real-world delay*.** Currently, relatively poor data are available on system travel time variability with respect to average experienced conditions. The aggregation of small events such as stopped, parking, or unloading vehicles could cause as much variation in travel time as a longer-lasting incident Better data and metrics will be key to distinguishing recurrent and non-recurrent delay, identifying potential high-payoff ITS deployments and to improving the utility of modeling efforts.

- ***Tool development for and assessment of integrated ITS user services. As*** expected, there is considerable interaction among ITS user services. As demonstrated in these studies, these interactions may have both positive and negative impacts on benefits. Understanding and quantifying these relationships will be key to guiding high-payoff ITS deployments.

Section 1

Introduction

This report documents five traffic simulation studies performed by Mitretek Systems to analyze the potential benefit of selected Intelligent Transportation Systems (ITS) services. The study results are being incorporated into Mitretek's ongoing analysis of ITS benefits, along with other results in the area of user service integration, safety, commercial vehicle operations, and other ITS services. This section discusses the role of traffic simulation models in studying ITS benefits and presents overviews of the five studies.

1.1 ITS Architecture Development Program

The U.S. Department of Transportation (DOT) Joint Program Office (JPO) for ITS sponsored a major program to develop a national system architecture for ITS. The architecture defines the components of ITS and their interrelationships on a logical, physical, and organizational level. It also defines the major functional and physical standards to help public and private entities to develop and implement functionally compatible ITS products and services. Government, academic, and commercial organizations contributed to the program.

The architecture deliverables cover architecture definition, deployment options, and a qualitative evaluation of specific ITS deployments that are consistent with the architecture. Evaluation was conducted in rural, interurban, and urban settings. Early in the program, three scenarios were selected and databases were developed to represent these three settings:

- "Mountainville," based on Lincoln County, Montana, represents a typical rural area (Harding, 1995a)
- "Thruville," based on the Interstate I-95 corridor between Philadelphia, Pennsylvania and Trenton, New Jersey, represents a typical interurban setting. (Harding, 1995b)
- "Urbansville," based on Detroit, Michigan and its suburbs, represents a typical urban setting. (Harding, 1995c)

Each database contains information about current and forecast population, commercial activity, personal income, roadway and transit networks, and communications services for the region. The ITS Architecture reports make extensive use of this information to develop estimates of deployment costs and qualitative analyses of the benefits of various ITS components in these three settings. These analyses provide common ground for forecasting deployment costs and benefits in specific localities.

The modeling activities described in this report concentrate on providing quantitative estimates of the benefits of ITS user services as deployed in scenarios compatible with the architecture. Since the studies grew out of the ITS architecture project, they use the Thruville and

Urbansville scenarios, making full use of the associated roadway network and traffic demand data. The Mountainville network was not modeled because the use of dynamic route guidance and adaptive traffic signals to relieve congestion is not a high priority in rural areas with sparse traffic. Maps of the Thruville and Urbansville networks as modeled are provided in later sections.

1.2 Role of Modeling in the ITS Program

Prototype ITS systems have been field tested across the country, including Los Angeles, Orlando, Detroit, Troy Michigan, Chicago, and Philadelphia. It is difficult to compare the performance of prototypes, however, since each environment is different and since most test conditions cannot be varied systematically. In addition, many operational tests involved small numbers of vehicles.

Simulation models can play an important part in studying the potential benefits of ITS deployment by enabling analyses of sensitivity to key deployment factors that cannot be collected from test deployments. Simulations can be developed to perform controlled experiments varying levels of ITS deployment, varying optimization strategies, and varying traffic demand patterns in quantifiable, reproducible scenarios. For example, models can simulate the effects of varying levels of market penetration much more easily than test deployment. Analyses of the simulation results can indicate the specific ITS strategies and deployment levels that are likely to provide meaningful improvements in the transportation system.

At a modeling workshop hosted by Mitretek on 14 March 1995, representatives from Mitretek, the architect contractor teams, and other interested parties discussed the role of modeling in the ITS Architecture Development program. A consensus was reached that it was not realistic or useful to use modeling to distinguish between different ITS architectures or to distinguish between ITS services with an ITS architecture and the same services without an ITS architecture. Rather the best role of modeling would be to evaluate ITS services alone in a design consistent with the architecture framework.

Secondly, the group considered the user services defmed by the ITS architecture and came to a consensus regarding those services that could potentially be modeled with tools available now or in the next few years, but did not recommend which ones should be modeled. Three major categories were defmed to capture the extent to which the group felt traffic modeling could be used to evaluate the user services: directly addressed, indirectly addressed, and not addressed. A question mark is shown where there was not substantial agreement among the participants.

- Directly addressed: The user services that can be modeled directly are those whose impact can be explicitly modeled with the traffic simulations.
    - En-Route Driver Information
    - Route Guidance
    - Pre-Trip Travel Information?

– Traffic Control

- Indirectly addressed: The user services that can be modeled indirectly have primary characteristics that cannot currently be modeled with traffic simulations but whose secondary impact on traffic flows can be assessed in some meaningful way.
  - Emissions Testing and Mitigation?
  - Incident Management
  - Emergency Notification and Personal Security?
  - Emergency Vehicle Management?
  - Ride Matching and Reservation
  - Demand Management and Operations
  - Traveler Services Information?
  - Electronic Payment Services (tolls)

- **Not addressed:** The primary or secondary impacts of the user service cannot be modeled with the current traffic simulation tools in a meaningful way.
  - Public Transportation Operations (four services)
  - Commercial Vehicle Operations (six services)
  - Advanced Vehicle Control and Safety Systems (seven services)

The modeling studies described in this report address the four user services in the first category above. The first three of these fall into the category of Advanced Traveler Information Systems (ATIS). Traffic Control falls into the category of Advanced Traffic Management Systems (ATMS).

1.3 Overview of Simulation Models Used

This section presents an overview of the simulation models used by Mitretek to evaluate ITS services.

1.3.1 Overview of INTEGRATION

INTEGRATION is a traffic simulation model developed by Michel Van Aerde & Associates (MVA), Kingston, Ontario. The model analyzes the operation of integrated freeway/arterial networks, real-time traffic control, and route guidance systems. INTEGRATION models vehicles at the individual vehicle level, and models each intersection explicitly. At the network level, INTEGRATION models the effects of incidents, dynamic flow rates and link-to-link interactions. The INTEGRATION model (in various forms) have been employed in a range of ITS studies over the last five years (Van Aerde et al., 1996).

Variants of INTEGRATION version 1.5x3 were employed for the Mitretek modeling studies. Version 1.5x3 is an enhanced version of INTEGRATION with features added at the request of Mitretek It models vehicle-to-vehicle interactions through a combination of macroscopic flow equations and simple queuing models. Lane changing and vehicle acceleration/deceleration are not explicitly modeled. Enhancements made for the ITS Architecture Development program include an improved probe vehicle model, new control capabilities in defining vehicle classes and route guidance functionality, enhanced vehicle tracking for simulation output, and the implementation of a corridor-based signal control optimization scheme (Hellinga and Van Aerde, 1995).

1.3.2 Overview of Smart-Shift

Smart-Shift is composed of two modules: a mode choice model and a traffic simulation. Data processing programs within Smart-Shift control the interaction between the two primary modules. An iterative process involves the exchange of data between the mode choice model and the traffic simulation. The traffic simulation reports roadway travel times for all vehicles in the network These data are then aggregated to provide an average travel time for each origin-destination pair and time of departure. These data are the key input to the mode choice model, which compares the roadway travel time to a table of constant off-roadway travel times. Based on the ratio of on-roadway to off-roadway travel times, the mode choice model generates a new demand pattern for input to the traffic simulation.

1.3.3 Overview of THOREAU

The Traffic and Highway Objects for REsearch, Analysis, and Understanding (THOREAU) model is an object-oriented simulation tool developed at Mitretek to evaluate ITS services. Vehicles moving along lanes on links are maneuvered by actions defined by current position, speed, driver type, maximum acceleration/deceleration rates, and available headway. Turns, lane changes, incident avoidance, right-of-way, and the merging of single-lane traffic from multiple source lanes at each intersection are processed as required.

THOREAU tracks individual vehicles along their trips from their origin to their destination. Each vehicle is assigned a path through the network Paths may change due to dynamic route guidance, but that feature was not used in this study. Each traffic signal controller in the network is represented in THOREAU by a traffic light object. The base case for signalized traffic control is the fixed timing plan. Currently THOREAU supports three alternative methods for adaptive signal control.

1.3.4 Communications Modeling

Communications simulation models are also essential for testing the feasibility of various ITS deployments in heavy traffic scenarios, since communications among vehicles, roadside detectors or beacons, information service providers, and traffic management centers comprise a vital component of most ITS installations. ITS planners must be assured that planned communications systems will be able to handle the communication loads for most realistic situations. Mitretek has built communications models for Cellular Digital Packet Data as used for ITS and has performed communications simulation studies using parameters drawn from the traffic simulation studies. The results of those studies are documented in a separate report (Biesecker and Wang, 1995).

1.4 Contents of this Report

Sections 2 through 6 of this report document the five modeling studies and section 7 present a summary and conclusions. Table l-l summarizes the scenarios and primary goals of the five studies.

Table l-l. Summary of Modeling Studies

	Study Title	Network	Model	Primary Goals
1	Benefits of Dynamic Route Guidance in Congested Urban Networks	Urbansville	INTEGRATION	Measure impact of congestion on benefit of dynamic route guidance.
2	Dynamic Route Guidance Compared to Advisory Messages	Thruville, Thruville subset	INTEGRATION	Compare benefits of high versus low functionality ATIS services.
3	Impact of Network Surveillance on Dynamic Route Guidance Benefits	Thruville subset	INTEGRATION	Reduce number of probes or detectors, measuring impact on route guidance.
4	Pre-Trip Mode Shift Benefits Assessment	Test two-mode network	Smart-Shift, INTEGRATION	Measure benefit of mode shiis enabled by pre-trip planning information.
5	Adaptive Signal Control Strategies	Urbansville Commercial Business District (CBD), grid network	THOREAU, INTEGRATION	Compare adaptive signal plans to fixed signal plans reacting to traffic changes.

The following paragraphs describe and summarize the contents of each section.

- **Study 1: Benefits of Dynamic Route Guidance in Congested Urban Networks:** This study lays the groundwork for studying the potential benefit of dynamic route guidance. It uses the INTEGRATION model to demonstrate the value of route guidance to guided vehicles in a scenario representing morning rush hour in the Urbansville network The primary variables are demand levels as they vary by hour and increase by year. The hypothesis is that the benefits associated with a near-term route guidance user service depend on the level of recurrent congestion on the roadway network.

- **Study 2: Dynamic Route Guidance Compared to Advisory Messages:** This study compares the benefits of dynamic route guidance to advisory message information in the Thruville network under varying congested conditions. The first scenario represents a minor incident blocking one lane of a three-lane freeway segment, the second scenario represents a major incident blocking all lanes of a three-lane freeway segment, and the third scenario represents major construction along a freeway. The hypothesis is that the higher level of route guidance provides more benefits to users than the lower level, but not significantly greater. The study seeks to quantify this differential in benefits in terms of travel time savings for guided vehicles and for the system as a whole. It is also expected that non-guided vehicles will also benefit slightly, since fewer guided vehicles will contribute to congestion.

- **Study 3: Impact of Network Surveillance on Route Guidance Benefits:** This study examines the benefits of route guidance in the Thruville scenario, with and without incidents blocking lanes on major inter-city highways. It then examines the effect of reducing the amount of information collected by the Traffic Management Center (TMC), either by reducing the number of locations with detectors or reducing the number of probe vehicles in the system. The goal is to measure the degradation in the benefit to guided vehicles as the amount of information gathered by probes or detectors decreases. The study also investigates methods of providing most of the benefit of route guidance with a minimum of collected information.

- **Study 4: Pre-Trip Mode Shift Benefits Assessment:** This study introduces a new model, the Smart-Shift framework developed by Mitretek. Its purpose is to represent a two-mode transportation system (highway and rail) to capture travelers' preferences between the two modes as a function of anticipated travel time. Smart-Shift examines what will happen to system and individual travel time if travelers are supplied with pre-departure information on highway and rail trip times. Thus, the study addresses the Pre-Trip Travel Information ITS user service. The study investigates three scenarios: minor reduction of capacity on all highway links, an incident on a major highway link, and construction on a major highway link. It also compares the benefits of pre-trip travel information to route guidance and lane capacity construction.

- **Study 5: Adaptive Signal Control:** This study uses the THOREAU traffic simulation model for a network representing the Commercial Business District (CBD) and for a simple grid network Three schemes for adaptive ATMS were modeled: (1) isolated signal optimization to determine optimal cycle lengths and phase splits, (2) dynamic corridor optimization to synchronize signals along selected corridors, and (3) actuated signals that extend green phases based on real-time traffic counts and queue lengths. The hypothesis is that when traffic follows an expected pattern, adaptive signals do not perform significantly better than a set of fixed signal timing plans developed to optimize the flow of traffic for that pattern. When traffic deviates from the predicted levels, either in total volume or in the direction of traffic flow, adaptive traffic signals can improve travel times by actuation or by changing signal cycle lengths, phase splits, and offsets. The study identifies conditions under which adaptive strategies are most effective and quantifies their impact in terms of travel time savings and delay reduction.

- **Summary, Conclusions, and Recommendations:** This section summarizes the conclusions from the five studies and presents some overarching conclusions that may be drawn across multiple studies. A set of recommended near-term modeling studies is presented.

Section 2

Benefits of Dynamic Route Guidance in Congested Urban Networks

This study examines the hypothesis that trip performance benefits expected from dynamic route guidance arc dependent on overall network congestion conditions. If a network is lightly loaded and there are no incidents, dynamic route guidance has little value for the traveler since the most direct, obvious paths are likely to offer excellent travel time performance. On the other hand, when the network is so highly congested that no uncongested alternative path can be identified, dynamic route guidance may provide only limited benefit The study focuses on the ability of dynamic route guidance to reduce travel delay by finding new paths in real-time for en-route vehicles. Thus, this study does not attempt to quantify the improvements in trip performance with respect to way finding or more efficient static assignment.

The purpose of the study is to establish a quantitative relationship between recurrent network congestion and the travel-time reduction benefits of a dynamic route guidance user service. The approach is to use the Urbansville network under a range of demand and congestion conditions and to quantify the benefits of dynamic route guidance using the INTEGRATION traffic simulation.

A near-term dynamic route guidance user service is described for the purpose of the study. A market penetration (user base) of 5% of the vehicle population is assumed. The guidance provided is assumed to be based on the fastest path calculated using current real-time estimates of link travel time. Anticipatory or predictive dynamic route guidance techniques are not considered. The study was originally documented by Wunderlich (1995).

Recurrent network delay conditions for the Urbansville network in three time frames are established. Two experiments are presented. The first examines the benefit of dynamic route guidance against a driver behavior model of experienced commuters. The second considers an aggregate model of driver behavior including familiar and unfamiliar drivers.

2.1 Introduction to Dynamic Route Guidance

This subsection reviews the three major activities required for the support of a dynamic route guidance system: data collection, route selection, and transmission of information to guided vehicles. The second and third activities may occur in either order, depending on how the system is implemented. A simple example of dynamic route guidance illustrates the concepts of congestion spillback and diversion delay.

2.1.1 Data Collection

The ability to collect real-time network information is an essential component of many ITS capabilities. Both ATIS and ATMS rely heavily on timely and accurate information about current traffic conditions for efficient operation. Network surveillance provides this information by monitoring the behavior of vehicles traversing a network. Key factors in the

&sign of a network surveillance system are how many vehicles contribute to that information and how and where this information is collected.

There are two basic methods of network surveillance for collecting data. These are generally termed roadside and in-vehicle devices. A roadside device, typically a form of detector, collects information from vehicles as they pass by it. The most basic detector simply counts vehicles, but a more intelligent detector may measure the speed of every vehicle that passes it and use this information to estimate the travel time on its link. Roadside devices provide fixed data collection points that must be installed by roadway maintenance authorities. Information collected by detectors is transmitted by a communications link to a TMC.

A network surveillance system may use a combination of the two types of devices. One example is using a detector to write a time stamp on a passing probe vehicle and using the next downstream detector to read the time stamp and compute travel time. Another example is using detectors to trigger a probe vehicle to report its link travel tune directly to the TMC.

2.1.2 Computation of Fastest Routes

Information about the current travel times on network links is used to compute the fastest route for each guided vehicle to its destination. This determination may be performed by a computer onboard the vehicle, given link travel times transmitted periodically from the TMC. Alternatively, the best route may he selected at the TMC and transmitted directly or indirectly to guided vehicles.

While these two approaches differ significantly in implementation, the end result is equivalent from a modeling standpoint. Sometimes this report uses the terminology of the first approach (link travel times transmitted to guided vehicles with onboard computers) and sometimes it uses the second (best route transmitted to guided vehicles). The dynamic route guidance service analyzed in sections 2 through 5 of this report could be implemented using either approach.

2.1.3 Transmission of Data to Guided Vehicles

Periodically, each guided vehicle receives updated information. The update may consist of link travel times (for in-vehicle processing) or suggested routes (for centralized route selection). The frequency and detail of the updates are major design decisions, significantly affecting the value of the information to guided vehicles, as well as communications system workloads. If a route other than the driver’s current route becomes the best route, the information must be received by the driver prior to the point where the current and alternate routes diverge.

2.1.4 Windows of Opportunity for Dynamic Route Guidance

A network bottleneck may be caused either by an incident or a link with a high Volume to Capacity (V/C) ratio. If the demand level at a network bottleneck is less than the capacity of the bottleneck, no significant delays from queued vehicles are generated. In this case, there is little value for diversion, and therefore little value in dynamic route guidance information.

When the demand exceeds the capacity at the bottleneck, then queues of delayed vehicles begin to build back on the links upstream from the bottleneck, increasing travel times on those links. For small queues, the additional travel time incurred by diversion to an alternate route may not exceed the delay time at the bottleneck. Only when the queue has been built up to a point at which delays exceed the extra time requited for diversion do guided vehicles change route. The "window of opportunity" has now been opened for route guided vehicles to take advantage of the alternative route. In figure 2-1, good and weak (low diversion delay and high diversion delay) alternative routes are depicted around a bottleneck on the "mainline" route.

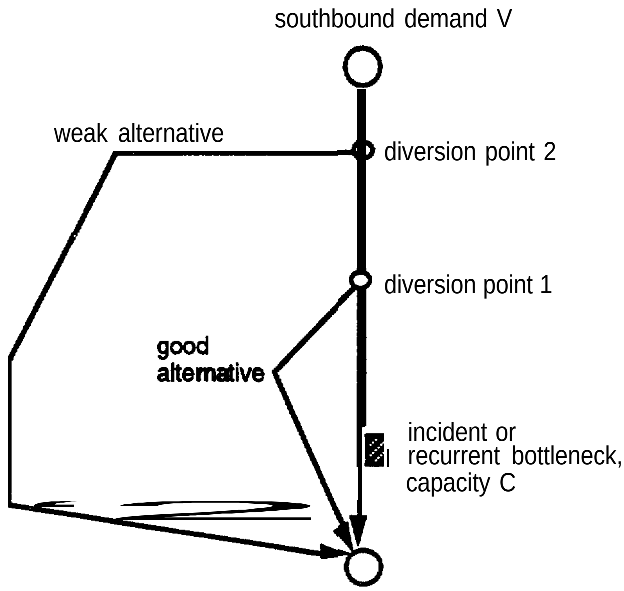

Figure 2-1. Real-Time Diversion Opportunity for Route Guided Vehicles

The value of the dynamic route guidance information is directly related differential in travel time between the mainline and alternative paths. Travel time savings increases as the time associated with the delay grows in proportion to total trip time.

Clearly, dynamic route guidance benefits are higher when vehicles have the opportunity to take the low diversion delay, "good" alternative than when the relatively high diversion delay "weak" alternative is the only option. However, the opportunity for free access to alternative routes may be restricted by link spillback effects. The growing queues introduce longer and longer delays and eventually may block access to an alternative. The value of the alternative is now dependent on the length of the queue of vehicles. Most critical is the proportion of delay incurred between the rear of the queue and the diversion point, compared with that between the diversion point and the bottleneck itself. In figure 2-1, when queues reach back to diversion point 2, then the "good" alternative may be a result in longer travel times than the "weak" alternative.

The nature of the window of opportunity for route guided vehicles in this example is highly transient. At low demand levels, there is no benefit in diversion. As demand builds, opportunity and value for diversion grows with the growth of the delay at the bottleneck. At some point, however, link spillback causes the value of the diversion alternative to drop because the access to the diversion points also incurs delay.

For this example network, this notion of dynamically changing value of diversion seems straightforward. For more complicated networks with many origin-destination pairs and continually changing link delays, a simulation provides the best method of determining the value of diversion.

2.2 Urbansville Scenario

This subsection describes the Urbansville network, the demand scenarios, and the controlled experiments Mitretek performed to quantify the benefit of dynamic route guidance under variable congestion conditions.

2.2.1 Overview of the Urbansville Network

The Urbansville network employed as the test scenario for this study is an abstraction of a 233 sq. km (90 sq. mi.) area in metropolitan Detroit. It includes major freeways and arterials connecting the downtown area to the suburbs, and others running across the region. Roughly 2,000 links are modeled, including freeways, arterials, and ramp interchange facilities. High-Occupancy Vehicle (HOV) lanes are included on some links. There are approximately 200 origin and destination (O-D) points. Some O-D pairs represent trips entirely within the modeled region, but others represent trips that begin and/or end outside of the modeled region. Figure 2-2 presents a map of Urbansville.

2.2.2 Demand Scenarios

The general approach of this study is to employ the Urbansville network under a no-build assumption (fixed capacity) and to introduce progressively heavier demands onto this network, measuring the performance of guided and unguided vehicles in each case. Three demand pattems for the a.m. peak correspond to estimated demand in 1997,2002, and 2012 (figure 2-3). Demand increases by 2 percent per year, compounded. This growth corresponds to an overall increase in travel demand of roughly 35 percent between 1997 and 2012, from 160,000 to 217,000 vehicles. Network capacity remains constant, so the level of network congestion steadily grows. The time-of-day demand pattern was developed from Detroit-area trip survey data (SEMCOG, 1990) and Highway Capacity Manual data (TRB, 1995).
Peak network demand in 2012 is 115,000 vehicles per hour entering the network during the 7:30-8:l5 am. time frame. Vehicles are introduced onto the network for 2.5 hours. This allows for data collection in two critical phases. The fast is the “loading period” where rush hour demand ramps up onto a relatively empty network. The second is a period in which the network demand flattens out or drops, but the roadway network is still relatively congested with a vehicle population en route from the earlier time periods. Demand directionality is predominantly southbound and eastbound during the period (figure 2-4).

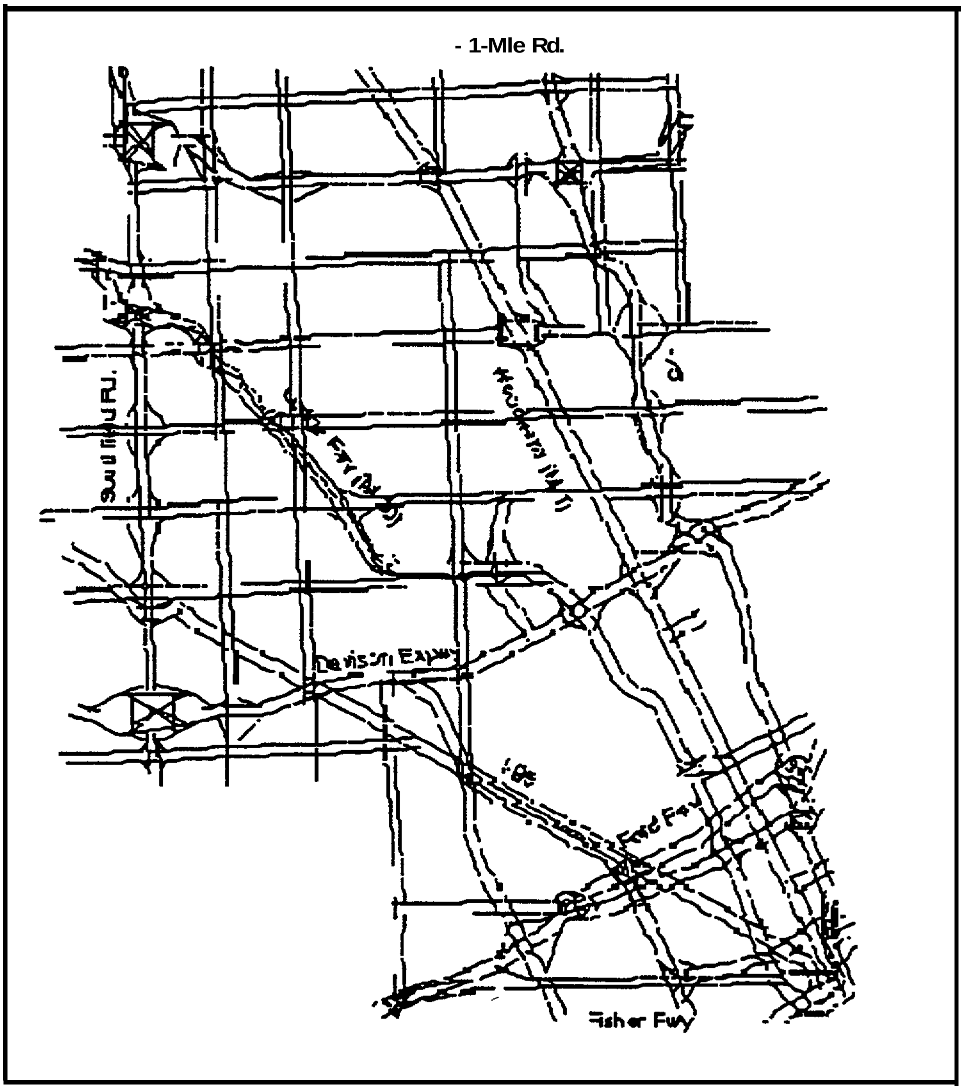

Figure 2-2. Map of Urbansville

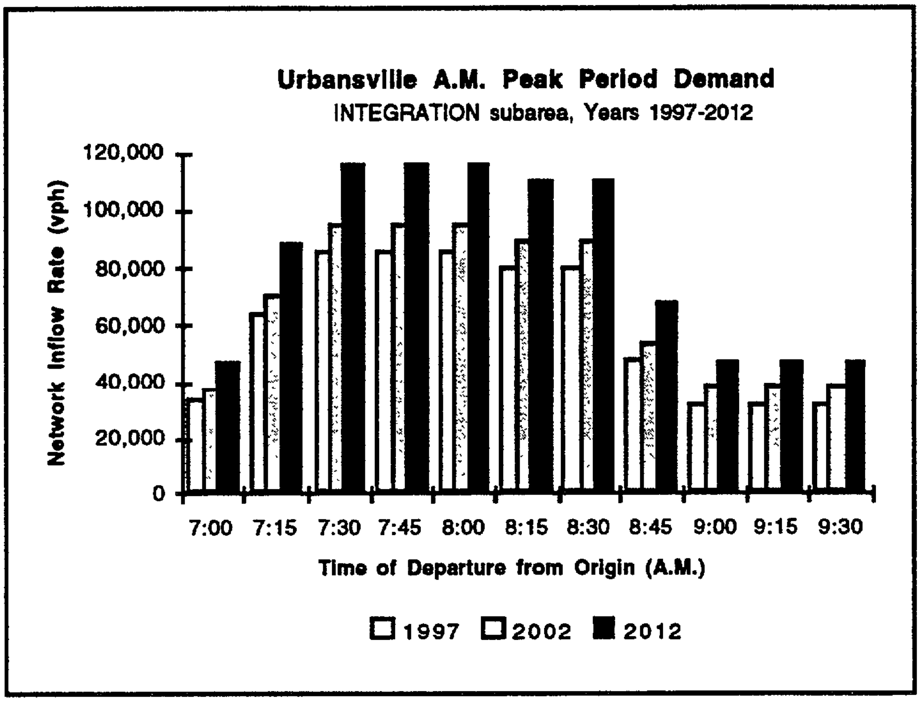

Figure 2-3. Increasing Demand in Three Time Periods

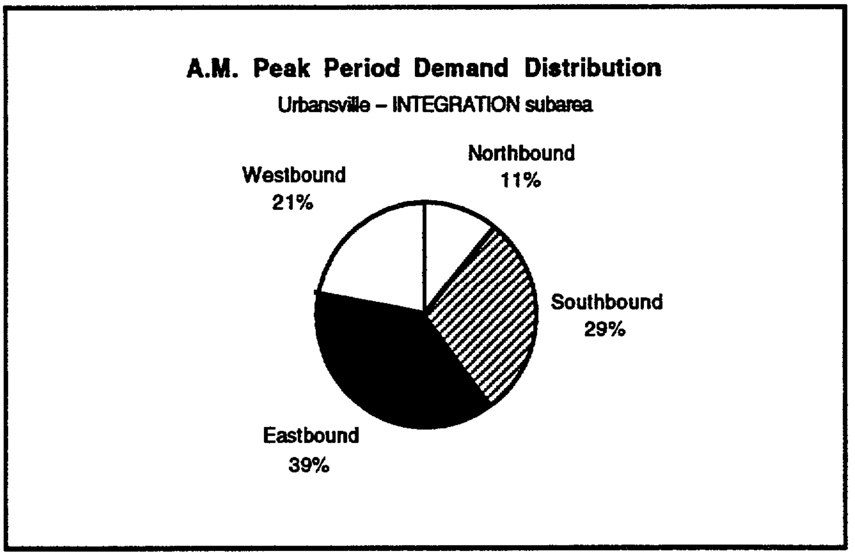

Figure 2-4. Demand Directionality in Urbansville

Average trip length in the portion of Urbansville that is modeled is shorter than national averages for commute distance. DOT statistics (DOT, 1994) indicate that the average commute distance (one way) in the United States was roughly 16 km (10 mi.). Trips modeled in Urbansville average 10.5 km (6.5 mi.), but more than one-third of all trips traverse paths from external origins to internal destinations. The simulated Urbansville network models only a portion of a total commute distance for these trips. Therefore, Urbansville models commuter activity within the defmed cordon area, including trips that are actually longer than the distance traversed in the simulation. The longest modeled trip-segments are 30 km (18 mi.) in length, while the shortest modeled trip-segments are .81 km (0.5 mi.) long. The median trip-segment length is roughly 10.5 km (6.5 mi.). Complete trip length (including travel outside the simulated area) is not considered in this study. Hereafter, a reference to a "trip" in this study refers only to the modeled trip-segment.

2.2.3 Quantitative Congestion Metrics

Three congestion metrics were generated to describe recurrent (non-incident) conditions for the Urbansville network: average network trip time, maximum time-variant average system trip time, and percentage of total roadway surface operating at levels of service D, E, or F. The first two measures are related to aggregated trip statistics and trip delay. The third measure is related to delay measured on links during the course of the simulation. The Urbansville network is based on Detroit, but differs in terms of demand directionality. Therefore, the metrics are not presented in order to claim that Urbansville is a validated representation of Detroit. Rather, the metrics are presented to place delays and congestion levels in context against national averages.

Average network trip time is computed as a function of the experienced trip times of all vehicles that begin traversing the network from 7:00 a.m. through 9:00 a.m. Although vehicles do continue to enter the network after 9:00 a.m., these vehicles are not tracked for the purposes of calculating this metric. Thus, the traffic which enters the network after 9:00 a.m. runs interference for the vehicles in our sample, namely the vehicles that enter between 7:00 a.m. and 9:00 a.m.

Average network trip times in Urbansville straddle the current national average of 22.4 minutes. Table 2-l summarizes trip times and network speeds generated as outputs from the simulation. If the trip times in Urbansville are normalized against the longer average national trip length with a network speed metric, then the average speed for Urbansville 1997 is slightly higher than the national average commute speed of 29 mph (47 kph). (DOT 1994). The 2012 Urbansville average speed of 13 mph (21 kph) is slower than any U.S. urban area in the DOT survey.

Trip statistics are also collected for groups of vehicles entering the network within the same 10 minute time-window. This approach allows for the examination of trip statistics across the changing network conditions of a single rush hour period. Each group is called a cohort, and an average trip time for all vehicles in a cohort is computed. The maximum travel time experienced by any cohort in the peak period is used as another congestion measure.

Table 2-1. Average Trip Times and Speeds

Year	Average Trip Time (min)	Average Trip Speed (mph)	(kph)
1997	12.2	30	48
2002	15.0	24	39
2012	27.4	13	21

Figure 2-5 illustrates the peaking nature of average cohort travel times in the Urbansville network. In the 1997 time frame, the longest cohort trip times (8:40-8:50 departures) are roughly twice the average free flow time of 7.5 minutes. In 2002, the maximum cohort trip time increases to just under three times free flow trip time (21 minutes). In 2012, maximum cohort trip times are more than five times free flow trip time (40 minutes). A 1992 study of Portland (DKS & Associates, 1992) measured a peak deviation of 2.2 times free flow travel time in the a.m. peak period. Data from a 1994 experiment in Tokyo (UTMS News, 1994) places the maximum peak trip time at roughly 4.0 times free flow travel time. For this congestion measure, then, Urbansville 1997-2012 spans the range from current-day Portland, OR to current-day Tokyo.

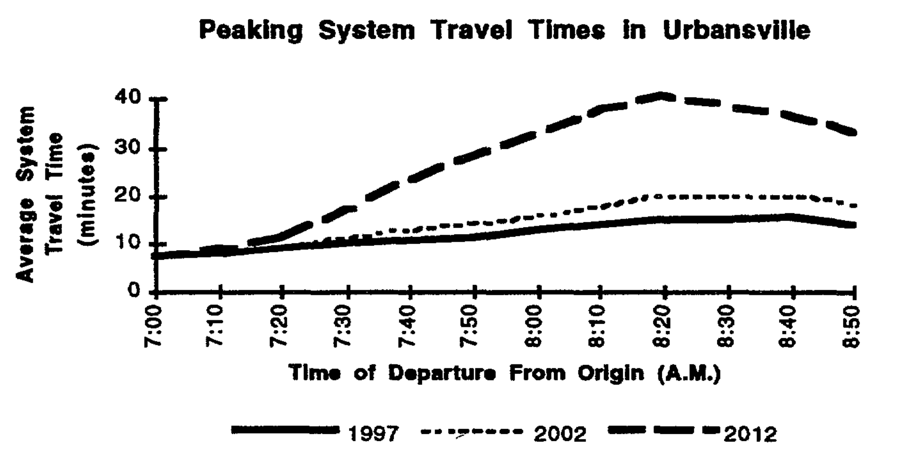

Figure 2-5. Congestion Within the Peak Rush Hour Period

Another useful measure of the breadth of network congestion is a description of link-related statistics such as vehicle density and average link speed. For the Urbansville scenario, data were collected at 30 minute periods throughout each of the simulations. Link level of service based on vehicle densities and average vehicle speed was used to describe conditions on all the links in the network. (TRB, 1994) The number of links that fell into the congested range of service (D, E, F) were tallied and normalized for link length. This procedure allows for the calculation of total roadway surface in the network operating under congested conditions. Figure 2-6 illustrates the growth of congested conditions from 6% to 22% of all lane-miles. This percentage is computed as a measure of total roadway surface, including the off-peak directions (west and northbound). Total congested roadway expressed as a percentage of peak-direction roadway surface are roughly double these figures (12-44%).

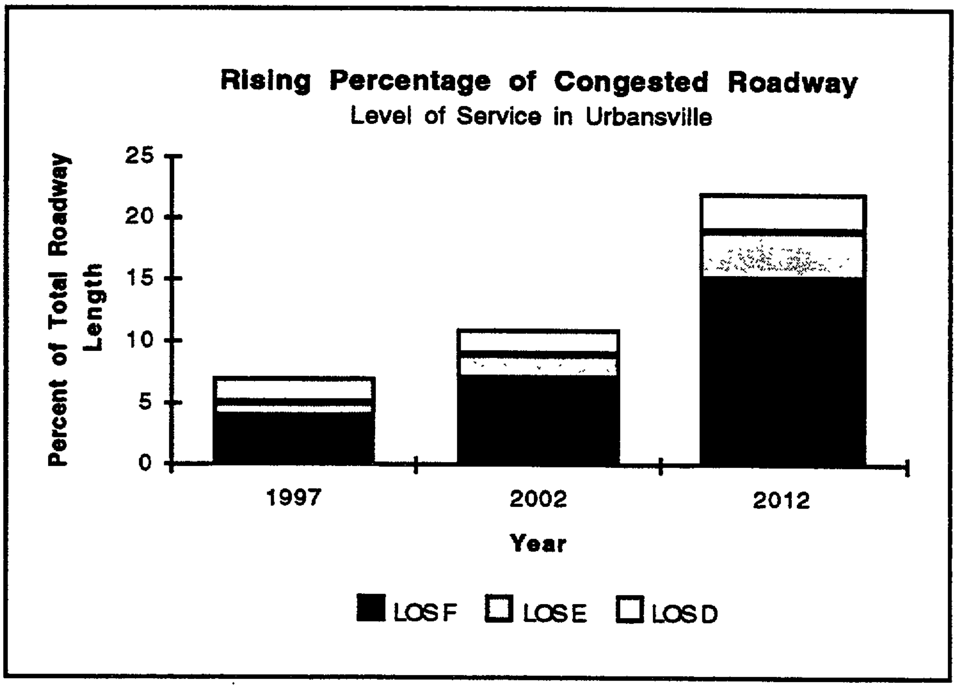

Figure 2-6. Link-Based Congestion in Urbansville

2.2.4 Qualitative Congestion Measures

Qualitative assessments of network congestion may be made during simulation run-time. For example, key bottlenecks in the Urbansville network occur on or around freeway on- and off-ramps. These are not the only sources of backups, but delays are often generated from these bottlenecks.

The most congested areas in Urbansville are the facilities that carry south and eastbound traffic, the peak directions. In particular, stretches of I-75, I-696, the Southfield Freeway, and the Ford Freeway have highly congested components during the simulation. These hot spots are also typically encountered in the current Detroit network. The underlying arterial grid appears less heavily loaded in Urbansville, particularly within the modeled city limits of Detroit. Suburban arterials, most notably 8-Mile Road, tend to be congested. This is also consistent with typical Detroit traffic patterns. This combination of congested freeways with relatively uncongested arterials appears to provide good opportunity for diversion within the network. In addition, the flat, unconstrained nature of the Urbansville (Detroit) geographic region does not feature any natural "choke point" for demand. This can be compared to highly constrained networks like the San Francisco Bay area, where the bay and the availability of bridges limits the number of alternate routes between many major commuter origins and destinations.

2.3 Experimental Parameters

Mitretek performed two experiments using the Urbansville network. Each experiment used the demand levels for 1997,2002 and 2012 described in the previous subsection. Cases with and without incidents are modeled.

- In Experiment 1, trip times for guided vehicles were compared to trip times for a driver behavior model corresponding to knowledgeable commuters. Commuters are considered to be familiar with both the network structure and typical network delays associated with the morning peak period.
- Experiment 2 examines the benefit of dynamic route guidance against an aggregate model of familiar and unfamiliar drivers.

2.3.1 Simulation Parameter Settings

In both experiments, the following scenario settings apply:

- Network capacity remains constant (except in the incident cases).
- Five percent of vehicles are equipped with a non-predictive dynamic route guidance capability.
- Route guided vehicles receive updates every 10 minutes. A detector at the end of every link records the link travel time of every vehicle exiting the link and reports it to the TMC. The TMC computes optimal routes for all guided vehicles given the latest link travel times. Detector reports are assumed to be available immediately at the TMC without a tune lag.
- Five percent of vehicles arc HOV-capable, proportionally represented among both route guided and unguided vehicles.
- No changeable message signs (CMS) are modeled.
- Isolated signal optimization is active as the default for this study (see section 6.2 for an explanation of isolated signal optimization).

- No probe vehicles are modeled.

- Each statistic reported as a result of an experiment is averaged over four simulation runs with different random seeds in Experiment 1, eight runs in Experiment 2. All reported results are statistically significant unless otherwise noted.

Trip statistics are generated with the use of the Cohort15 post processor, developed by Mitretek This post-processor allows analyses to be performed on specific temporal subsets of vehicles, e.g., while the network is loading, after it is loaded, and during the draw-down of demand at the tail of the peak period

Average system trip time over all vehicles entering the network between 7:00 AM and 9:00 AM is used as the measure of congestion. Trip travel time savings attributable to dynamic route guidance (also referred to as "RG benefit") is calculated as the difference between average travel times for guided and unguided vehicles in the sample, calculated as a percentage of the unguided vehicle travel time.

2.3.2 Unguided Vehicle Assignment

Two techniques were employed for unguided vehicle assignment. One technique is the default unguided vehicle assignment module provided with INTEGRATION (ASSIGN). This model is best described as an aggregate model of driver behavior including both familiar drivers choosing relatively efficient paths and unfamiliar drivers choosing relatively inefficient paths. A second approach isolates a subset of vehicles representing experienced commuters.

2.3.2.1 Aggregate Driver Behavior Model

A detailed inspection of individual vehicle trip times reveals that the ASSIGN module is not uniformly accurate in finding high-performing paths for all of the vehicles during the peak period. The ASSIGN module finds a set of routes through the network based on a Frank-Wolfe static equilibrium assignment technique. The module therefore inherits strengths and weaknesses of the static Frank-Wolfe technique. Under certain conditions, this assignment identifies excellent routes for background vehicles. For example, for nearly every origin-destination pair in Urbansville, the ASSIGN module identifies routes for some of its vehicles which match the routes taken by the route guided vehicles. However, the ASSIGN module also identifies routes for some background vehicles that are significantly worse.

These poor routes typically represent roughly one-fifth to one-quarter of all the background vehicles, and have much higher delays (75-200% of the best paths). The reason these paths are so much worse is that the ASSIGN module cannot accurately foresee or quantify the delays associated with network bottlenecks. The ASSIGN module estimates network congestion by comparing historical network demand and capacity. At regular intervals, ASSIGN generates paths for unguided vehicles based on these delay estimates.

Whether or not the network is in an oversaturated condition based on the past demands, ASSIGN estimates delay based on current entering demand. However, if a part of the network is oversaturated, the delay will be exponentially proportional to the duration of the oversaturated flow. In other words, if 100 vehicles per minute are queuing up behind a bottleneck, and the bottleneck capacity is never increased, then that queue will grow ad ***infinitum*** unless demand eventually decreases. ASSIGN cannot accurately account for this effect because only current demand is used as input in each routing cycle.

Second, the ASSIGN module makes the assumption at every update point that the network is in equilibrium. Therefore, queues which have built up in the previous time periods cannot be accounted for in the assignment technique.

The result of these two elements of the ASSIGN module is that although the location of specific bottlenecks in the network can be predicted with ASSIGN, the delays associated with those bottlenecks cannot be accurately estimated. ASSIGN sends some vehicles around the bottlenecks (high performing background vehicles) and some directly at the bottleneck (poor performing background vehicles). Since ASSIGN cannot accurately predict the delays (either existing or future), it cannot efficiently or optimally choose the correct weighting for each of the paths chosen.

In fact, no model which exists today can solve this problem correctly. INTEGRATION has the widest variety of routing algorithms available to the user of any traffic simulation currently in use. ASSIGN represents the most efficient multi-path option in INTEGRATION. Further, it is likely that a 100% accurate dynamic equilibrium solution is also not likely to be an accurate representation of aggregate driver behavior.

What is the impact of ASSIGN on these results? ASSIGN may be considered an aggregate model of routing behavior in Urbansville which reflects a mix of familiar and unfamiliar drivers. This mix may or may not be representative of typical driver behavior, but since no other aggregate model is available either in INTEGRATION or other similar modeling tool, it provides at least one estimated value. For the large, complicated Urbansville network, estimates of dynamic route guidance benefits made in comparison with the ASSIGN module must be viewed with appropriate caution. Note that for less complicated networks like the Thruville subset used for other studies in this report, this effect is mitigated by the relatively small number of routes available in the network. In addition, for the Thruville subset, congestion levels are not typically oversaturated except in incident cases.

2.3.2.2 Experienced Commuter Behavior Model

Mitretek also performed a study to provide more detailed insights on the benefit of dynamic route guidance with respect to alternative routing behavior models for unguided vehicles. Vehicles following routes from ASSIGN are not tracked for the purpose of travel time performance calculation.

This model represents experienced commuter traffic, so-called “expert” or “familiar” drivers. These drivers have accurate experiential information on congestion conditions during an average am. peak period. This knowledge extends to a knowledge of typical dynamic network congestion features by time of departure. This model is facilitated by identifying the routes taken by the route guided vehicles in the average a.m. peak period. The expert commuter vehicles follow these paths in all subsequent runs of the simulation. The route guided vehicles calculate routes as before, depending on current network conditions. If the system is perturbed, either through a reduction in capacity or unexpected demand, then the route guided vehicles may choose diversion routes which differ from the best average case routes followed by the experienced commuters. When realized conditions are similar to expected conditions, then route guided vehicles generally avoid diversions and have travel time performance close to the experienced commuters.

2.4 Experiment 1: Dynamic Route Guidance Benefits Compared With Experienced Commuter

Demand patterns from each of the three Urbansville time periods were employed in this experiment. In the first experiment, one run was made with four moderate incidents introduced onto the network to perturb the system. These incidents were located near typical network bottlenecks on I-75, I-696, the Southfield Freeway, and the Jeffries Freeway. The incidents occur between 7:30 and 8:0O a.m., each with a duration of roughly 15 minutes. All restrictions to network capacity are removed by 8:15 am., although queues from the earlier bottlenecks persist beyond this time.

In the non-incident case with expected demand, route guided vehicles performed marginally better than the expert commuters, ranging from **4-5%** in travel time differential. This positive differential between the route guided vehicles and commuter drivers in the expected case can be explained by the conditions under which the best paths for the expert commuters were identified. The best average case paths were generated under the assumption of no route guided vehicles in the expected case. The addition of the route guided vehicles causes small changes to the location of overall network congestion. The route guided vehicles can avoid these new pockets of congestion, while the expert commuters cannot.

2.4.1 Incident Case

The introduction of incidents in the network causes total system travel time to increase in all the time periods. For example, in the Urbansville 2002 scenario, total travel time increases 0.33 minutes compared with the non-incident case (11.59 minutes to 11.92 minutes). Both guided and commuter drivers experience higher travel time in the incident case, but route guided vehicles have a smaller inctease in travel time (table 2-2). The additional delays are 0.56 minutes for unguided commuters compared with 0.27 minutes for route guided vehicles.

Another metric computed for this experiment is delay reduction. The travel time of the guided vehicles under non-incident conditions arc taken as the baseline for delay calculations. Delay is measured as the differential from this value in each time period under the incident and heavy demand cases. Percent delay reduction is the relative measure of the reduced delay experienced by route guided vehicles compared to non-guided experienced commuters. In the incident case, guided vehicles experienced delays 11-28% smaller than experienced commuters.

Table 2-2. Results of Experiment 1: Travel Time Comparison

Expected Conditions				
Year	Expert Commuters	Guided Drivers	RG Benefit	
1997	8.86	8.43	4.9%	
2002	9.63	9.22	4.3%	
2012	13.46	12.92	4.0%	
Incident Case				
Year	Expert Commuters	Guided Drivers	RG Benefit	Reduced Delay
1997	9.46	8.69	8.1%	25.2%
2002	10.19	9.49	6.9%	27.8%
2012	14.18	13.07	7.8%	11.9%
Unexpected Heavy Demand Case				
Year	Expert Commuters	Guided Drivers	RG Benefit	Reduced Delay
1997	9.47	9.17	3.2%	28.8%
2002	12.21	10.63	12.9%	52.8%
2012	17.15	15.99	6.8%	27.4%

2.4.2 Unexpected Heavy Demand Case

In a second case using the experienced commuter model for background routing behavior, no incidents were introduced. Instead, an unexpected 10% increase in demand over the entire rush hour period was introduced in Urbansville. Further, individual origin destination pairs had demand which varied from average values by plus/minus 10%. This level of variation is consistent with assessments of current day-today variation in demand.

Results under this unexpectedly heavy demand are similar to the incident case, although travel time is markedly increased. For example, in Urbansville 2002, guided vehicles experience an increase in travel time of 1.41 minutes, while unguided commuters experience an increase in travel time of 2.58 minutes. Guided vehicles experienced delays 28-53% smaller than experienced commuters in the heavy demand case.

Since the guided and expert commuters do not have the same performance in the expected (non-incident case), a more conservative estimate of the benefit of route guidance in finding new routes in non-recurrent congestion may also be calculated. Trip time reduction attributable dynamic routing is calculated by reducing the differential between expert commuter and guided vehicle travel times by the absolute differential of the two vehicle classes seen in the expected conditions case. This reduced differential is then taken as a percentage of trip time in the expected case and reported in table 2-3. This more conservative estimate of the value of route guidance for trip time reduction under non-recurrent conditions ranges between -1.5% to 13%. With the exclusion of the 1997 heavy demand case, the benefit is always positive (5 of 6 cases).

Table 2-3. Trip Time Reduction Attributable to Dynamic Routing

	Year		
Case	1997	2002	2012
Incident Case	4.0%	3.1%	4.4%
Heavy Demand Case	-1.5%	12.7%	4.8%

2.5 Experiment 2: Dynamic Route Guidance Benefits Compared With Aggregate Driver Baseline

In this experiment, unequipped vehicles follow routings from INTEGRATION's ASSIGN module. These routings represent time-variant applications of a Frank-Wolfe static equilibrium multi-path assignment technique. Each assignment is based on current demand, updated every 30 minutes. Unequipped vehicles do not receive updated information on network conditions. In addition, a case with an incident was run. The incident case is identical to the recurrent case with the exception that a single lane of southbound I-75 is blocked for 15 minutes beginning at 7:40 during the a.m. peak period.

2.5.1 Presentation and Analysis of Results

In the recurrent congestion case, aggregate dynamic route guidance trip time benefit was roughly 19% in 1997,26% in 2002, and 8% in 2012. The reason for this increase in benefit compared with the results of Experiment 1 is related to the way guided vehicles avoid delay-inducing bottlenecks in the Urbansville network, and the inability of the ASSIGN model to accurately predict the length of delays at recurrent network bottlenecks.

Unguided vehicles stay on the fixed routes computed by the ASSIGN module throughout the simulation, which are updated every 30 minutes. When some unexpected delay occurs in the network, either at an incident location or a bottleneck in the network that the ASSIGN module did not predict, then delay may begin to build on the links leading into the bottleneck The value of the dynamic route guidance information is directly related to the size of the delays that build at the network bottleneck and the size of the window of opportunity for diversion.

Figure 2-7 illustrates this point The figure organizes the dynamic route guidance benefit for each cohort (vehicles starting trips in the each 10 minute segment of the peak period). The benefits values from all three time periods are presented in a scatter plot with network travel time as the independent (x-axis) variable. When the average system travel time ranges between 7-15 minutes (55-26 mph, or 88-42 kph respectively), dynamic route guidance benefit grows linearly with increasing trip time. Beyond 20 minutes in trip time (< 19.5 mph or 31 kph), dynamic route guidance benefit drops off sharply, but does not become negative. This 20 mph break point is consistent in all three sets of runs. Although a linear regression model was not employed in the two regimes, the pattern strongly suggests a two-part linear relationship.

The results support the notion of transient diversion opportunity on a network level. Benefit levels experience linear growth from no benefit to some maximum benefit as congestion builds. As queues begin to restrict unimpeded access to alternative routes, the value of dynamic route guidance declines (but remains positive). In figure 2-7, this critical point occurs when system travel time reaches 20 minutes. In a network environment, the value of the alternatives may also decrease as a demand associated with other origin-destination pairs are directed onto all or part of these alternatives.

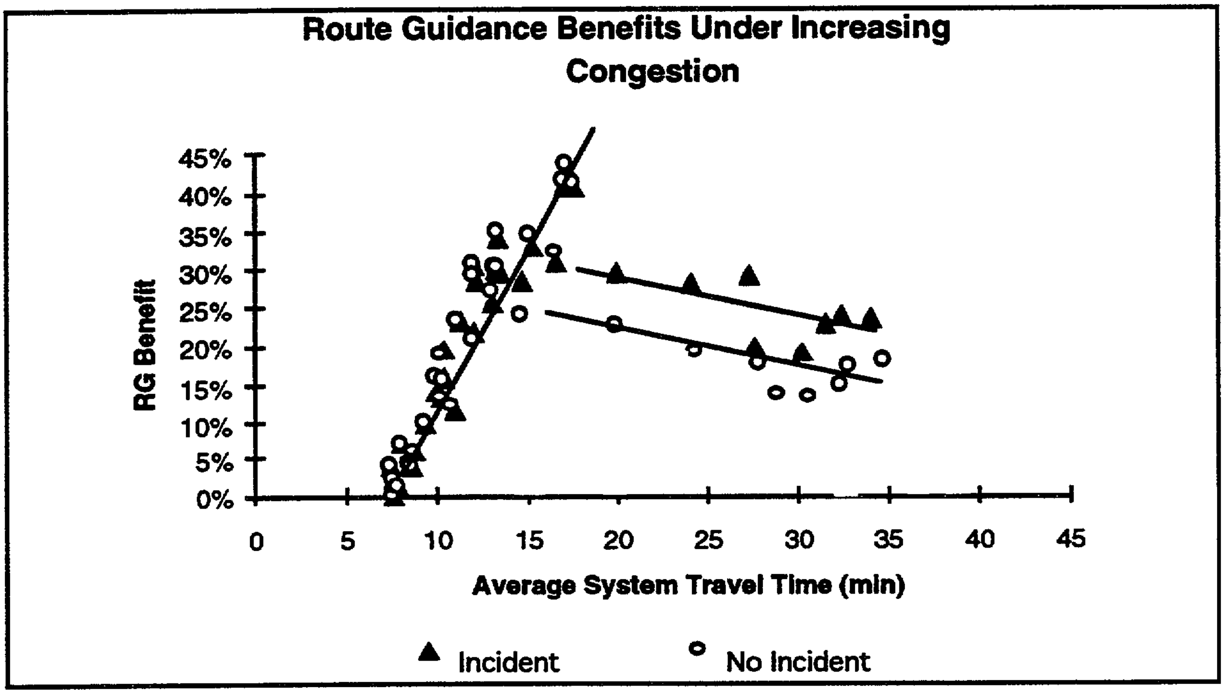

Figure 2-7. Dynamic Route Guidance Performance Under Incident, Non-Incident Conditions

As expected, the value of dynamic route guidance in the incident case remains higher than the non-incident case when the network is congested (> 20 minutes trip time) but returns similar results in a relatively uncongested network.

Another key point brought out in this experiment is the impact of network structure. Because we must restrict our analysis to a cordoned area, the availability of alternative routes in Urbansville significantly drops when queues form at or near network entry stations. In the larger Detroit/Urbansville roadway system, there may be other routes outside of our area of simulation we cannot consider.

In addition to this work on aggregate trip statistics with respect to time of network entry, another analysis was performed to examine the relationship between RG benefit and trip length in the Urbansville 2002 scenario (figure 2-8). As expected, longer trips have higher benefit from dynamic route guidance. Trips longer than 10 miles in the Urbansville 2002 scenario have more than four times the relative benefit of trips shorter than 3 miles. Because the longer trips also have higher travel times than shorter ones, the difference in absolute savings for these trips is even more dramatic. Again, these results are expected since the longer trips generally have more opportunity for diversion.

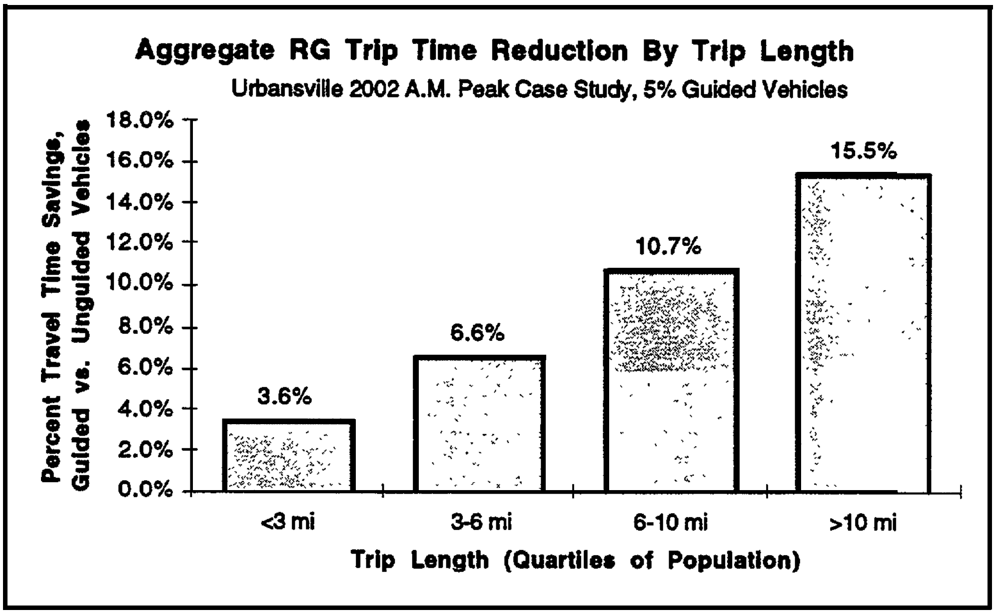

Figure 2-8. Increasing Benefit With Length of Trip Distance

2.6 Conclusions

The results of this study have several implications for ITS benefit assessment. First, route guided vehicles that receive reliable data on network conditions (including incidents or demand variation) gain up to 13% travel time savings over unguided vehicles which follow optimal routes based on average network congestion conditions. Route guided vehicles may exploit information about unexpected delays in the network related to incidents as well as variability in daily traffic patterns. In these cases, route guided vehicles can expect to cut delays by as much as 50% when compared with experienced commuters.

These estimates generally support other analytic studies appearing in the literature regarding dynamic route guidance. These studies do not explicitly examine the effect of congestion levels and time-of-hip start, but do report averages for the conditions studied. Examples include a 20% travel time savings estimate for a corridor models (Rakha, et al., 1989; Hounsell, et al., 1991). Other models of familiar or expert drivers and variation in travel time based on demand variability (Smith and Russam, 1989) estimate a travel time benefit for guided vehicles at the 5% level. The Urbansville network, both from the standpoint of number of links and number of vehicles represents a significantly larger and more complicated network than these earlier studies. Trip lengths are shorter in Urbansville (6.5 miles) than the current national average (10 miles). Given the increasing relationship between trip length and dynamic route guidance benefits identified in Experiment 2, the Urbansville benefits estimates may be conservative.

Second, route guided vehicles on average have the same performance as the highest-performing unguided vehicles. This implies that dynamic route guidance does not discover new, superior routes on the network which other travelers do not use. Instead, route guided vehicles gain benefit by avoiding the worst congestion in the network In a series of day-to-day simulations, route guided vehicles should experience a much smaller variability in trip time. In fact, this minimization of the maximum travel time for the daily commute may be the most significant benefit of the dynamic route guidance system for the commuter driver.

Third, the results indicate that benefits of dynamic route guidance are directly related to the level of recurrent congestion in a network. This suggests that a near-term poor market for dynamic route guidance may evolve over time into a good market for these services. Likewise, a good market for a dynamic route guidance user service may deteriorate if overall network congestion reaches very high levels. This implies that for the most highly congested urban areas, demand management techniques may be necessary if dynamic route guidance is to retain its highest value.

Section 3

Dynamic Route Guidance Compared to Advisory Messages

This study investigates the travel time benefits provided by dynamic route guidance (a high functionality ATIS service) and advisory messages (a low functionality ATIS service). These user services represent two ATIS market packages defined in the National ITS Architecture.

3.1 Introduction

One of the key functions of ITS is the development of services to provide travelers with a variety of information about the current condition of the transportation system. Eight ATIS market packages are defined in the IIS Physical Architecture document. Market packages are described as "deployment elements." Each market package "...represents a service which the architecture team feels will be deployed as an integrated capability" (Loral and Rockwell, 1996). Functionality and cost vary across the packages. It is expected that higher levels of functionality will result in higher benefits to travelers, but at a higher cost.

The Architecture document defines Route Guidance as a high functionality market package that "offers the user advanced ATIS capabilities including in-vehicle route planning and guidance." The dynamic route guidance service modeled in this study is a form of route guidance that provides real-time traffic information to drivers en-route, enabling them to choose paths with the shortest travel time.

The Architecture document defines Broadcast Based ATIS as "the collection of traffic conditions, advisories, general public transportation and parking information, and the near real time dissemination of this information over a wide atea through existing infrastructures and low cost user equipment" The advisory message service modeled in this study is one form of Broadcast Based ATIS. CMS are modeled at selected locations, warning all passing drivers to avoid certain congested links. A specified percentage of drivers heed the warning and choose alternate routes, using historic (not real-time) link travel times. Other drivers do not respond and do not change their planned routes.

3.2 Study Methodology

This section describes the roadway network used for the study, the features of the simulation model used, and the series of experiments performed. The study employs the INTEGRATION version l5x3d traffic simulation model, described in section 2.2.1.

3.2.1 Network Description

The roadway network used in this study is the Thruville (Inter-urban) scenario. Thruville is based on the Philadelphia-Delaware Valley region. The area consists of a portion of the I-95 corridor from the Delaware/Pennsylvania state line to the 1-95/I-295 junction in New Jersey (figure 3-l). Thruville consists of several major freeways, including I-295, I-95, and the

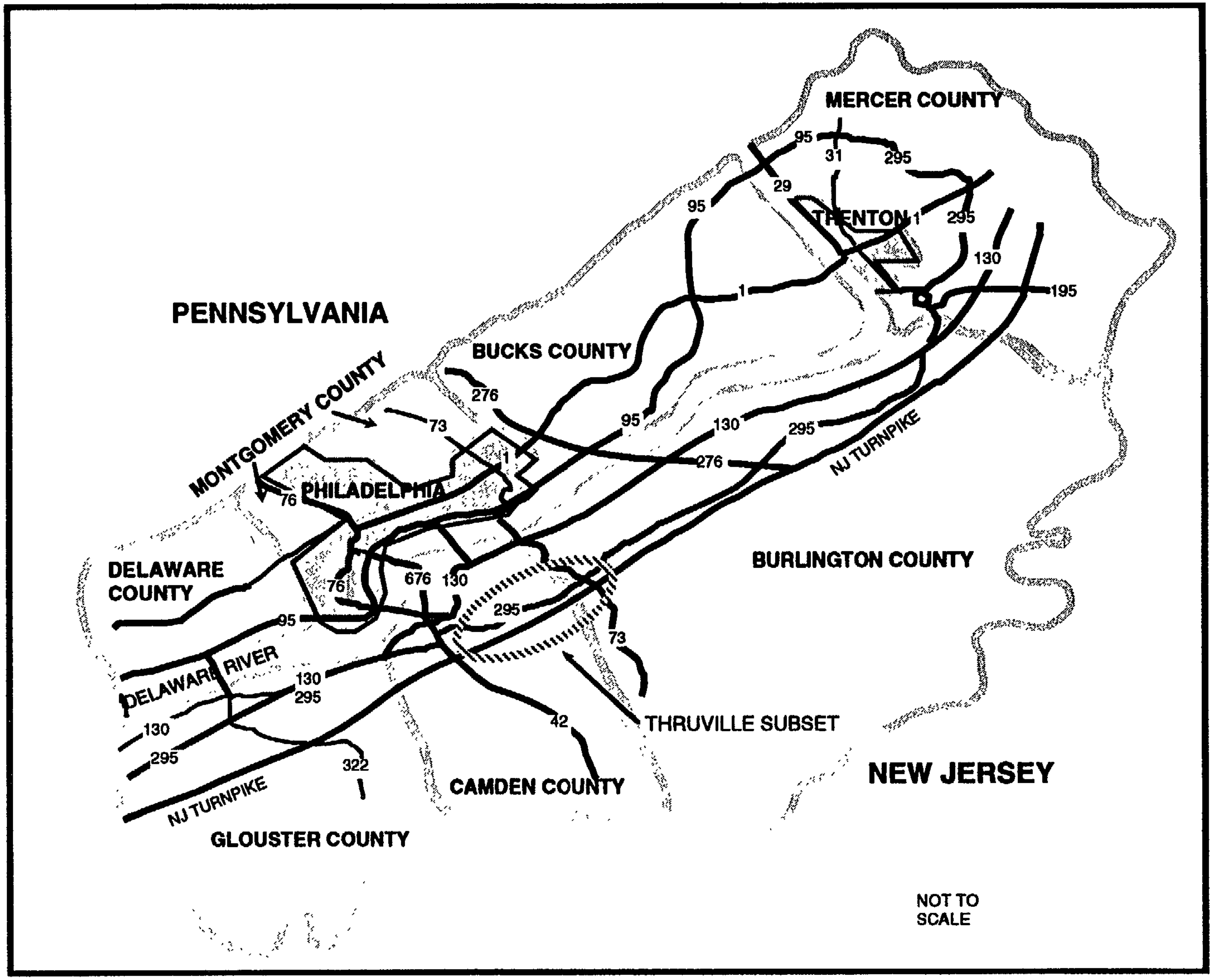

Figure 3-1. Thruville, the Inter-urban Region

New Jersey Turnpike. Also modeled are several major expressways and arterials, such as US Route 1 and NJ-38. The network is approximately 80 km long (50 mi.) and 14 km (9 mi.) in width. The regional domain is estimated to cover 3,560 square kilometers (1,373 sq. mi.). The modeling area used in INTEGRATION is approximately 1,075 square kilometers (450 sq. mi.). A more detailed description of Thmville can be found in the Inter-urban Scenario Guide (Harding, 1995).

The first of the three scenarios focuses on a subset of Thmville. This subset is based on the Cherry Hill, New Jersey area (figure 3-2), consisting of three north-south corridors: the New Jersey Turnpike, I-295, and Rings Highway (a local arterial running parallel to the freeway facilities). Also modeled are several local arterials that cross perpendicular to these three facilities, providing some opporumities for alternative route choices. There are approximately 16 kilometers (10 miles) between exits three and four of the turnpike, which form the east and west boundaries of the network. Rings Highway and the New Jersey Turnpike form the northern and southern borders of the 4 kilometer wide study area. In the subset, both the turnpike and I-295 are three-lane freeways, while the arterials are two-lane.

3.2.2 Modeling ATIS Functionality Using INTEGRATION

The high functionality dynamic route guidance service is well modeled by INTEGRATION. Routing strategies for guided vehicles am based on real-time link travel times. Equipped vehicles receive non-predictive updates of link travel times for the entire network every ten minutes. If an alternative path takes a shorter travel time than its current path, a guided vehicle may divert.

There is no INTEGRATION feature that directly corresponds to wide-area broadcast of traffic information. Mitretek used the following approach to model advisory messages provided by short range information dissemination devices. CMS were placed at major diversion point nodes, warning of high travel time for congested links. Upon encountering an information device, a “responding” driver chooses a new route, assuming infinite travel time on the indicated links and using a database of historic travel times on all other links. Responding drivers for this case are analogous to equipped vehicles for the route guidance case. Non-responding drivers do not change routes. The percentage of responding and non-responding drivers was specified as an input parameter.

The theory behind the approach chosen for modeling localized advisory messages is as follows. In the simulation, drivers receive information that indicates high travel time on the link containing the delay. This corresponds to the information that real world drivers might receive from such broadcast information as “Accident Ahead Major Congestion.” The actual mechanism for delivering this information could be beacon, CMS, FM sub-carrier, or other method. Drivers also receive baseline historical travel times for the remaining links in the network This corresponds to the knowledge that real world drivers familiar with the road network might possess about it. Familiar drivers would also know the layout of the road network, but would have no additional knowledge on the current state of the network, other than the existence of the incident and its location. A certain percentage of them would divert to an alternative. Their route choice would be based on their prior experience, corresponding to the non-incident baseline data It might be argued that not all diverting drivers have such a knowledge of the network. However, most drivers can base their knowledge on a typical roadway map and estimate travel times as a function of distance.

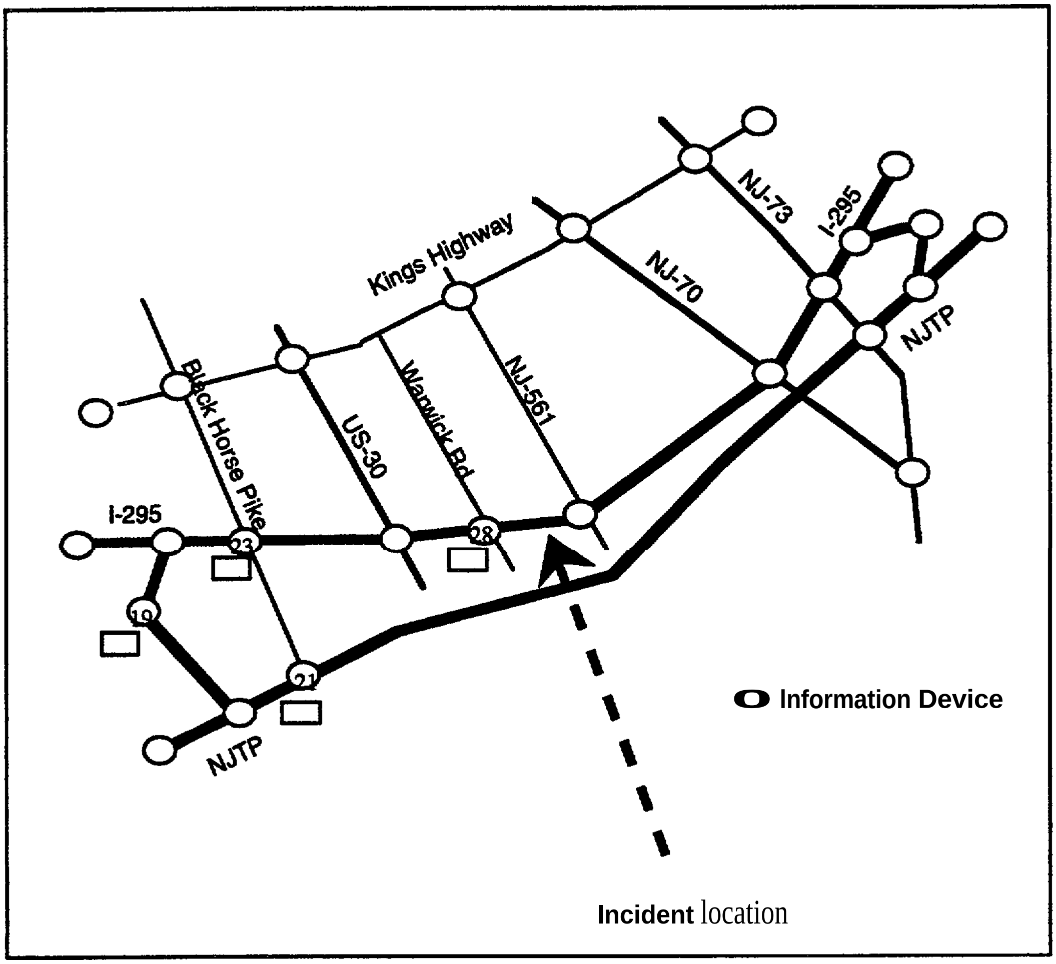

Figure 3-2. Thruville Subset with Information Devices

3.2.3 Experimental Design

The ATIS functionality study is composed of three experiments. Each experiment analyzes the benefit of the two market packages in a different scenario. The scenarios are described as follows:

1 A subset of the Thruville network based on the Cherry Hill, New Jersey region is used to study the effects of the two market packages under an incident condition. This scenario was discussed in a preliminary report released by Mitretek (Salwin, 1995).

2. Similar to scenario 1, the second scenario introduces an incident onto the full Thruville network to generate unexpected non-recurrent delay.

3. Finally, the capacity of a large section of a freeway in the full Thruville network is reduced for the entire simulation period. This scenario represents conditions for a major roadway construction project.

Two levels of market penetration were modeled for route guidance: 5% and 20%. These market penetrations are consistent with the near-to-medium term route guidance market penetration estimates in the ITS Architecture.

There is limited knowledge to guide the modeling activities to determine the percentage of drivers that divert in response to advisory messages. However, a study carried out as part of the INFORM project determined that 5% to 10% of the traffic would divert in response to CMS messages (Smith, 1992). Further, that study noted that "as a rule of thumb, adding a diversion message will double the normal passive diversion percentage." Thus 5% and 20% (2 times 10%) would seem to bound the percent of drivers diverting in response to CMS messages.

Eight cases were run for each of the three scenarios, consisting of two baseline cases and six comparison cases. Other cases that are unique to each scenario are described in the scenario descriptions. Each case consists of the average results over eight modeling runs that are identical except for variation in random seed. The eight cases are described as follows:

- Baseline 1: This baseline case models no ATIS functionality. It corresponds to unguided vehicles during non-incident or expected travel conditions. In this case all vehicles follow routes selected by INTEGRATION's ASSIGN module.

- Case 1: This case models the effect of dynamic route guidance in recurrent congestion, assuming a 5% market penetration for route guidance devices. The reduction in travel time from this case is compared to Baseline 1. The impact is expected to be small for scenarios with low recurrent congestion.

- Case 2: This case is the same as Case 1 except that a 20% market penetration is used.

- Baseline 2: Similar to Baseline 1, this baseline models no ATIS functionality. However non-recurring congestion (resulting from an incident) is introduced into the network Baseline 2 is compared to Baseline 1 to measure the delay caused by the incident.

The remaining four comparison cases are used to study the impact of the two ATIS market packages on average travel time in the presence of the non-recurring congestion.

- **Case 3**: This case models the effect of a 5% market penetration for dynamic route guided among vehicles encountering non-recurrent congestion. The results from this case are compared to Baseline 2.

- **Case 4**: This case is the same as Case 3 except that a 20% market penetration is used.

- **Case 5**: This case models the effect of advisory messages in reducing incident-caused delay, assuming 5% of the passing vehicles respond to the messages. The effects of this advisory message case are expected to be smaller than for the route guidance cases 3 and 4.

- **Case 6**: This case is the same as Case 5 except that 20% of the vehicles respond to the advisory message information.

Table 3-1 illustrates the relationship among the eight cases for each scenario.

Table 3-1. Eight Cases for Each Scenario

		Route Guidance		Advisory Messages	
	No ATIS	5 %	20 %	5 %	20 %
No incident	Baseline 1	Case 1	Case 2		
Incident	Baseline 2	Case 3	Case 4	Case 5	Case 6

3.2.4 Other Modeling Assumptions

Following are some additional assumptions about the modeling for this study:

- All vehicles have access to all links. No HOV, commercial vehicles, or transit vehicles are modeled.

- No traffic signals are modeled in either the subset or the full Thruville network.

- All links contain detectors to determine link travel time for each vehicle to exit the link. These detectors work 100% of the time.

- The update cycle for all information dissemination to guided vehicles is 10 minutes.

- The placement of information devices is as shown in figure 3-2.

Because of limitations in the INTEGRATION model, for the full Thruville network scenarios, information &vices are only updated every 30 minutes for the advisory message cases. Incident timing was chosen so that this limitation does not cause a bias in the simulation results. The advisory message cases using the subset network are updated every 10 minutes.

3.3 Scenario 1: Thruville Subset

This section describes the Thruville subset network, the demand scenario, and the results of the modeling activity.

3.3.1 Scenario Description

The Thruville subset (figure 3-2) is well-suited for an initial scenario of this study. It highlights the effect of an incident on a realistic network with few points of naturally occurring congestion. The congestion caused by a small incident on a large network may be overshadowed by the effects of recurring congestion. The subset provides two routes, I-295 and the New Jersey Turnpike, with almost the same length, and approximately the same "normal" travel time. The introduction of an incident provides enough delay that the alternative routes become attractive to guided vehicles.

There are limited rerouting opportunities in the Thruville Subset network. The most important routing decision is the choice between the two expressways. A northbound vehicle entering the network at the upstream end of the corridor (the left side of figure 3-2), will experience low cost in diverting from one freeway to the other. Diversion onto other routes, such as the Kings Highway arterial, are of higher cost. These high cost diversion options are the only feasible ones available to downstream vehicles. Diverting to these routes can take longer than proceeding along the expressways. Therefore, diversion onto them is generally an unattractive option.

For this network and traffic volume, the recurrent congestion does not provide enough delay for alternative routes to become appealing to route guided vehicles. In the expected (non-incident) case, very little rerouting is performed by guided vehicles, and vehicles remain on a set of geographically direct routes, otherwise known as preferred routes. These routes are found by the ASSIGN module in INTEGRATION. When an incident is introduced onto the network, equipped vehicles have the opportunity to reduce non-recurrent delay. The subset network therefore, allows us to view benefits to equipped vehicles in incident conditions witbout the effects of recurrent congestion.

For this scenario, the total simulated time is 5,400 seconds (1.5 hours). The first 900 seconds are used to load the network with traffic. At the end of this period, those vehicles with the longest trips are exiting the network. The population of vehicles who enter the network between 900 and 3,600 seconds are considered for data collection. Only vehicles in this population whose primary or alternate paths could reasonably be expected to go through the incident location are used for data collection. Any data collected on vehicles not traversing links with delay would represent an approximately constant additive noise. There are 5,611 vehicles in the sample population used for data collection.

The remaining simulation tune, from 3,600 to 5,400 seconds, allows all the vehicles in this population to complete their trips and exit the network Vehicles entering the network after 3,600 seconds can be considered background traffic running interference for those vehicles in the population sampled. During the entire simulation 49,620 vehicles are produced.

The traffic demand used in this study is dubbed "holiday' demand because there is near-capacity volume on the major freeways in the network but relatively light traffic on the arterials. If there are no incidents, travelers experience heavy but steady (level of service B-C) traffic flows on all the major facilities. Northbound traffic on the freeways constitutes 40% of the overall network demand. This demand is held at a constant rate throughout the simulation period.

3.3.2 Results Under Non-Incident Conditions

To ensure that recurrent congestion has little effect on incident condition results, the impact of route guidance for non-incident conditions is investigated. Table 3-2 compares the results for Cases 1 and 2 (no incident, route guidance) with Baseline 1 (no incident, no ATIS). These cases can be considered to represent the best possible benefits an equipped vehicle population could acquire on the subset network with no incident.

Table 3-2. Reduction in Travel Time Under Non-Incident Conditions Thruville Subset

	Percent Reduction in Travel Times from Baseline 1		
	Guided Vehicles	Unguided Vehicles	Average for Sample
Case 1 (5% guided vehicles)	1.7%	0.0%	0.1%
Case 2 (20% guided vehicles)	1.6%	0.5%	0.8%

As expected, the impact of route guidance on recurrent congestion is minimal for the subset network. Under normal conditions, drivers familiar with a road network tend to remain on the preferred path for their trips. Perhaps the most positive observation for these cases is that, for the network studied here, equipped vehicles do not experience gains at the expense of unequipped vehicles. The total system benefit is small, but positive. Rerouted vehicles do not cause travel times on alternative routes to exceed their expected values.

3.3.3 Results Under Incident Conditions

The incident used for the Thruville subset scenario occurs on northbound I-295, as shown in figure 3-2. It has a duration of 1,800 seconds, beginning at time 1,500 seconds and ending at time 3,300 seconds. The difference in travel time between Baseline 1 (no-incident, no ATIS) and Baseline 2 (incident, no ATIS) is attributable to the non-recutrent delay resulting from the incident.

For Baseline 2, turnpike speeds and V/C ratios are lowered only slightly from Baseline 1. However, the incident results in significant degradation in performance on I-295. Average speeds fall below 31 kph and the flow on the incident link drops below 67% of the full capacity of the link. Table 3-3 tabulates the difference between the two baselines for the sample population of vehicles.

Table 3-3. Delay Caused by the Incident

	Average Time Per Trip	Total Sample Travel Time
Baseline 1 (no incident)	12.81 minutes	1,198.86 hours
Baseline 2 (incident)	17.72 minutes	1,657.72 hours
Non-recurrent delay	4.91 minutes	458.86 hours

The non-recurrent delay resulting from the incident is computed by taking the difference between the two baselines. Travel times increase by 38% for the sample population of vehicles due to tie delay caused by the incident. This is the delay that route guidance and advisory messages have the opportunity to reduce.

3.3.4 Results for Dynamic Route Guidance

Case 3 determines the reduction in non-recurrent delay when 5% of the vehicle population is equipped with route guidance devices. Case 4 determines the same benefit when 20% of the vehicle population is so quipped. The sample population is the set of vehicles traveling northbound near the incident site. The results are shown in table 3-4 and figure 3-3.

Table 3-4. Reduction in Travel Time - Dynamic Route Guidance

		Travel Time Baseline 2 (minutes)	Travel Time Reduction (minutes)	Percent Travel Time Reduced
Case 3	Guided	17.72	2.75	15.52%
5% guided	Unguided	17.72	0.23	1.30%
Case 4	Guided	17.72	2.31	13.04%
20% guided	Unguided	17.72	0.85	4.80%

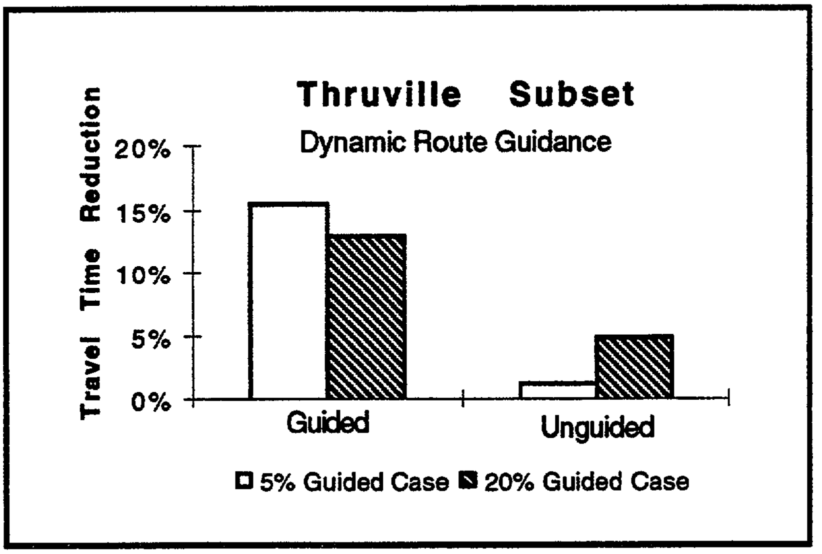

Figure 3-3. Percent Reduction in Travel Time - Dynamic Route Guidance

When there is 5% market penetration for route guidance, equipped vehicles in the sample experience a travel time reduction of 2.75 minutes (15.5%). Because equipped vehicles are being removed from the most congested links, the unequipped vehicles traveling over those links also experience a slight reduction in delay.

At a 20% market penetration, the equipped vehicles begin to compete among themselves on alternative routes. As a result, as shown in the figure, the benefit they experience is somewhat less than the benefit realized for the 5% market penetration case. The equipped vehicles for the 20% market share case experienced a 13% reduction in travel time relative to the incident baseline (Baseline 2). However, because more vehicles are being diverted from the congested links, both the unequipped vehicles and the system receive a larger benefit.

A closer inspection of paths taken by the equipped vehicles show that the most common diversion path is away from the I-295 incident and onto the New Jersey Turnpike, as expected. This is because the cost for diverting onto the Turnpike from I-295 is low. However, some vehicles have already passed the diversion point when incident congestion arises. These vehicles must either proceed through the incident or divert onto Kings Highway. The high cost of diversion onto this arterial limits the practicality of this route for many of the vehicles.

Table 3-5 and figure 3-4 express the results of these cases in terms of delay reduction. When there is a 5% market penetration for route guidance, equipped vehicles in the sample experience a reduction of 2.75 minutes (56%) of the 4.91 minutes of non-recurrent delay.

Table 3-5. Reduction in Delay - Dynamic Route Guidance

		Non-recurrent Delay Baseline 2 (minutes)	Non-recurrent Delay Reduction (minutes)	Percent Non-recurrent Delay Reduced
Case 3	Guided	4.91	2.75	56.01%
5% guided	Unguided	4.91	0.23	4.68%
Case 4	Guided	4.91	2.31	47.05%
20% guided	Unguided	4.91	0.85	17.31%

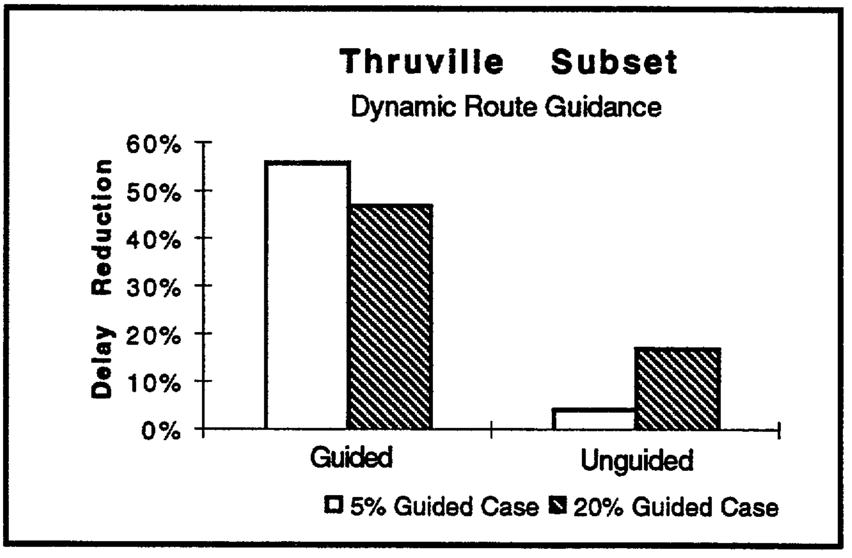

Figure 3-4. Percent Reduction in Delay - Dynamic Route Guidance

3.3.5 Results for Vehicles Responding to Advisory Messages

Case 5 determines the reduction in non-recurrent delay when 5% of the vehicle population responds to advisory messages. Case 6 determines the same benefit when 20% of the vehicle population responds. The sample population is the set of vehicles traveling northbound near the incident site. The results are shown in table 3-6 and figure 3-5.

Table 3-6. Reduction in Travel Time - Advisory Messages

		Travel Time Baseline (2) (minutes)	Travel Time Reduction (minutes)	Percent Travel Time Reduced
Case 5	Responding	17.72	1.99	11.23%
5% responding	Non-responding	17.72	0.29	1.64%
Case 6	Responding	17.72	1.41	7.96%
20% responding	Non-responding	17.72	1.1	6.21%

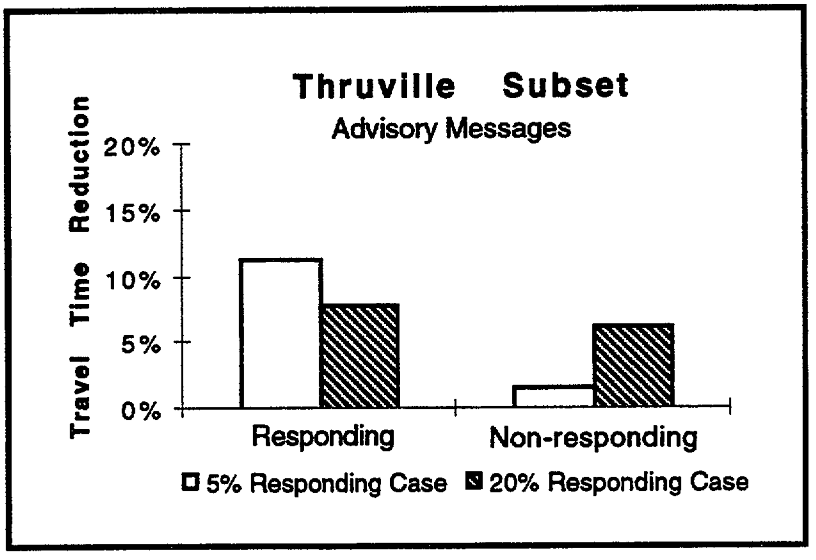

Figure 3-5. Percent Reduction in Travel Time - Advisory Messages

The results from the advisory message cases are similar to those from the dynamic route guidance cases. In particular, as shown in the figure, responding vehicles experience less benefit when there is a higher diversion rate. When 5% of the vehicles divert in response to the information, their travel time is reduced by 11%. When 20% of the vehicles divert, those vehicles experience an 8% reduction in travel time. As in the route guidance cases, vehicles that do not respond to the information also benefit from the diversion of the responding vehicles.

Table 3-7 and figure 3-6 demonstrate the reduction in delay for the advisory message cases. When 5% of the vehicles respond to the messages, those vehicles experience a reduction of 1.99 minutes (40.5%) of the 4.91 minutes of non-recurrent delay.

Table 3-7. Reduction in Delay - Advisory Messages

		Non-recurrent Delay Baseline 2 (minutes)	Non-recurrent Delay Reduction (minutes)	Percent Non-recurrent Delay Reduced
Case 5	Responding	4.91	1.99	40.53%
5% responding	Non-responding	4.91	0.29	5.91%
Case 6	Responding	4.91	1.41	28.72%
20% responding	Non-responding	4.91	1.10	22.40%

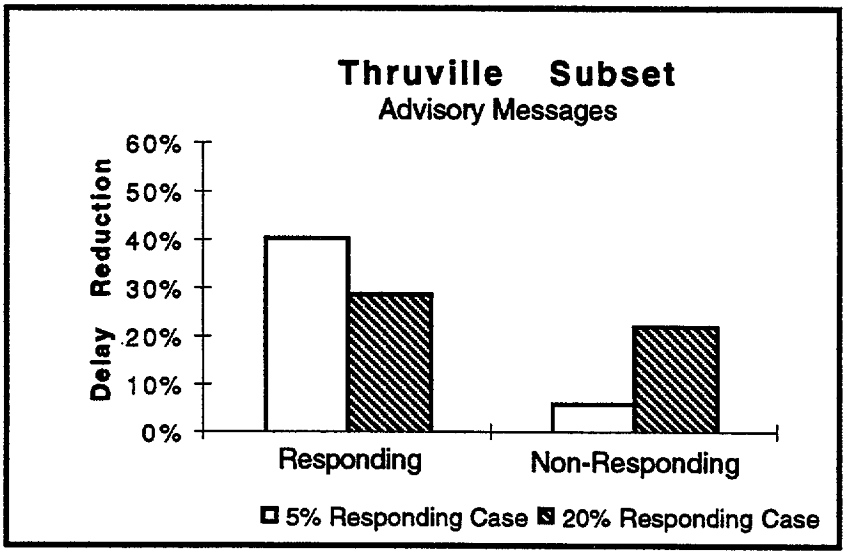

Figure 3-6. Percent Delay Reduction - Advisory Messages

3.3.6 Comparison of Results for Thruville Subset

Advisory messages provide a smaller benefit to diverting vehicles than route guidance does to the equipped vehicles. For example, at 5% equipage, the route guided vehicles experience a 56% reduction in non-recurrent delay, compared to a 41% reduction in delay for the corresponding advisory message case. Analysis showed that this difference was statistically significant. Nonetheless, this difference represents under a minute of travel time. This small absolute difference is attributed to the relatively minor severity of the incident and to the topology of the Thruville Subset network, in which the cost of diversion is high relative to the delay induced by the incident.

In a more richly connected network, route guided vehicles might be able to take advantage of detailed information about all the links on the network and find low cost diversion alternatives. They could select the optimal point to leave a freeway, divert around an incident, and return to the freeway at the optimal time. Even drivers unfamiliar with the road network could take advantage of this opportunity. With few low cost options in the Thruville Subset network, however, the guided vehicles cannot take full advantage of the detailed information they possess. They are faced with the same choices as the vehicles receiving coarser advisory information: either select I-295 or the Turnpike at the start of a trip, and commit to that road for most of the trip. In other words, a little information can provide most of the benefits on a small network with few choices.

3.3.7 Sensitivity of Results to Placement of Information Devices

The results for advisory messages can be highly sensitive to the placement of information devices on the road network. Locations where information is disseminated can strongly affect the benefits achieved. The sensitivity to placement of the devices was therefore investigated for the Thruville subset. Several variations with the incident and 5% of the vehicles responding (Case 5) were run for this purpose. A single random seed was used for each variation.

First, the two devices along the New Jersey Turnpike were removed from the simulation (nodes 19 and 21 in figure 3-2). There was little impact on the results. Benefits decreased from 44% reduction in non-recurrent delay to 42% reduction. For this scenario, vehicles beginning on the Turnpike generally remain on the Turnpike for the duration of their trip. The additional information that there is an incident on I-295 does not cause changes in driving patterns for these drivers.

Next, the information device at the entrance to I-295 was also removed (node 23 in figure 3-2). This leaves only the device on the link immediately before the incident (node 28 in figure 3-2). Thus vehicles are not forewarned about the incident as they enter I-295 and do not take advantage of the low cost diversion possibility onto the Turnpike. They divert onto Rings Highway, the less desirable, high cost diversion alternative. Consequently, travel times for the responders increase dramatically, actually resulting in a 24% increase in delay over Baseline 2. This increase in delay is because the impedance of the link containing the incident was set sufficiently high to cause all responding vehicles to divert, whether or not it was really in their interest to do so. This would correspond to a real world case where the only information, on a CMS for example, is “Accident Ahead Major Congestion”. A certain percent of vehicles divert in response, for lack of better information. In this scenario, they would have been better off not diverting to the alternative path. Of course, this result is dependent upon the intensity of the incident. For a more severe incident, the diverting vehicles would indeed do better than those going straight through the incident. Route guided vehicles, on the other hand, would know that diversion to Rings Highway is,a poor strategy in this case.

Finally, the information &vice immediately before the incident (node 28) was removed, but the one at the entrance to I-295 (node 23) was restored. The non-recurrent delay is reduced 47% from the baseline and represents the best performance observed for the advisory message information system. The improved performance results because vehicles now have the option to divert onto the Turnpike and avoid the incident. That is, they can take the low cost diversion alternative. Meanwhile vehicles who have passed the diversion point when the incident occurs do not divert immediately before the incident as in the previous experiment. Nonetheless, the delay reduction still remains less than that for the route guidance cases.

The placement of the dissemination devices is critical to the performance of an advisory message ATIS system. Furthermore, the amount of information provided can affect system performance. Vehicles receiving information such as “congestion ahead” may unnecessarily divert. Information on the extent of the delay should improve system performance.

3.3.8 Interaction of the Two ATIS Market Packages

The study was designed with separate cases for dynamic route guidance and advisory messages, as described in the preceding sections. To determine if there are interactions between these two services, an additional case uses both market packages at the same. A 10% market penetration for dynamic route guidance was used along with 10% responders to the advisory messages. Thus a total of 20% of the vehicles received and responded to travel time information. For comparison purposes, two additional runs were carried out: a run with dynamic route guidance at 10% market penetration, and a run with 10% of the vehicles responding to advisory messages. Tables 3-8 and 3-9 present the results. The measure shown is the average travel time for the route guided vehicles (table 3-8) and for vehicles responding to advisory messages (table 3-9).

Table 3-8. Travel Times for Route Guided Vehicles

	Travel Time for Equipped Vehicles
10% market penetration guided vehicles	15 02 minutes
10% market penetration with an additional 10% responding to advisory messages (mixed case)	15.70 minutes
20% market penetration guided vehicles	15.60 minutes

Table 3-9. Travel Times for Responding Vehicles

	Travel Time for Responding Vehicles
10%responding to advisory messages	15.80 minutes
10% responding to advisory messages with an additional 10% Route Guidance (mixed case)	16.55 minutes
20% responding to advisory messages	16.53 minutes

As shown, the mixed case (10% equipped for dynamic route guidance + 10% responding to advisory messages) gives results similar to the 20% cases, not to the 10% non-mixed cases. The difference between results for the mixed case and the 20% cases are less than the differences usually attributable to variation in random seed. This shows that in a network with few diversion points, drivers responding to a low functionality advisory message system are routed to the same or similar paths as those using route guidance. Therefore, congestion on alternative routes for a case of 20% market penetration of either user service is the same congestion found for the case of combining the two. Travel times on the alternative routes are approximately the same in both cases.

In near-term deployment, low functionality advisory message systems can be implemented and achieve a certain level of benefit. As higher functionality systems develop in small networks, low functionality system users may see a reduction in benefit as more equipped vehicles contribute to congestion on alternative routes.

3.4 Experiment 2: Major Incident on Full Thruville Network

The second experiment features a major incident for the full Thruville scenario. The following sections describe the scenario and present results for the benefits of dynamic route guidance and advisory messages.

3.4.1 Scenario Description

The full Thruville network (shown in figure 3-1) provides many alternate routing strategies. Most important is the choice among I-95, I-295, and the New Jersey Turnpike. The Turnpike and I-295 provide two routes with approximately the same travel time and distance, while I-95 provides a competitive route for high congestion periods. Advisory message signs are placed at major diversion points between freeways.

As in the Subset scenario, the holiday demand used in this study produces a near-capacity volume on the major freeways in the network Unlike the subset, the demand for the Thruville network varies as a function of time. The variation represents an increase in demand to an eventual peak period, followed by a gradual decrease in traffic as time approaches late evening hours of what might be a typical holiday. This change is not as dramatic as it may be due to a normal average evening rush hour, as traffic will continue to be somewhat heavy for several hours on freeways during the holiday. Through trips on the freeways constitute 50.4% of the traffic on the network Local traffic consists of 27.1% of the total demand. Other traffic makes up the remaining trips for the network.

The network contains some naturally occurring delay under the “holiday” demand pattern. These delays are primarily located at or near the interchanges between arterials and at locations where arterials meet with the freeways. This recurrent delay can potentially be Educed by dynamic route guidance. Vehicles equipped with route guidance are told that this delay is present and will be able to choose routing strategies to minimize it However a vehicle responding to an advisory message is only told a high travel time for links with non-recurrent delay. Therefore, the low functionality system will not reduce recurrent delay except as a side-effect of routing to avoid non-recurrent delay.

For this scenario, a total simulated time of four hours is used. The first hour of simulated time is considered to be the time to load the network. The population of vehicles that enter the network for the next 1.5 hours are considered for data collection. The remaining simulation time allows for most of the vehicles in this population to complete their trips and exit the network. As before, vehicles entering the network after 2.5 hours can be considered background traffic running interference for those vehicles in the population sampled.

Vehicles whose paths are considered to be through trips on the freeways are used for data collection. This constitutes approximately 50.6% of the total vehicle population. Two sub-populations of the sample are also examined: (1) vehicles whose paths have the potential of traversing the area of the incident on northbound I-295 (labeled as selected), and (2) vehicles whose preferred path is northbound I-295.

During the simulation 229,619 vehicles are produced; 46,393 of these appear in the sample vehicle population. Approximately 9,280 vehicles of the sample have paths that potentially could traverse the incident location. 1,530 of these travel northbound on I-295.

3.4.2 Results for Non-Incident Conditions

Similar to the Subset scenario, the ability of dynamic route guidance information to alleviate recurrent congestion is examined first Because there is much more recurrent congestion in the full Thruville network, route guidance has the potential to reduce travel times under non-incident conditions. Table 3-10 illustrates the reduction in recurrent delay for Cases 1 and 2 (no incident, route guidance) compared to Baseline 1 (no incident, no ATIS).

Table 3-10. Reduction of Recurrent Congestion

	Percent reduction in Travel Time from Baseline 1 (no incident/no ATIS)			Guided/ Responding Travel Time Reduction (min.)
	Trips	Responding or Guided	Non-responding or Unguided	
Case 1 5% guided	Through	9.6%	1.7%	4.38
	Selected	7.0%	1.9%	4.04
	NB I-295	4 5 %	-0 4%	2 26
Case 2 20% guided	Through	7.7%	3.4%	3.53
	Selected	7.4%	3.7%	4.27
	NB I-295	3 0%	-1 0%	1 92
5% Responding	Through	7.3%	1.5%	3.32
	Selected	5.3%	1.6%	3.06
	NB I-295	2 4 %	-0 2%	1 1 9
20% Responding	Through	6.8%	3.6%	3.12
	Selected	5.8%	4.0%	3.36
	NB I-295	1.2%	-0.1%	0.58

Unlike the Subset scenario, in the larger network INTEGRATION's ASSIGN module is unable to generate efficient equilibrium path trees for all vehicles. This results in areas with significant congestion and areas with little congestion. Thus, guided vehicles are able to save a significant percentage of their trip time under non-incident conditions. Because guided vehicles are diverted away from congested areas, unguided vehicles are also able to experience some reduction.

Because of the potential of ATIS to alleviate non-recurrent congestion, two additional cases arc examined. These cases are used to determine the reduction in recurrent delay for 5% and 20% response to advisory messages. These results are also presented in table 3-10. The responding vehicles are able to reduce a portion of their travel time under these conditions. Again this is caused by the inefficiency of the ASSIGN module. When the responding vehicles pass an information device in INTEGRATION they receive expected link travel times and are capable of choosing an alternative route based on that information. This process overrides ASSIGN, permitting a better routing strategy for these vehicles during expected non-incident conditions.

Table 3-10 indicates that recurrent congestion will be a factor in the benefits with the network under incident conditions. For example, considering through trips, the 5% guided vehicles are able to save 4.4 minutes (9.6%) of what would be a 45.8 minute trip. These vehicles wilI be capable of reducing a percentage of both recurrent and non-recurrent delay created under incident conditions. If vehicles had been initially assigned to more efficient paths, recurrent congestion would have been minimized. However, since the scenario represents holiday demand, recurrent congestion could be considered a result of driver unfamiliarity with the network

3.4.3 Results Under Incident Conditions

The incident used for this scenario occurs on northbound I-295 at the NJ-38 interchange. It has a duration of 40 minutes, beginning at simulation time 60 minutes and ending at time 100 minutes. This incident blocks all of northbound I-295, causing the traffic flows to come to a stop. Northbound I-295 begins to look like a parking lot as queues build to jam density along the freeway. Once the incident is over, the queue is released at the freeway capacity and is observed to dissipate in a shock wave type pattern upstream of the incident site. Eventually this delay has an effect on the I-295/I-76 interchange area before completely dissipating. The entire affected area throughout the simulation constitutes approximately twelve kilometers (7 miles) of I-295. The difference in travel time between Baseline 1 (non-incident, no ATIS) and Baseline 2 (incident, no ATIS) is attributable to the non-recurrent delay resulting from the closing of I-295. Table 3-l 1 examines the effect of trip times caused by the incident. Guided vehicles and vehicles responding to advisory messages have the opportunity to reduce both this delay and the delay caused by recurrent congestion. However, it becomes difficult to distinguish between the recurrent and non-recurrent delay reduced under these conditions. Therefore the percent reduction in travel time from baseline 2 wilI be examined for the comparison cases.

Table 3-11. Amount of Non-recurrent Delay Caused by Incident

	Trip Time (minutes)		Increase in
	Baseline 1	Baseline 2	Delay
Trips	(no incident)	(incident)	(minutes)
Through	45.77	50.29	4.52
Selected	57.68	75.94	18.26
NB I-295	50.35	75.19	24.84

The non-recurrent delay corresponds to a 9.8% increase in travel time for the freeway through traffic in the sample population of vehicles. The average speed of these vehicles was also observed to decrease by approximately six kph (4 mph). For those vehicles traveling northbound I-295 travel time increases by 49.3% and average speeds decrease by more than 25 kph (16 mph).

3.4.4 Dynamic Route Guidance Results

The results of the two comparison cases under incident conditions for dynamic route guidance are shown in table 3-12 and figure 3-7.

The incident introduces 18.3 minutes of additional &lay over that of the non-incident case for the sub-population of vehicles who have the potential of encountering the incident. However, 5% guided vehicles are able to reduce 16.3 minutes of delay, or 21.5% of their travel time.

Table 3-12. Reduction in Travel Time for Guided Vehicles Thruville-Incident Scenario

	Trips	Travel Time Baseline 2 (minutes)	Travel time Reduction (minutes)	Percent Travel time Reduced
Case 3 5% guided	Through	50.29	7.17	143%
	Selected	75.94	16.31	21.5%
	NB I-295	75.19	16.28	21.7%
Case 4 20% guided	Through	50 29	5.50	109%
	Selected	75.94	13.76	18.1%
	.NB I-295	75.19	14.80	19.7%

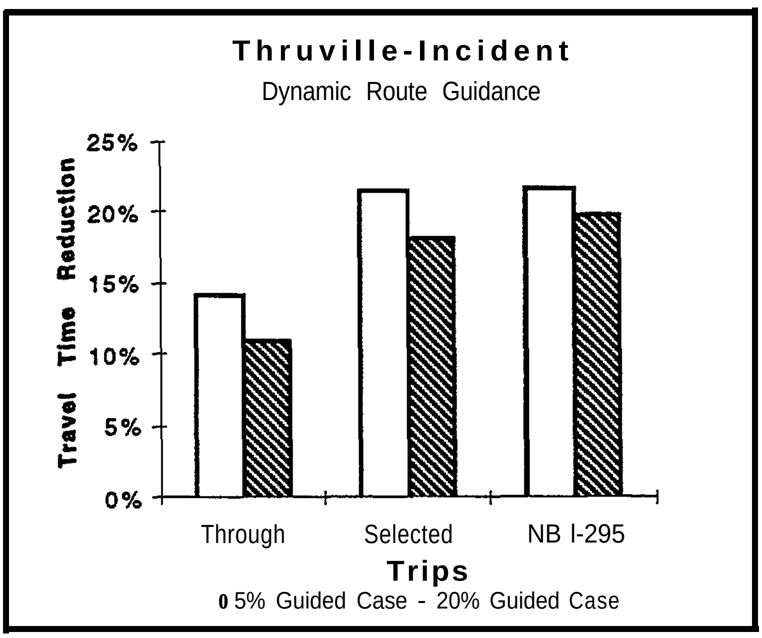

Figure 3-7. Percent Reduction of Travel Time from Baseline 2

3.4.5 Results for Vehicles Responding to Advisory Messages

As in the Thruville Subset scenario for the advisory message cases, vehicles that respond to the messages do not experience as great a reduction in travel time as route guided vehicles. These vehicles choose alternate routes based on historical data. Table 3-13 and figure 3-8 illustrate the results of the two advisory message cases (Cases 5 and 6).

When 5% of the vehicles respond, the sub-population of vehicles who have the potential of encountering the incident are able to reduce their delay by 10.5 minutes, or 13.8% of their travel time. There is a 5.8 minute (7.7%) difference between the results for route guidance and advisory messages for this vehicle population.

Table 3-13. Reduction in Travel Time - Advisory Messages

	Trips	Travel Time Baseline 2 (minutes)	Travel time Reduction (minutes)	Percent Travel time Reduced
Case 5 5% Responding	Through	50.29	4.10	8.2%
	Selected	75.94	10.48	13.8%
	NB I-295	75.19	3.78	5.0%
Case 6 20% Responding	Through	50.29	4.92	9.8%
	Selected	75.94	12.69	16.7%
	NB I-295	75.19	9.16	12.2%

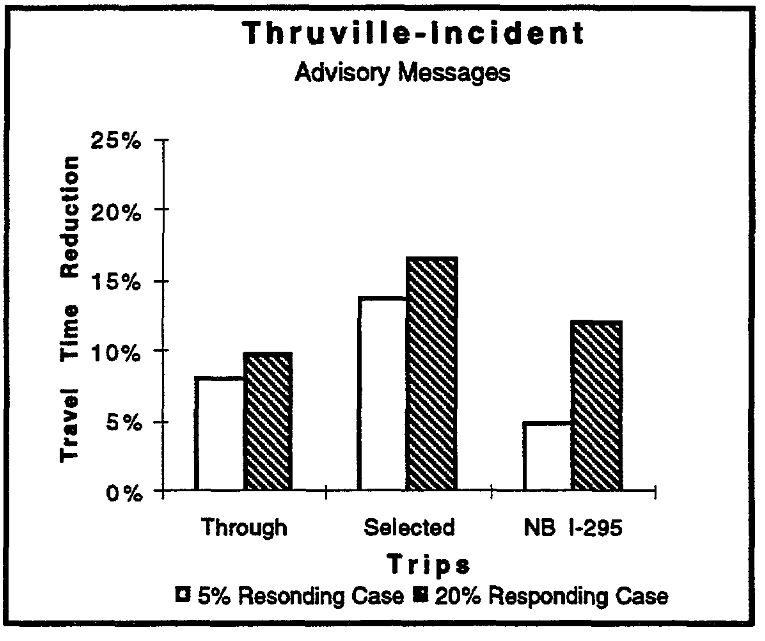

Figure 3-8. Percent Reduction in Travel Time from Baseline 2

Figure 3-8 also shows that a 20% responding vehicle population performs better than 5%. The 20% population causes the alternative paths to become more congested. However, queues building behind the incident do not build as fast with 20% routing to an alternative route. Therefore, queues reach the diversion point at a later simulation time than they do with 5%. This effect allows more vehicles to route to the alternative and obtain a better average travel time (see section 2.1.4 for a discussion of queuing past the diversion point). Figure 3-9 demonstrates the difference in travel time for the two different percentages of responding vehicles.

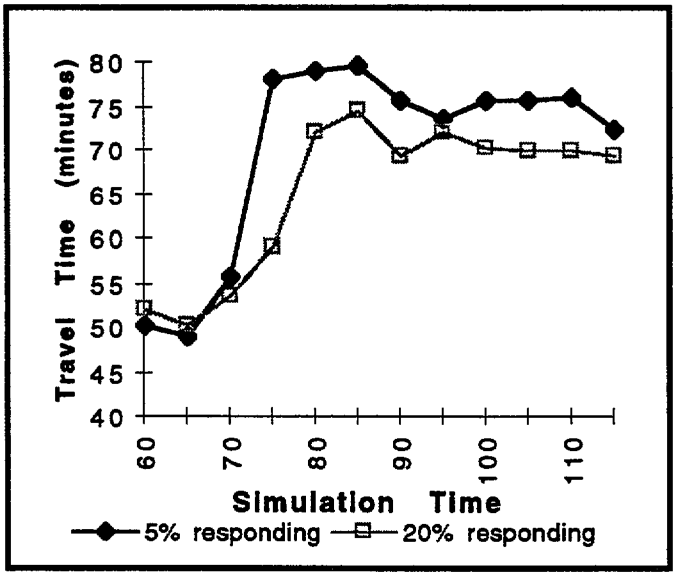

Figure 3-9. Travel Times for Responding Vehicles

3.5 Experiment 3: Construction in Thruville

This scenario places a construction project on the Thruville network. The construction site is located on southbound I-95 and begins before the Tacony-Palmyra Bridge. Southbound I-95 is reduced from four to three lanes from the beginning point to the I-676/I-95 interchange. The interchange area on I-95 southbound is reduced to two lanes before returning to normal past the interchange. Speed limits on the freeway are also reduced from 110 kph to 75 kph (68 mph to 47 mph). This reflects Pennsylvania's restrictions on speed in construction zones. This area was chosen at the construction site because of the recurrent congestion located at the I-676/I-95 interchange. The construction is being performed to improve the interchange and to help alleviate recurrent congestion for normal flow periods. The construction area is approximately 15.6 kilometers (10 mi.) in length. Advisory messages are located at major diversion points between freeways.

Congestion is observed to build behind the construction area for the holiday demand throughout the simulation. At the end of the simulation, congestion affects extend to the NJ-31 interchange approximately 36 kilometers (22.3 mi.) upstream from the Tacony-Palmyra

Bridge. Although this is a very long segment of freeway, traffic is observed to continue to flow at higher densities. There are areas of stop and go traffic but average speeds on I-95 southbound are reduced from 83.4 kph (52 mph) in the non-construction case to 66.8 kph (41.5 mph) for this scenario.

For this scenario, a total simulated time of 4.5 hours is used with the full Thruville network under the holiday demand pattern. As explained in section 3.2, traffic demand is not constant throughout the simulation period for the Thruville network. The first hour of simulated time is considered to be the time to load the network. The population of vehicles that enter the network for the next 1.5 hours arc considered for data collection. The remaining simulation time allows for most of the vehicles in this population to complete their trips and exit the network As before, vehicles entering the network after 2.5 hours until time 4 hours arc considered background traffic running interference for those vehicles in the population sampled. The final half hour of simulation has no additional traffic loaded onto the network and is used to allow the remaining vehicles in the sample population to complete trips. These vehicles are still affected by traffic on the network running interference.

As in the incident scenario, data are collected from the sample population for vehicles whose paths arc considered to be through trips on the freeways only. Statistics are also reported for two sub-populations of the sample. Selected vehicles are those vehicles whose paths have the potential of traversing the construction area. Site path vehicles are those vehicles whose original path includes the section of I-95 under construction.

During the entire simulation 229,619 vehicles are produced; approximately 45,380 of these appear in the sample vehicle population. Approximately 11,350 vehicles of the sample have paths that potentially could traverse the construction site, 2,225 of which are on the site path.

3.51 Results Under Non-Construction Conditions

As in the incident scenario, the ability of ATIS to alleviate recurrent congestion without the construction on the network is examined first. Table 3-14 illustrates the reduction in recurrent &lay for cases 1 and 2 (no construction, route guidance) with baseline 1 (no construction, no ATIS). The results of the 5% and 20% response to advisory messages are also presented in table 3- 14.

Again route guided vehicles arc able to save a significant percentage of their trip time under expected conditions. For trips that traverse the construction site path, the 5% guided vehicles are able to save 5.41 minutes (9.0%) of what would be a 60.4 minute trip. These vehicles will be capable of reducing a percentage of recurrent delay plus a percentage of the additional delay created by the construction.

3.52 Results for Delay Due to the Construction

The difference in travel time between Baseline 1 (no construction, no ATIS) and Baseline 2 (construction, no ATIS) is attributable to the non-recurrent delay resulting from the reduction in capacity through the construction site. Table 3-15 examines the effect of trip times due to the construction. Guided and responding vehicles have the opportunity to reduce both this delay and the delay caused by recurrent congestion.

Table 3-14. Reduction of Recurrent Congestion

	Percent reduction in Travel Time from Baseline 1 (no construction/no ATIS)			Responding/ Guided
	Trips	Responding or Guided	Non-responding or Unguided	Travel Time Reduction (min.)
Case 1 5% guided	Through	9.6%	1.7%	4.38
	Selected	9.5%	2.5%	4.36
	Site Path	9.0%	2.3%	5.41
Case 2 20% guided	Through	7.7%	3.4%	3.53
	Selected	7.2%	3.5%	3.28
	Site Path	5.9%	1.7%	3.55
5% Responding	Through	7.3%	1.4%	3.32
	Selected	8.0%	2.2%	3.66
	Site Path	6.9%	2.5%	4.14
20% Responding	Through	6.9%	3.6%	3.15
	Selected	6.0%	3.6%	2.73
	Site Path	4.9%	3.0%	2.96

Table 3-15. Delay Increase Caused by Construction

	Trip Time (minutes)		Increase in
Trips	Baseline 1 (no construction)	Baseline 2 (construction)	Delay (minutes)
Through	45.77	51.99	6.22
Selected	45.78	72.94	27.16
Site Path	60.39	81.02	20.63

The non-recurrent delay corresponds to a 13.5% increase in travel time for the freeway through traffic in the sample population of vehicles. The average speed of these vehicles was also observed to decrease by approximately 9.5 kph. For those vehicles traveling the path through the construction site, travel time increases by 34.2% and average speeds decrease by more than 25 kph (16 mph).

3.5.3 Dynamic Route Guidance Results

The results of the two route guidance cases under construction conditions are shown in table 3-16 and figure 3-10. The 5% guided vehicles having the potential of traversing the construction site are able to reduce 30.4 minutes (41.7%) of their travel time over that of Baseline 2.

Table 3-16. Reduction in Travel Time for Guided Vehicles
Thruville-Construction Scenario

	Trips	Travel Time Baseline 2 (minutes)	Travel Time Reduction (minutes)	Percent Travel Time Reduced
Case 3 5% guided	Through	51.99	10.45	20.1%
	Selected	72.94	30.38	41.7%
	Site Path	81.02	26.65	32.9%
Case 4 20% guided	Through	51.99	9.43	18.1%
	Selected	72.94	29.61	40.6%
	Site Path	81.02	24.42	30.1%

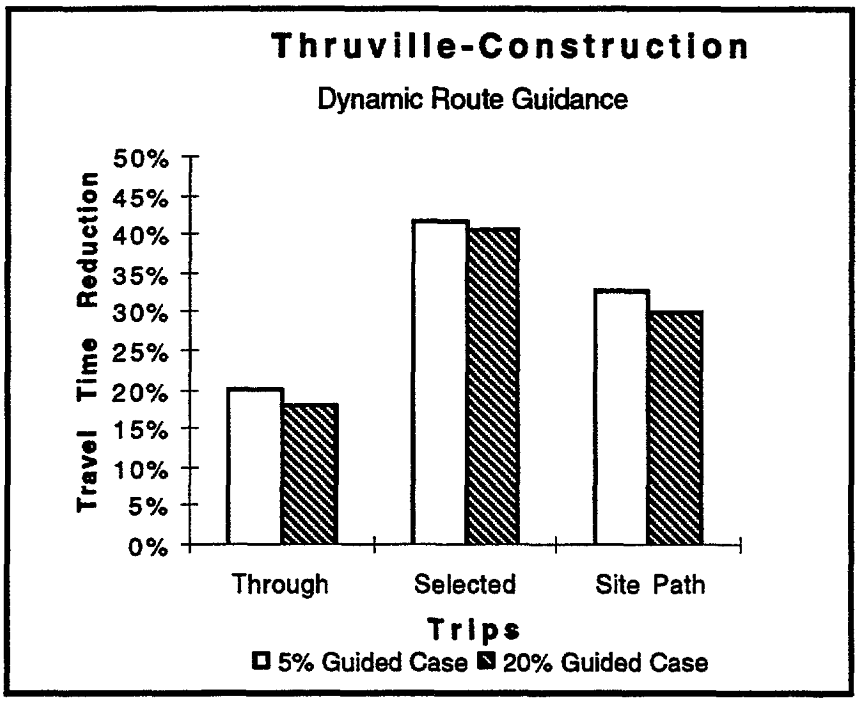

Figure 3-10. Percent Reduction of Travel Time from Baseline 2

3.5.4 Results for Vehicles Responding to Advisory Messages

Table 3-17 and figure 3-11 illustrate the results of the two advisory message cases (cases 4 and 5). As in the other two scenarios, the vehicles responding to the messages do not receive as great a benefit as in the route guidance case.

For the advisory message case, the 5% responding vehicles having the potential of traversing the construction site are able to reduce their delay by 24.0 minutes of delay, or 32.9% of their travel time. There is a 6.4 minute (8.8%) difference between the route guidance and advisory message cases for this vehicle population.

Table 3-17. Travel Time Reduction - Advisory Messages Thruville-Construction Scenario

	Trips	Travel Time Baseline 2 (minutes)	Travel Time Reduction (minutes)	Percent Travel Time Reduced
Case 5 5% Responding	Through	51.99	6.04	11.6%
	Selected	72.94	24.03	32.9%
	Site Path	81.02	8.73	10.8%
Case 6 20% Responding	Through	51.99	6.75	13.0%
	Selected	72.94	27.14	37.2%
	Site Path	81.02	14.92	18.4%

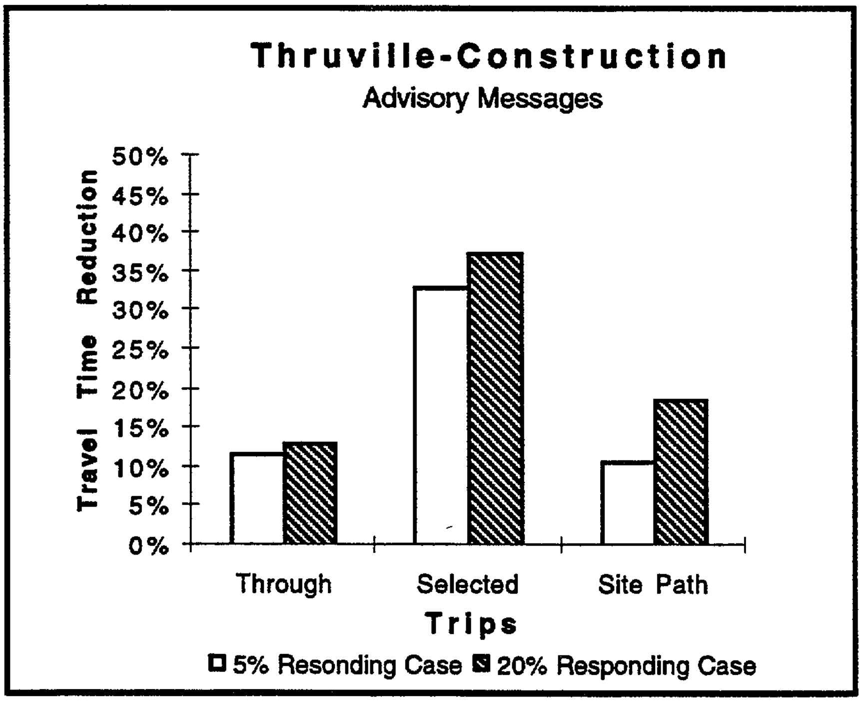

Figure 3-11. Percent Reduction in Delay Caused by the Construction

3.6 Summary of Results

Table 3-18 summarizes the results of the 5% market penetration for both the high functionality and low functionality market packages. This section also contains some general conclusions from the study.

- Both dynamic route guidance and advisory message systems are effective at reducing delay. Vehicles responding to advisory messages are unlikely to receive the same amount of benefit that a route guidance user service would provide. However, the low functionality system is able to capture more than half of the travel times savings of the high functionality system.

- Unguided and non-responding vehicles experience small benefits as guided or responding vehicles are diverted away from congestion.

- If advisory messages are disseminated by short-range devices such as CMS, the performance of the message system is critically dependent on the location of the devices.

Table 3-18. Summary of Results

			Percent Travel Time Reduction For Guided or Responding Vehicles		
	Scenario	Functionality	Full sample	Selected	Site Path
Subset	No Incident	5% Guided	1.7%		
		5% Responding	1.6%		
	Incident	5% Guided	15.5%		
		5% Responding	11.2%		
Thruville	No Incident	5% Guided	9.6%	7.0%	4.5%
		5% Responding	7.3%	5.3%	2.4%
	Incident	5% Guided	14.3%	21.5%	21.7%
		5% Responding	8.2%	13.8%	5.0%
Thruville	No Construction	5% Guided	9.6%	9.5%	9.0%
		5% Responding	7.3%	8.0%	6.9%
	Construction	5% Guided	20.1%	41.7%	32.9%
		5% Responding	11.6%	32.9%	10.8%

Section 4

Impact of Network Surveillance on Dynamic Route Guidance Benefits

Sections 2 and 3 of this report show that vehicles with dynamic route guidance can save significant amounts of time given current information about link travel on their original and alternate routes. The route guidance capability modeled for those subsections required surveillance on all links throughout the network to collect the link travel times. However, the cost of installing intelligent detectors on every link or equipping every vehicle as a probe may be prohibitively expensive.

This section discusses the results of a study of network surveillance options. Its purpose is to determine how much of the benefit of route guidance can be obtained with reduced (less costly) levels of network surveillance. The study also explores methods for compensating for the reduced amount of information obtained from a less comprehensive and less expensive surveillance system.

4.1 Study Design

This section describes the approach and goals of the network surveillance study, the model features used, and the basic network scenarios. The components of a route guidance service have been previously introduced in section 2.1. That section describes how current travel times for a roadway network are collected using detectors on links or probe vehicles and then disseminated to guided vehicles.

4.1.1 Study Approach

The study begins with the benefits of dynamic route guidance described in sections 2 and 3. It then explores the relationship between the amount of link travel time information collected by network surveillance devices and the benefit realized by route guided vehicles in an inter-urban traffic network as the level of network surveillance is decreased. The expectation is that the benefit to route guided vehicles, in terms of time savings compared to non-route guided vehicles, will decrease as the amount of network surveillance information decreases.

The study modeled two ways of decreasing the amount of network surveillance: (1) assuming that all surveillance information is provided by probe vehicles and reducing the percentage of vehicles to perform that function, and (2) reducing the number of reporting opportunities by allowing probes or detectors to report travel times on a subset of links. Either of these partial surveillance approaches could represent a less costly system than one with full surveillance. Following each method of reducing surveillance is a case representing an information management scheme to compensate in part for the reduction in information.

The study is composed of six experiments. The first three investigate reductions in the number of probe vehicles. The second three investigate reductions in the number of information-reporting locations. The experiments arc summarized as follows:

1. Assume all surveillance is conducted by probe vehicles. How is the benefit of route guidance affected as the percentage of probe vehicles decreases?

2. Assume that five percent of all vehicles are probes. How is the benefit of route guidance affected as the frequency with which routing information is disseminated to guided vehicles is increased?

3. Assume that only guided vehicles function as probes. Is the benefit of route guidance reduced without unguided probe reports, and if so, can the situation be improved?

4. Assume reporting capability on a subset of links. How is the benefit of route guidance affected as the information is reported for fewer links?

5. Assume that the link travel time can be reported only for every third link or only on a link with an incident. How is the benefit of route guidance affected if the incident is relocated to various locations in the network?

6. Assume that probes report travel times only if those times are at least 20% greater than expected. How is the benefit of route guidance affected as the amount of information collected and disseminated is reduced in this manner?

4.1.2 Network Surveillance Modeling in INTEGRATION

The analyses employ the INTEGRATION version l5x3d traffic simulation (Hellinga and Van Aerdc, 1995). This traffic model is well-suited for the study of network surveillance deployments because of the way its parameters for network surveillance can be varied and the way it can measure the performance of separate classes of vehicles.

INTEGRATION has the ability to model two forms of surveillance: probe vehicles and link detection systems. The information provided by link detectors in INTEGRATION is of higher quality than most detectors in use today. Link detectors in INTEGRATION have the ability to measure vehicle travel time on a link. Every vehicle passing a detection device is counted and the relevant data is incorporated into the calculation of the current link travel time estimate. In comparison, current loop detector technology provides a count of vehicles and sometimes an estimate of current vehicle speed at the loop detector position on the link.

The second method of surveillance used in INTEGRATION is to assign vehicles as probes. In this case, travel time information is available only from the sub-population of vehicles that are probes. Other vehicles do not contribute to that information unless they encounter a detector.

The role of a TMC is modeled in INTEGRATION by maintaining a database with a travel time for each link in the network. Each time information from a detector or a probe vehicle is received by the routine maintaining the database, the routine calculates the new value for link travel time as a weighted average of the old value and the value just received. The resulting travel time estimate is said to be exponentially smoothed.

There are three occasions when a link's travel time is updated in the database:

1. Whenever a vehicle exits the link, if the vehicle is a probe or a detector has been specified for the link.

2. Whenever a vehicle spends more time on the link than the current TMC estimate, if the vehicle is a probe or a detector has been specified for the link. The travel time is sent for every second the vehicle remains on the link until the exit occurs. Known as intermediate reporting, this capability allows for updates during situations when sudden significant delays prohibit vehicles from completing an exit. Intermediate reporting implies that the detectors or probe vehicles know current link travel time estimates.

3. If no vehicles are present on a link, the link travel time estimate moves automatically toward free flow travel time.

Although link travel times are transmitted to the TMC throughout the simulation, guidance information is only transmitted to guided vehicles at specified periodic intervals.

The similarity in the way INTEGRATION models link detectors and probe vehicles allows for a consistent method for evaluating the value of information in the network. Full detectorization, for example, provides the same information as equipping the entire vehicle population to act as probes. Similarly, a network with no probes and no detectors will generate the same result in INTEGRATION as a network that has no guided vehicles.

The key differential between the link detector and probe models occurs when only a subset of the links of the network is detectorizd, or when only a fraction of the vehicles in the network act as probes. These intermediate deployments may significantly change the travel times of guided vehicles. Probe vehicles report to the TMC whenever they traverse a link in the network, but probe reports may be infrequent if the number of probe vehicles is small. Link detectors report for every vehicle that traverses the link, but no information is collected on links where detectors have not been installed. INTEGRATION can model a network in which a mix of detectors and probe vehicles is present.

Each result reported in this study is the average of results obtained from eight INTEGRATION runs, using different starting random seeds. This procedure was used to reduce the variability inherent in random-number- driven discrete-event simulation.

4.1.3 Network and Scenario Descriptions

The network used in this study is a subset of the Thruville (Inter-urban) scenario. Section 3.3.1 describes the boundaries and major components of the Thruville subset. The Subset network is depicted in figure 4-1. The only differences from figure 3-2 are that information &vices are not depicted and some nodes have different numbers.

The demand used in this study is the same as the "holiday" demand described in section 3.3.1, with near-capacity volume on the major freeways but light traffic on the arterials. Northbound traffic on the freeways constitutes 40% of the overall network demand. If there are no incidents, travelers experience heavy but steady (level of service B-C) traffic on all the major facilities.

For this study five percent of the vehicles are modeled with dynamic route guidance. This small market penetration is consistent with the near-to-medium term route guidance market penetration estimates provided in the ITS Architecture. In the holiday demand scenario, this sub-population of guided vehicles, when routed to alternate paths, has little effect on traffic densities occurring on those routes.

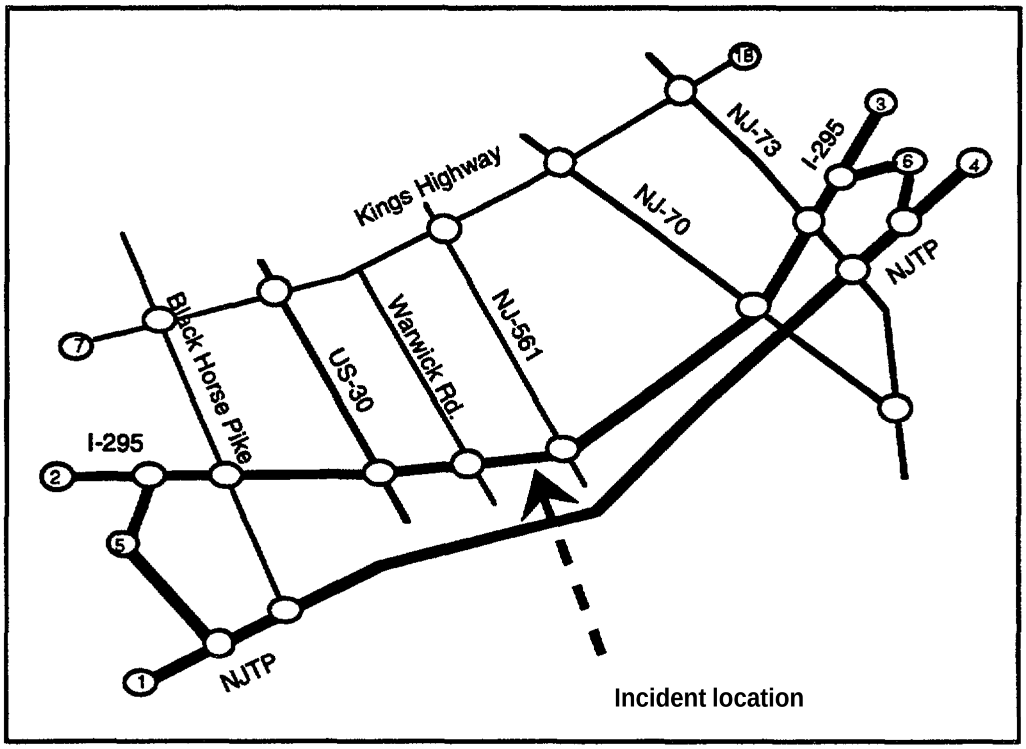

Figure 4-l. Thruville Subset Network

The scenario network contains some naturally occurring delay spots. These delays are primarily located at or near the interchanges between artcrials and at locations where arterials meet with the freeways. However, the recurrent congestion does not cause enough delay for alternate routes to become appealing to route guided vehicles. Therefore, in the expected (non-incident) case, there is little value in diversion for guided vehicles and correspondingly low value for updated real-time information on the status of the network. Vehicles remain on a set of generally geographically direct routes, also called preferred routes. For the New Jersey Turnpike, I-295 and Kings Highway traffic, the average travel time and speed are approximately 12.3 minutes and 79.5 kph (49.4 mph).

This situation is not the case when an incident is introduced onto the network The incident causes significant delay for travelers who take routes passing through the incident site. The incident creates a situation in which the preferred route may no longer represent the path with the shortest trip time. In this case, guided vehicles may choose alternate paths based on the network status information obtained by probes or detectors.

4.1.4 Vehicle Classes and Characteristics

Three vehicle types are used in this study: background, probe, and guided vehicles. Background vehicles follow routes identified under expected, non-incident conditions generated by the multi-path ASSIGN module in INTEGRATION. These vehicles represent unguided vehicles and only travel along their preferred routes. They do not receive nor do they transmit any information about network conditions. When an incident occurs, these vehicles remain on the preferred paths and do not divert

Guided vehicles are the only vehicles permitted to change routing strategies based on information received from the TMC. Guided vehicles receive updated route information at regular time intervals during the course of the simulation. The level of ATIS functionality represented by guided vehicles in this study corresponds to a non-predictive dynamic route guidance user service. Guided vehicles are generated as a uniform percentage of each origin-destination demand pair.

Probe vehicles always transfer information about network conditions to the TMC. In all cases but Experiment 3, probe vehicles are unguided. When probes are unguided they follow the same paths assigned to background traffic. When guided, probe vehicles are capable of changing to the same routing strategies as normal guided vehicles.

Probe vehicles arc generated as a uniform percentage of the traffic generated for each origin-destination pair throughout the network. In an inter-urban scenario such as the Thruville subset, where the majority of the vehicles have the same or similar paths, it is reasonable to assume that probe vehicles travel on all links of the network. Section 4.8.7 discusses the urban setting where this assumption may not be realistic.

4.2 Experiment 1: Decreasing the Number of Probe Vehicles

This experiment investigates the percentage of the maximum benefit guided vehicles are able to obtain for different percentages of probe vehicles. The starting hypothesis is that the maximum benefit will be realized by guided vehicles with the network under full surveillance, and that smaller numbers of probes will result in smaller benefits to guided vehicles. This experiment was also discussed in a preliminary report (Proper, 1995).

4.2.1 Experiment Description

In this experiment, results for twelve levels of probe vehicle population are compared to results from a fully detector&d network configuration. These levels range from 0 to 100 percent of total vehicle population. In all cases guided vehicles make up 5% of the vehicle population. Guided vehicles receive updated information every 10 minutes throughout the simulation. Probe vehicles are considered to be unguided for this experiment, except in the case of 100% probes. In this special case, 5% of the probes arc guided.

The experiment aims to identify probe vehicle population levels at which vehicle travel time performance approaches that of a completely detectorized network Although the percentage of unguided probes varies for the different experiments, the total number of all vehicles modeled remains constant.

For this experiment, an incident is located on northbound I-295 at the State Route 561 interchange. The incident has a duration of 30 minutes, beginning at simulation time 25 minutes and ending at time 55 minutes, blocking 33% of the roadway (one lane of I-295). The total simulated period is 2 hours. Even after the incident has been removed, queues persist in the network for the remainder of the simulated period. These queues are observed to have a realistic shock wave pattern of queue dispersion, with queues gradually dissipating from the front rather than the rear.

4.2.2 Route Guidance Benefit for Full Surveillance

Table 4-l presents the results of the first (base) case for this experiment. In this case all vehicles are probes. The results are identical to the case where all links have detectors. When there are no guided vehicles in the network, the incident creates an average of 0.80 minutes of delay per vehicle in the network. There is a total of 66 1.6 hours of additional delay for all 49,620 vehicles generated in the network. The average system travel time and speed for the incident case are 11.0 minutes and 38 kph (24 mph).

Table 4-l. Non-Incident Case Compared to Incident Case

	Avg. Trip Time No Incident (minutes)	Avg. Trip Time Incident (minutes)	Delay Caused by Incident (minutes)
No route guidance			
All Vehicles	10.20	11.00	0.80
Vehicles in corridor	12.27	13.68	1.42
Northbound Vehicles only	12.34	15.15	2.81
With route guidance and full surveillance			
Guided Vehicles in corridor	12.15	12.88	0.73
Unguided Vehicles in corridor	12.27	13.64	1.37
Northbound Guided Vehicles	12.20	13.66	1.46
Northbound Unguided Vehicles	12.33	15.08	2.74

Vehicles with routes containing both origins and destinations on Rings Highway, I-295, or the New Jersey Turnpike (called corridor traffic) represent through-trips or inter-city corridor traffic. When there are no guided vehicles, the incident causes an average 1.42 minutes of delay for corridor traffic. Since the incident location blocks northbound traffic on I-295, the northbound corridor trips experience the largest delay. When there are no guided vehicles, the average vehicle in the northbound corridor experiences 2.81 minutes of delay caused by the incident.

The benefit of route guidance to corridor traffic is minor for the non-incident case but significant for the incident case. In the latter case, the average trip time for unguided corridor traffic is 13.64 minutes, while the average trip time for guided corridor traffic is 12.88. Thus route guidance saves these vehicles an average of 0.76 minutes (45.8 seconds) for a total of 31.6 hours. This figure is the maximum achievable savings for guided corridor traffic.

For northbound corridor trips only, route guidance reduces the average trip time from 15.08 minutes to 13.66 minutes for the incident case. This results in an average savings of 1.42 minutes per vehicle. These trips represent vehicles that traverse either the incident link on I-295 or a link parallel to the incident link on Kings Highway or the New Jersey Turnpike.

Delay reduction is not uniformly distributed across all route guided vehicles in the network. A sample of O-D pairs is presented in table 4-2 and figure 4-2 to illustrate this point. O-D pairs 4-2 and 6-5 experience no increase in delay in the incident case from the non-incident case. Route guided vehicles cannot experience reduced delay because there is no delay to be reduced. Both of these O-D pairs generate vehicles making southbound trips in the network.

Table 4-2. Incident-Caused Delay for Selected Origin-Destination Pairs

Selected O-D Pair	No guided veh. (Seconds)	5% Guided Vehicles: Unguided (Seconds)	5% Guided Vehicles: Guided (Seconds)
2-4	376.2	362.3	34.8
2-18	375.3	361.7	254.8
4-2	9.9	4.0	-0.8
5-6	261.1	254.6	6.3
6-5	0.1	-1.1	1.6
7-4	385.0	365.3	52.4

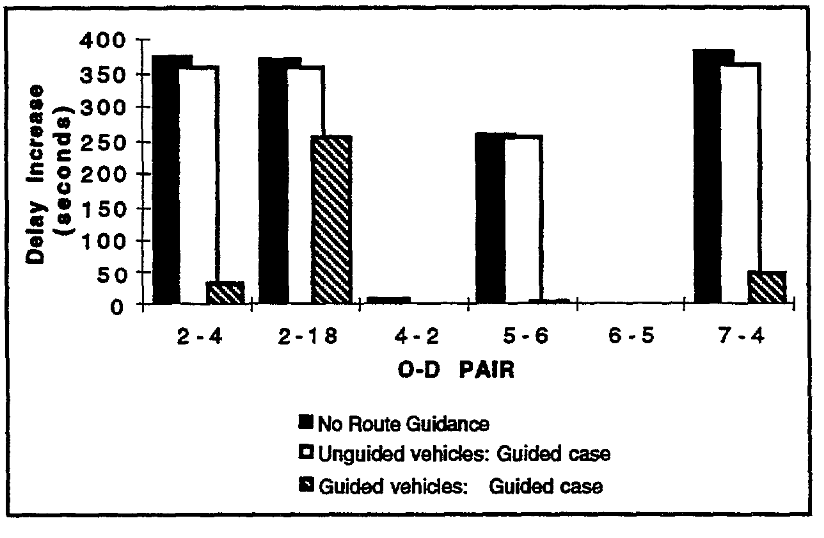

Figure 4-2. Incident-Caused Delay for Selected Origin-Destination Pairs

Northbound O-D pairs 2-4, 2-18, 5-6, and 7-4 do experience delay caused by the incident. For example, in the no route guidance case (solid black columns in figure 4-2), O-D pair 2-4 experiences an average delay of 376 seconds per vehicle. Route guided vehicles (shaded columns) for the same O-D pair experience only 35 seconds of delay. Unguided vehicles also benefit to a lesser degree from the introduction of route guided vehicles for O-D pair 2-4, experiencing an average savings of 14 seconds per vehicle. The other northbound O-D pairs demonstrate that a range of delay reduction may be achieved. Guided vehicles on O-D pair 2-18 do not experience as dramatic a reduction in delay in the incident case as O-D pair 2-4, for example.

Reduction in travel delay is largely a function of two factors related to O-D pair characteristics. The first factor is the likelihood that the incident location creates delay on a preferred route between trip origins and destinations. The second factor is the availability of alternate routes for a particular O-D pair and the additional cost of diverting to the alternate route.

Figure 4-3 illustrates an example of high and low-cost diversion routes. The preferred route for a vehicle traveling from point A to point E would pass through point C. If an incident occurs between points A and C and increases the travel time on link AC, the route through point B provides a low-cost alternative for that vehicle. Route guidance would have a significant benefit for this vehicle since all the delay on link AC can be avoided at small cost. A vehicle traveling from point A to point D with preferred route A-C-D, however, has no low-cost altemative if link AC is congested. The delay on link AC would have to be very large before route A-B-E-D becomes faster than route A-C-D. Such a vehicle would derive very little benefit from route guidance when there is a minor incident, because of the high cost of diversion around link AC.

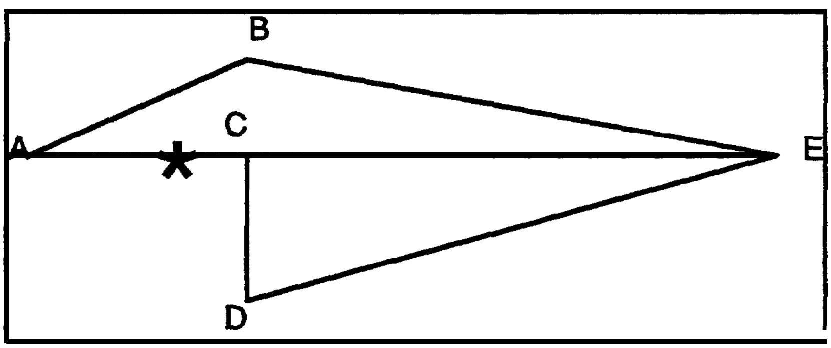

Figure 4-3. Example of Low-Cost and High-Cost Alternate Routes

4.2.3 Route Guidance Benefit with Partial Information

Following the establishment of base case values, Mitretek ran the same incident scenario with partial surveillance, varying the percentage of vehicles acting as probes. Only a uniformly generated fraction of the vehicle population contribute to the travel tune estimation process.

Table 4-3 summarizes the results of the experiment. The first row is the 100% probe/ full detectorization case described in the previous section. "Savings" (the benefit of route guidance) is calculated as the difference in average travel time between guided and non-guided vehicles in the northbound and southbound corridors. The third column shows the time savings as a percentage of the time savings for the 100% probe case (45.8 seconds). Figure 4-4 graphs the percentages.

The key result is that small sub-populations of probes are sufficient to provide the majority of the benefit to route guided vehicles. For example, when one percent of the vehicle population act as probes in the simulation, guided vehicles are able to realize over 50% of the potential benefit of the route guidance user service (35 seconds of a potential 46 seconds). With a probe population of 20% of total vehicle population, guided vehicles capture all of the benefit of the route guidance user service.

The results reported in table 4-3 are not strictly monotonic. A 75% probe deployment returned a slightly higher performance than a deployment with 100% probes. A deployment with 1% probes was slightly more effective than a 2% probe deployment. These results are indicative of inherent variability in the experiments and are not statistically significant. The average travel times of route guided vehicles are especially variable at the lowest probe population levels.

The results from this experiment strongly indicate that the use of uniformly generated probe vehicles, even at low levels, provides sufficiently accurate information to support a route guidance user service in an incident case.

Table 4-3. Savings for Route Guided Vehicles as Function of Probe Percent

Detectors	Savings (seconds)	Percent of 100% Probe Case
Full Detectors/100% Probes	45.8	100.0
75% Probes	47.3	103.3
50% Probes	45.7	99.8
30% Probes	44.2	96.5
25% Probes	45.6	99.6
20% Probes	45.8	100.0
15% Probes	44.3	96.7
10% Probes	43.8	95.6
5% Probes	37.4	81.6
2% Probes	33.8	73.8
1% Probes	35.0	76.4
No Detectors/0% Probes	0.0	0.0

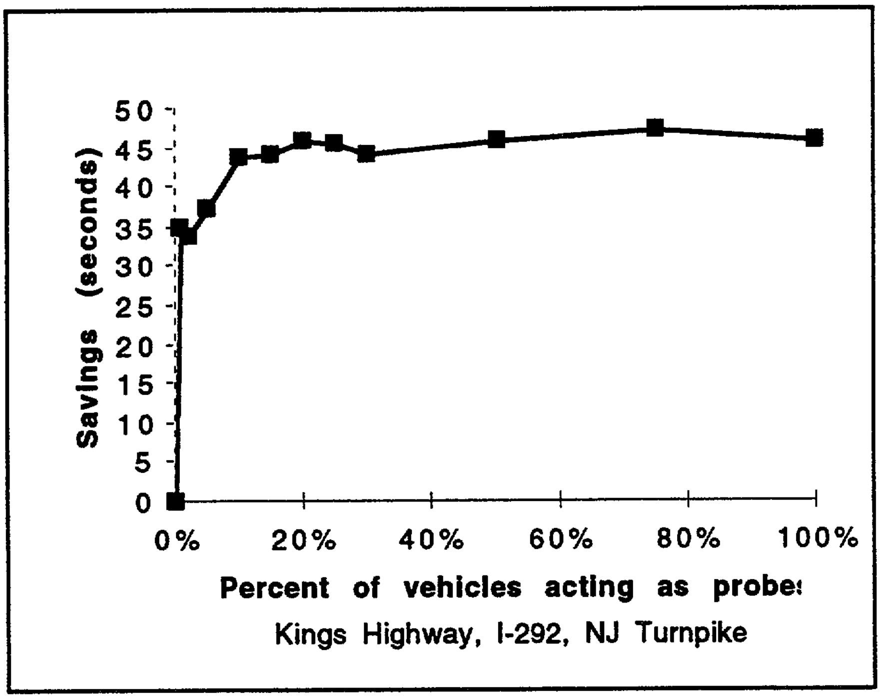

Figure 4-4. Guided Vehicle Travel Time Savings vs. Probe Percent

Very low percentages of probes result in poorer performance because of the time value of information. When there is an incident, congestion builds on the affected link(s) and travel times for the original routes of some O-D pairs increase. At some point in time, the travel time on the original route becomes greater than the travel time for an alternate route for some O-D pair. A guided vehicle on its original route will not realize this, however, until two things happen: (1) probe vehicles report the longer travel time on the original link, and (2) the information is transmitted from the TMC to the vehicle. The lower the percentage of probes, the more time is likely to pass before event (1) happens. The longer it takes for the system to recognize that the alternate route is shorter, the more guided vehicles pass the diversion point and miss the opportunity to save time by rerouting.

Figures 4-5 and 4-6 illustrate this point. The horizontal axis in the figures represents the simulation time at which vehicles of a certain O-D pair start their trips. The vertical axis plots the travel time for those vehicles. Time T_P is the time required for the preferred route under expected (non-incident) conditions. Time T_A is the time expected on an alternate route. The rising and falling curve represents the travel time incurred by unguided vehicles following the preferred route for an incident case. The incident occurs at simulation time t_1, causing queues to build and travel time to increase. At some point, the incident is cleared and queues dissipate, bringing travel time back to its original level.

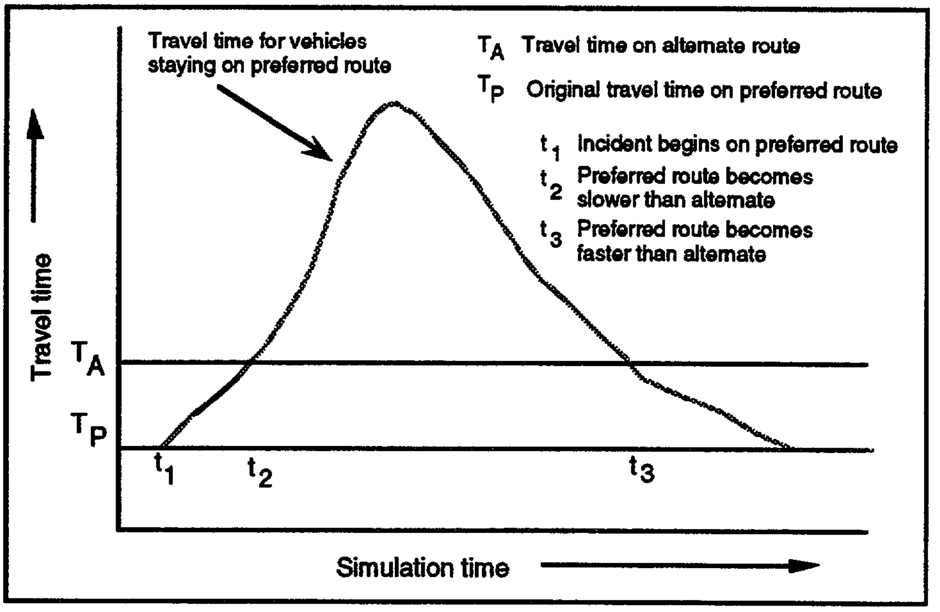

Figure 4-5. Travel Times on Preferred and Alternate Routes

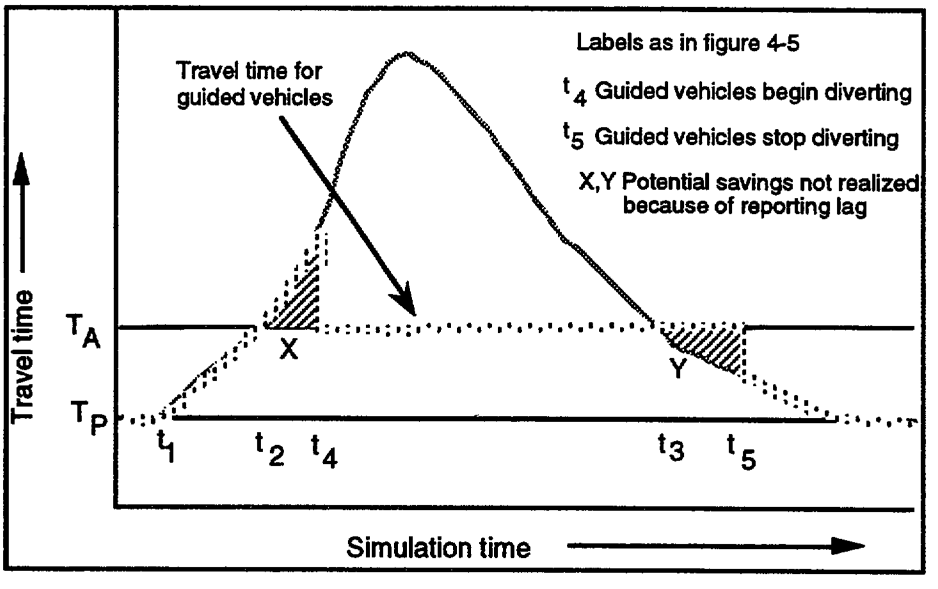

Figure 4-6. Effect of Lags in Data Collection or Dissemination on Route Guidance

If there were no incident, all vehicles for the O-D pair would follow the preferred route and would incur travel time T_P throughout the simulation. However, when the incident occurs at time t_1 , the travel timebegins to rise. At time t_2, the travel time on the preferred route has increased to the point where the alternate route is faster. Any guided vehicles that are informed of this before reaching the point where the alternate route diverges from the preferred route should take the alternate route until time t_3, when the preferred route again becomes the faster route. During this window of opportunity, the travel time for guided vehicles is T_A,While travel time for unguided vehicles is higher.

Figure 4-6 depicts the effects of a lag in data collection or dissemination time. The dotted line represents the travel time experienced by guided vehicles for the selected O-D pair. Travel times rise between time t_1 and t_2, and continue to rise, following the preferred route until time t_4, when the guided vehicles learn that the alternate route is shorter. Shaded area X is the time that could have been saved but was not because of the lag in reporting time.

Similarly, shaded area Y is the time lost by guided vehicles continuing to take the alternate route past the point t_3 when the preferred route again becomes shorter than the alternate route. The longer the lag between the time when one route becomes faster than another and the time when guided vehicles receive the information, the more potential time savings are lost The lag can be caused by either a scarcity of probes, infrequent updates to guided vehicles, or both.

Sensitivity to the timeliness of link travel time is not uniform. Some trips arc associated with O-D pairs that have good alternate routes around the incident site. When the cost of diversion is small, the period during which the alternate route is faster than the original route is large, and the total benefit gained by diversion is large. Even if some opportunities for diversion are lost, the remaining opportunities make up most of the benefit of route guidance. Figure 4-7 illustrates an example of such an O-D pair (5-6). The average time saved is so high that a few missed opportunities do not bring down the average.

For other O-D pairs, a good alternative may not exist. Figure 4-7 also illustrates the sensitivity curve of an O-D pair (2-3) where there is a significant cost to divert. Its cost of diversion is so high that the maximum benefit is less than half of that for O-D pair 5-6. The time window when the alternate route is better than the original route is very short. Each opportunity for diversion lost during this period because of a lag in reporting represents a significant portion of the total savings possible. Thus a high percentage of probes is necessary to increase the probability that the window of opportunity for diversion is detected as soon as possible.

Figure 4-8 portrays the trip time for vehicles with only a high-cost alternate path. In comparison to figure 4-6, the delay on the preferred route must become very high before the alternate route becomes the faster route, and the window of opportunity for diversion is short. If the beginning and end of the window am missed because of lags in data collection or dissemination time, resulting in lost time represented by areas X and Y, a significant portion of the benefit from route guidance is lost.

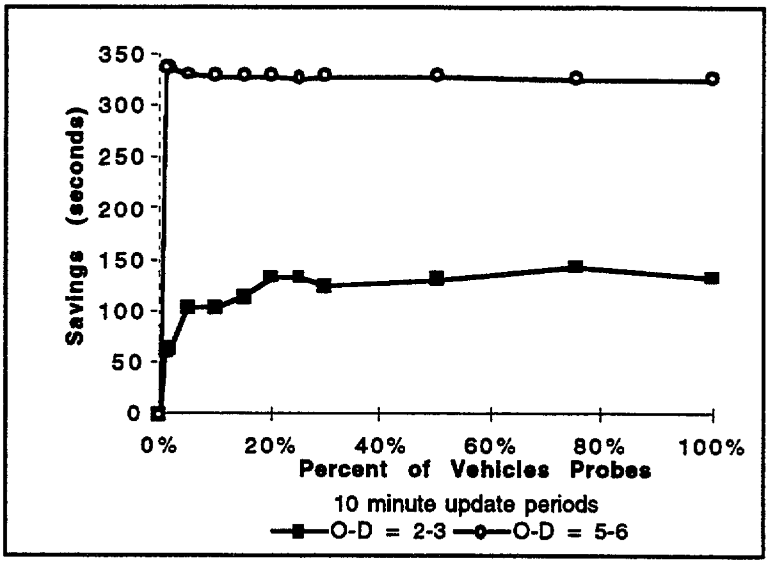

Figure 4-7. Savings for Sample O-D Pairs with Low and High Cost of Diversion

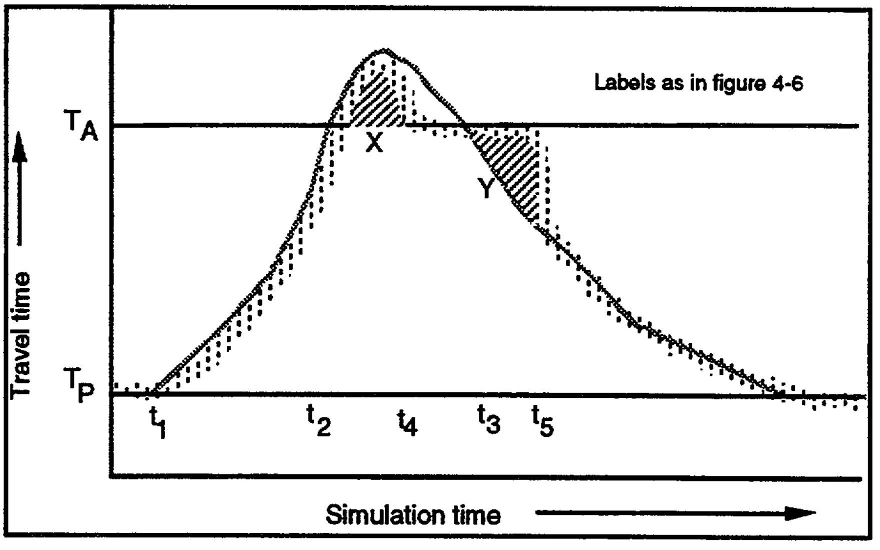

Figure 4-8. Effect of Lags in Data Collection or Dissemination on a Route with High Diversion Cost

4.3 Experiment 2: Increasing Frequency of Updates to Guided Vehicles

The previous experiment shows that the benefit to guided vehicles decreases as the probe population decreases below 20%. It may be possible to recover some of the lost benefit without paying to equip a large percent of vehicles as probes. This experiment investigates one method of doing so, namely increasing the frequency of sending network information to guided vehicles.

4.3.1 Experiment Design

In the previous experiment, guided vehicles receive updates on link travel times every ten minutes. In this experiment, the same twelve cases with varying percentages of probe population were rerun with an update time of five minutes, and then again with an update time of one minute, for a total of 24 new cases.

The rationale for increasing update frequency is that, as delay increases on a preferred path, an alternate path may exist with a lower trip time. Guided vehicles that do not receive current travel time information until after passing the diversion point to the alternate path will not be able to take advantage of the shorter route. More frequent updates will increase the likelihood that guided vehicles will get useful information in time to benefit from it. In terms of figures 4-6 and 4-8, the shaded areas X and Y should become smaller.

4.3.2 Benefits of Route Guidance with Increasing Update Frequency

Table 4-4 presents the average travel time savings of guided vehicles as the time between link travel time updates is decreased. Figure 4-9 graphs the same values.

As update frequency increases, guided vehicles are able to obtain a greater benefit from the information provided. This occurs because more guided vehicles receive the information before they pass diversion points on a current path. The maximum benefit of choosing alternate paths remains unchanged. Note that the scenario represents an implementation where all guided vehicles receive updated information at the same fixed times. An implementation where guided vehicles received updated information at fixed locations rather than fixed times would behave differently.

Table 4-4. Travel Time Savings for 10, 5, and 1 Minute Update Periods

	Savings (seconds)		
% Probes	10 Minute update period	5 Minute update period	1 Minute update period
100%	45.8	48 7	49.4
75%	473	51 3	484
50%	45.7	47.5	48.7
30%	442	45 4	489
25%	456	49.1	48.4
20%	45.8	48.0	49.1

Table 4-4. Travel Time Savings for 10, 5, and 1 Minute Update Periods (Cont.)

	Savings (seconds)		
% Probes	10 Minute update period	5 Minute update period	1 Minute update period
15%	44.3	46.3	48.9
10%	43.8	45.6	49.5
5%	37.4	45.1	47.9
2%	33.8	42.2	47.0
1%	35.0	35.6	44.4

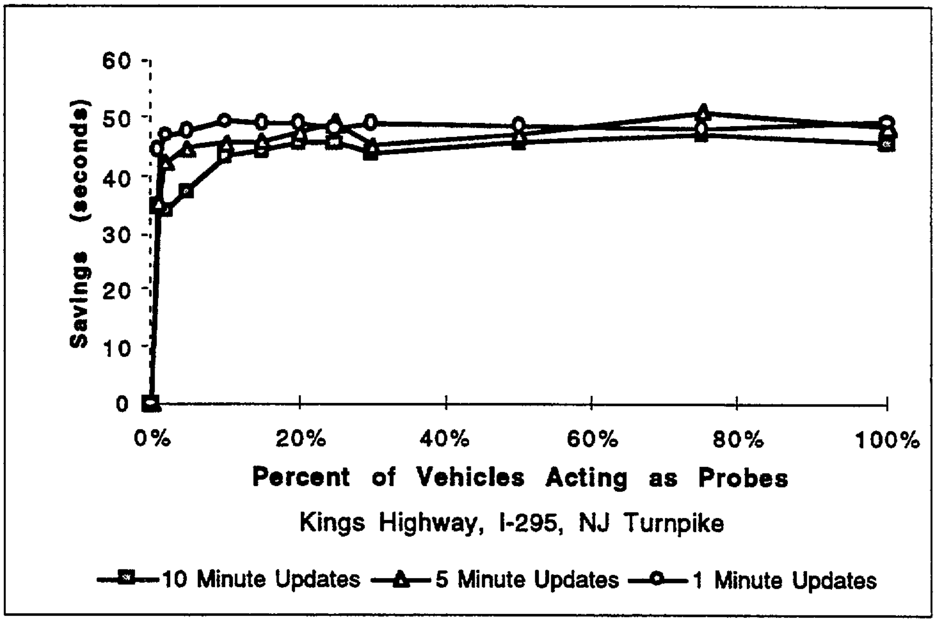

Figure 4-9. Guided Vehicle Travel Time Savings as a Function of Probe Vehicle Population and Update Period

Guided vehicles capture a greater amount of the total available benefit at lower percentages of probes when updates occur more frequently. For ten minute updates, one percent probes provide enough information for guided vehicles to capture approximately 75% (35.0 seconds) of the available 45.8 seconds of travel time savings. The savings increase to 90% (44.4 seconds) of an available 49.4 seconds when updates are occurring every minute. Similarly, a 15% to 20% probe population allows guided vehicles to obtain a 95% to 100% of the maximum benefit for a five minute update frequency. A one minute update frequency requires only 5% to 10% probe vehicles for guided vehicles to obtain this level of benefit.

These results suggest that it is possible to reduce the probe population proportionally for every minute reduction in update frequency and maintain a specified level of benefit. At probe percentages around 5%, the data suggest that each 1% decrease in probe levels could be compensated for by a one-minute decrease in time between updates. However, there must be some minimum probe population even at very frequent update periods. A system in which guided vehicles receive continuous updates would have to be sustained by this minimum probe population.

Conversely, if update frequencies become very long compared to network travel time, even a network under full surveillance will not provide guided vehicles with enough information to obtain significant delay reductions. At these long cycles, vehicles could potentially traverse the entire network on a longer trip time path without receiving any updated information about network conditions.

As explained in the previous section, reducing the time between the point when an alternate route becomes shorter than the original route and the point when guided vehicles receive that information is most important when the cost of diversion is high. Figure 4- 10 shows that a few missed opportunities for diversion do not affect the average savings for O-D pair 5-6 with a low cost of diversion, but noticeably degrade the average savings for O-D pair 2-3 with a high cost of diversion.

4.4 Experiment 3: Effect of Guided Probes

This experiment examines the effect of using guided vehicles as the only source of information about network conditions. The starting hypothesis was that if only guided vehicles act as probes in the network, the benefit of route guidance will diminish. If congestion occurs in some area and guided vehicles (the only probes in the system) are routed around it, the system has no way of knowing when the congestion has dissipated. Guided vehicles will not be routed back through the formerly congested area and will experience longer travel times than unguided traffic.

4.4.1 Experiment Description

In this experiment, average travel times for guided vehicles are compared to average travel times for background traffic. In all three cases, background traffic comprises 95% of the total traffic volume. The three cases are defined as follows:

1. In the first case the network has full surveillance (full detectorization).

2. In the second case, the 5% guided probe population becomes the only source of link travel time data.

3. In the third case as in the second case, the 5% guided probe population is the only source of link travel time data. However, 10% of the guided probes are not routed around congestion, but follow the same routes as unguided vehicles.

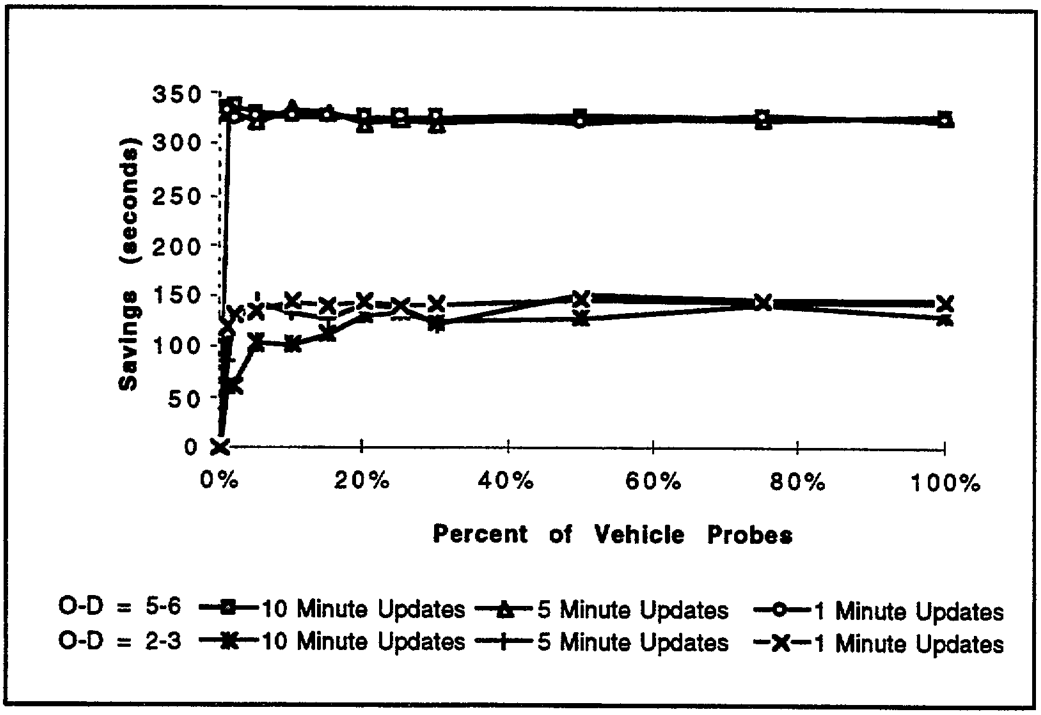

Figure 4-10. Examples of O-D Pair with Low and High Cost of Diversion Savings for Guided Vehicles 1, 5, and 10 Minute Update Periods

For this experiment, the incident is located on northbound I-295 at the State Route 561 interchange as in experiment 1. The incident has a duration of 30 minutes, beginning at simulation time 15 minutes and ending at time 45 minutes, blocking 33% of the roadway (one lane of I-295). The effect of the incident is reduced, however, because demand on I-295 is reduced from Experiment 1. Lower traffic levels allow the network to recover from the congestion formed by the incident before the end of the simulation. The total simulated period is 2 hours 40 minutes.

This scenario allows travel times on preferred routes to return to the pre-incident conditions, and guided vehicles to return to these paths. These conditions differ from Experiment 1 where travel times on preferred paths did not return to pre-incident conditions. In that experiment, guided vehicles did not return to preferred paths but instead remained on alternatives throughout the simulation.

In these cases, all guided vehicles are generated from all origins uniformly at 5% of the traffic volume, and guided vehicles receive updated network condition reports from the TMC every one minute of simulation time.

4.4.2 Benefits of Route Guidance with Full Surveillance

Figure 4-11 represents the difference in travel times between guided and unguided traffic with the network under full surveillance for the northbound I-295 O-D pair (2-3). As shown in

Experiment 1, this scenario features the greatest amount of information available from the network. The area between the two curves represents the total savings in trip time between guided and unguided vehicles for this O-D pair.

As the simulation progresses, travel time for the preferred route increases because of the incident. Guided vehicles remain on the preferred route until they receive a travel time update indicating that the alternative has a shorter travel time (this point is indicated by an A in figure 4-11). Guided vehicles follow the alternate route, with shorter travel time, until they get the message that the original preferred route is again the shortest. Before guided vehicles divert back to the preferred path, they experience an increase in travel time on the alternate route. This is caused by the delay moving upstream from the incident location and passing the diversion point. When this occurs guided vehicles have no choice but to experience this delay until they reach the diversion point. The effect is indicated by a B in figure 4-11. The TMC knows when the preferred path becomes shorter than the alternate path because it receives updates for travel times of non-guided vehicles on the preferred path.

With the network under full surveillance, guided vehicles that divert to alternate paths on northbound I-295 save an average of 77.8 seconds of trip time per vehicle over that of the background traffic. This accumulates to a maximum benefit of 8.5 hours of delay reduction for these 394 guided vehicles traveling north bound on I-295 during this time period.

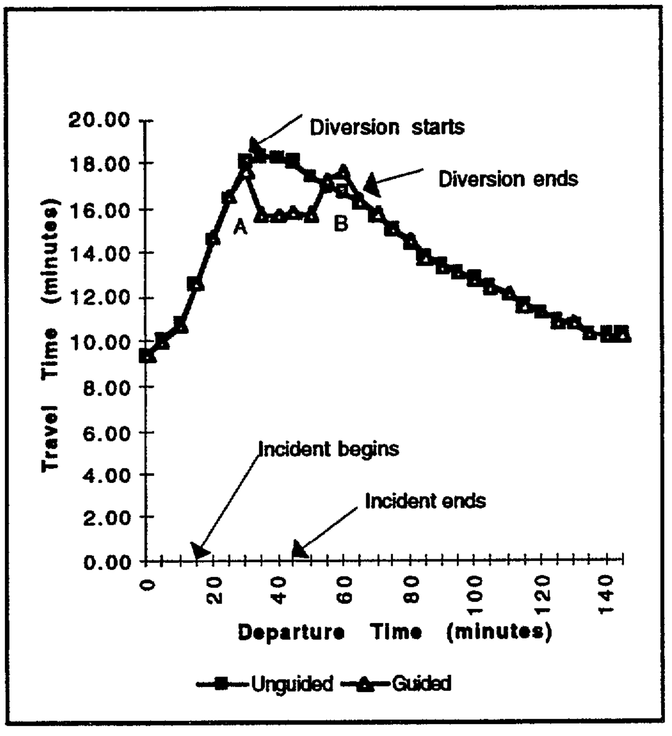

Figure 4-11. Average Travel Times as a Function of Departure Time Northbound I-295, Full Surveillance

4.4.3 Benefit of Route Guidance with 5% Guided Probe Surveillance

Figure 4-12 illustrates the difference in travel times between guided and unguided traffic when the 5% guided population are **guided probes**. The guided probe population is the only source of network information. The plot of travel times for guided vehicles shows that after travel times on preferred links fall below those of the alternate paths, guided vehicles do not return to the preferred paths. In this case, guided vehicles experience more delay than necessary.

At a point late in the simulation, guided vehicles do return to the preferred path. This only occurs because two guided probes have no alternate choice to reach their destinations except to traverse links located on I-295. The first (indicated by a 1 in figure 4-12) occurs after time 95 minutes, and permits guided vehicles to route back to part of I-295 and reduce some delay. The second vehicle (indicated by a 2 on figure 4-12) occurs after time 105 minutes, allowing the assignment of all I-295 northbound guided traffic back to its preferred path by time 110 minutes. In a test case where the probe vehicles providing these two updates were not produced, guided vehicles for northbound I-295 never returned to the preferred path, experiencing a near constant travel time until the end of the simulation.

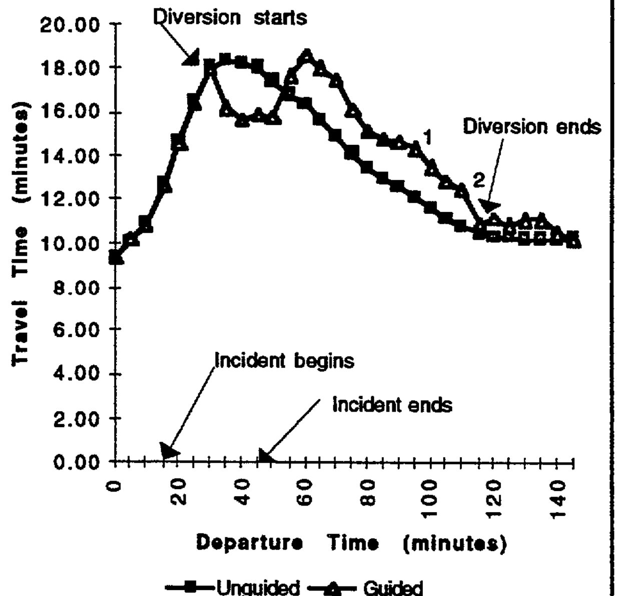

Figure 4-12. Average Travel Times as a Function of Departure Time Northbound I-295, 5% Guided Surveillance

The 1,039 guided probe vehicles following alternate route saved a total of 8.5 hours during the time when the alternate route was faster than the preferred route, but lost 23.3 hours unnecessarily when the preferred route was faster than the alternate. The net effect was 14.8 more hours of delay than background traffic during the diversion time period. This result demonstrates that some form of information is necessary to inform the TMC that most of the delay caused from the incident has dissipated from the preferred path. At that point, guided vehicles no longer require routing to alternate paths.

4.4.4 Benefits of Route Guidance with Some Guided Probes Routed Into Delay

This case examines the effect of allowing a percentage of the guided probes to experience the delay caused by the incident This set of guided vehicles could represent a population of guided vehicles not complying with the TMC information. Alternatively, it could be considered to be deliberately sent into the &lay to gather information.

The setup for this case is almost the same as the previous experiment. As before, 5% of the total traffic volume is considered to be guided probes. However, one tenth of the probe population (0.5% of the total vehicle population) is routed to the original preferred routes instead of alternatives (i.e., they use the same routing as background vehicles). These probes provide travel time updates for those links not normally traversed by the guided probe vehicles under incident conditions.

Figure 4-13 displays the results of this case. Guided vehicles do indeed return to the preferred path earlier in the simulation once updated travel information is received. However, this does not occur until a probe traverses the preferred path. The total savings in trip time for all guided vehicles in the network is reduced because of two inefficiencies. First, while most guided probe vehicles divert and have lower trip times, the few guided vehicles that are sacrificed to the congested links contribute to an overall increase in the average trip time of guided vehicles. Second, since the number of probe vehicles traversing congested links is small, the probability of a probe happening to traverse the link in question is low, and more time passes before such a probe transmits the information that the congestion has dissipated. During this time guided vehicles continue to take alternate paths that have higher trip times although the preferred route would have been shorter.

In this case, 682 guided probe vehicles are routed to alternate routes and 74 guided probes are routed onto the preferred path. The guided probe population experiences an average of 3.4 hours (18.5 seconds per vehicle) less delay than the background traffic. However, there are 5.1 hours of more &lay than in the full surveillance case because of the percentage of guided vehicles traversing the higher trip time preferred route.

The results from this experiment indicate that it is necessary to have some form of surveillance on links not taken by probe vehicles. Without information from these links, guided vehicles experience increased delay by unnecessarily taking longer alternate paths. As an alternative to relying on guided probes that ignore the guidance or to sending some guided vehicles deliberately into a congested area, the TMC could be notified by emergency vehicles or police when an incident has been cleared, and could then assume that travel times on the affected links return to normal following typical patterns of queue dissipation.

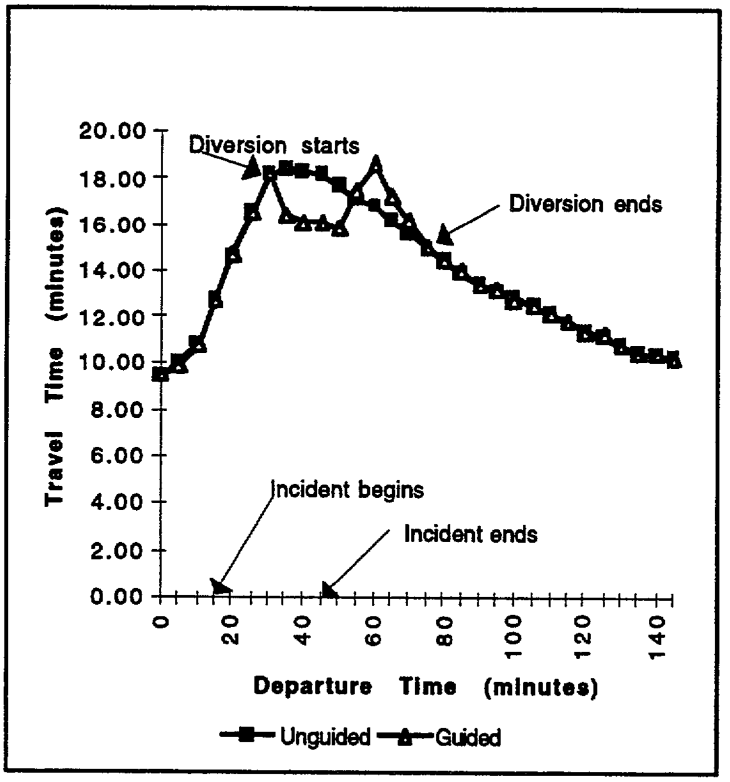

Figure 4-13. Average Travel Time as a Function of Departure Time Northbound I-295, 5% Guided Surveillance, 0.5 % Probes Taking Preferred Route

4.5 Experiment 4: Reducing Link Reporting Opportunities

The purpose of this experiment is to study the effect of limiting the opportunity for probe vehicles to report their travel times to the TMC, or, equivalently, reducing the number of links with detectors. The initial hypothesis was that as information becomes available from a decreasing number of links, the benefits to guided vehicles will diminish.

4.5.1 Experiment Description

As explained in section 4.1.2, the link travel time table in INTEGRATION is updated as an exponentially smoothed average. Link travel times are normally updated when a probe vehicle either completes an exit of the link or if it requires more time then the current smoothed average to traverse the link. This experiment explores five variations to the base case, each reducing the number of opportunities for link travel times to be reported.

Case 1. The ability to report travel times while on the link if travel times are greater than the current average (called "intermediate reporting") was removed. Travel times are only updated when probe vehicles exit links.

Case 2. Link travel times are only updated when a probe vehicle exits a freeway link. The travel times of arterial links used for route calculations remain at expected levels.

Case 3. Link travel times are only updated for every second freeway link when exited by a probe vehicle. The travel times for all remaining links remain at expected levels.

Case 4. Link travel times are only updated for every third freeway link when exited by a probe vehicle. The travel times for all remaining links remain at expected levels.

Case 5. Lii travel times are only updated for the link with an incident on it when exited by a probe vehicle. The travel times for all remaining links remain at expected levels. This case is called exception reporting.

The network is assumed to have no detectors. In all cases the travel time for northbound guided vehicles is compared to the travel time for northbound unguided vehicles.

Probe vehicles are modeled as unguided and are generated at a uniform percentage of the traffic demand from each origin in the network. These vehicles comprise of one percent of the total vehicle population. Five percent guided vehicles are produced only for trips with both origin and destination on I-295, New Jersey Turnpike, or Rings Highway. Guided vehicles do not transmit any information about travel times to the TMC. Guided vehicles receive updated link travel times every minute.

For this experiment, as in experiment 1, the incident is located on northbound I-295 at the State Route 561 interchange. The incident has a duration of 30 minutes, beginning at simulation time 25 minutes and ending at time 55 minutes, blocking 33% of the roadway (one lane of I-295).

4.5.2 Effect of Reducing Reporting Opportunity

The results of these cases are presented in table 4-5 and figure 4-14. For the base case, with the probes reporting trip times on all links, guided vehicles are able to reduce delay by 1.29 minutes per vehicle. This results in 79.2 hours of delay saved by the 3,684 guided vehicles sampled. When probes are only permitted to report travel times upon an exit of a link, guided vehicles capture almost 100% of the total benefit possible. The vehicles are able to capture a high percentage of the benefit because of the incident configuration. Since the incident only blocks one lane of I-295, probes are able to complete link exits and report increased travel times for these links. If the incident did not permit exits to occur (i.e., a complete freeway shutdown) no current link travel times would be available for these links. Under these conditions guided vehicles do not capture this high percentage of benefit.

Table 4-5. Savings in Trip Time for Northbound Corridor Traffic Given a Reduction in Probe Reporting Opportunity

Reporting Conditions	Unguided Trip Time (minutes)	Guided Trip Time (minutes)	Average Savings (minutes)
Full Reporting Capability (base case)	14.15	12.86	1.29
Report Only at Link Exits	14.15	12.87	1.28
Report at Exit of Freeways Links only	14.16	12.84	1.32
Report at Exit of every 2nd Freeway Link	14.31	13.44	0.87
Report at Exit of every 3rd Freeway Link	14.33	13.50	0.83
Exception reporting (link with incident)	14.21	12.96	1.25

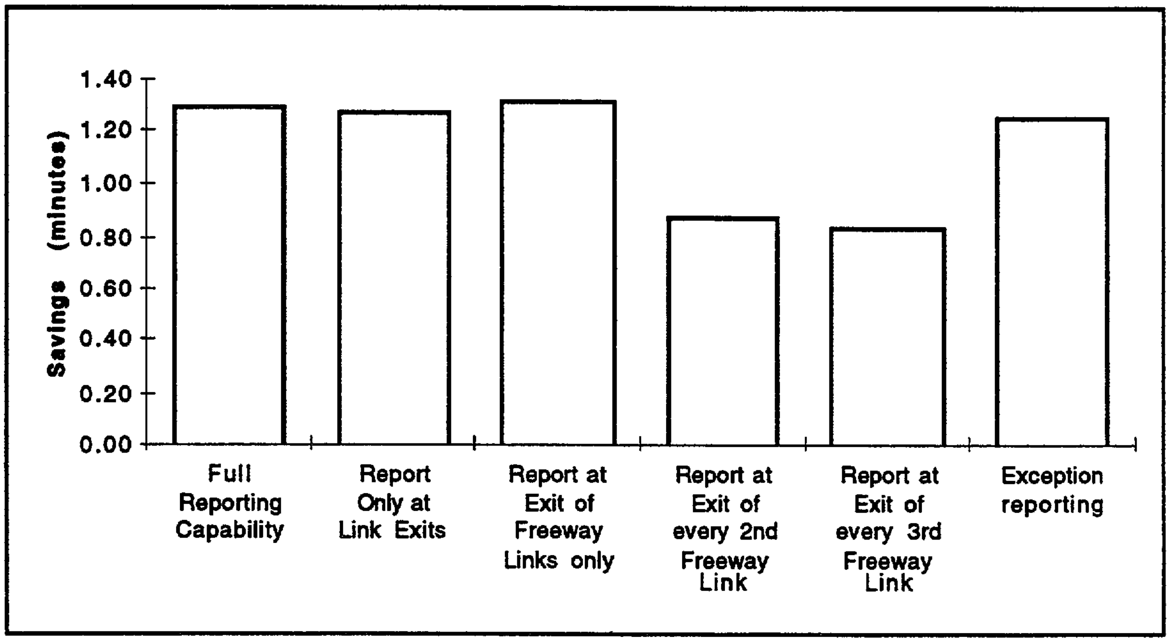

Figure 4-14. Savings in Trip Time for Guided Vehicles on Northbound Corridor, Given Reduction in Probe Reporting Capability

When probes are only permitted to transmit data concerning every second freeway link traversed, guided vehicles are able to capture 67.4% (0.87 minutes per vehicle) of the possible time savings, and when probes are only permitted to transmit data concerning every third freeway link traversed, this figure drops to 64.3%. However, if probes use exception reporting, where travel times are reported for the link with the incident, guided vehicles are able to achieve nearly all the available savings (97%) or 1.25 minutes per vehicle.

These results conform to expectations. As long as the incident-caused delay on a link is reported by probes, guided vehicles are routed along alternate routes. If the delay occurs on a link that is not reported, however, guided vehicles will continue to be routed onto the congested link. Only when congestion spills back onto a link that is reported does the information become known to the system.

4.6 Experiment 5: Effect of Incident Location

If probe vehicles report upon exiting every second and third freeway link, as modeled in the previous experiment, it is possible that they will not be able to report travel times for the link containing the incident. In that experiment, the incident is located on a link with no reporting capability' for probe vehicles. Under those conditions, much of the delay is not reported to the TMC and guided vehicles experience a reduction in benefit

4.6.1 Experiment Design

In Experiment 5, an incident is placed at different locations to study the effect of link reporting capability, queue formation, and opportunities for diversion. Each incident is of the same magnitude and duration as the incident used for Experiment 4. An alternate approach with the same results would have been to leave the incident in one place and to change the position of the detectors.

Northbound guided vehicles are monitored to determine the percent of time savings they are able to capture for three cases. The cases are defined by the times at which probes report link travel time: (a) at every link exit (the base case), (b) at the exit of every third freeway link, and (c) only at the exit from the incident link (exception reporting).

4.6.2 Effect of Incident Location

Tables 4-6a through 4-6c present the results of placing the incident in various locations. Table 4-6a (the base case) shows the maximum amount of time that can be saved by guided vehicles with the 5% probe population reporting on every link. Table 4-6b shows the time saved by guided vehicles when probes report on every third freeway link, and table 4-6c show the time saved by guided vehicles when probes report only on the link with the incident. Figure 4-15 illustrates the percent of possible time savings for the alternate cases compared to the base case.

The incident located on northbound I-295 at the US 561 interchange is not on a link that is reported in Case b. In that case, guided vehicles are not routed around the incident until congestion spilled back onto a link that was reported, so many guided vehicles lose time traveling on the congested link. In Case c, guided vehicles quickly learn of the incident and are routed around it.

The incident on I-295 at US 30 happens to be on a link that is reported in Case b, so the results across the three cases arc identical. The incident on I-295 between NJ 70 and NJ 73 is similar to the first incident location, where Case b shows significant degradation in travel time and Case c shows an improvement over Case b. The incident on the NJ Turnpike does not create enough delay to route guided vehicles onto alternate paths since there is excess capacity on the remaining lanes. In this case guided vehicles receive little benefit regardless of probe reporting capability.

The results indicate that the amount of time savings guided vehicles experience is a function of the incident location with respect to the placement of reporting opportunity. More than 80% of the potential benefit can be captured if the incident exists on a link that is reported, either because it happens to be part of the report-capable subset or because the reporting implementation permits probes to report longer-than-expected travel times.

Table 4-6a. Savings in Trip Times for Varying Incidents Northbound Corridor Traffic - Probes Report Every Link

	Normal reporting conditions		
Incident Location	Unguided Trip Time (minutes)	Guided Trip Time (minutes)	Savings (minutes)
Northbound I-295 @ RT 561	14.16	12.86	1 30
Northbound I-295 @ US 30	13.62	12.77	0.85
I-295 Between NJ 70 & NJ 73	13.10	12.44	0.66
Northbound NJ Turnpike @ EXIT 4	12.33	12.33	0.00

Table 4-6b. Savings in Trip Times for Varying Incidents Northbound Corridor Traffic - Probes Report Every 3rd Link

	Probes report upon exit of every 3rd link			
Incident Location	Unguided Trip Time (minutes)	Guided Trip Time (minutes)	Savings (minutes)	Percent savings captured
Northbound I-295 @ RT 561	14.34	13.50	0.84	64 62%
Northbound I-295 @ US 30	13.66	12.81	0.85	100 00%
I-295 Between NJ 70 & NJ 73	13.25	12.78	0.47	71 21%
Northbound NJ Turnpike @ EXIT 4	12.35	12.37	-0.02	0.00%

Table 4-6c. Savings in Trip Times for Varying Incidents Northbound Corridor Traffic - Probes Report on Incident Link

	Probes report only upon exit of the incident link			
Incident Location	Unguided Trip Time (minutes)	Guided Trip Time (minutes)	Savings (minutes)	Percent savings captured
Northbound I-295 @ RT. 561	14.21	12.96	1.25	96.15%
Northbound I-295 @ US 30	13.66	12.81	0.85	100.00%
I-295 Between NJ 70 & NJ 73	13.14	12.59	0.55	83.33%
Northbound NJ Turnpike @ EXIT 4	12.31	12.30	0.01	0.00%

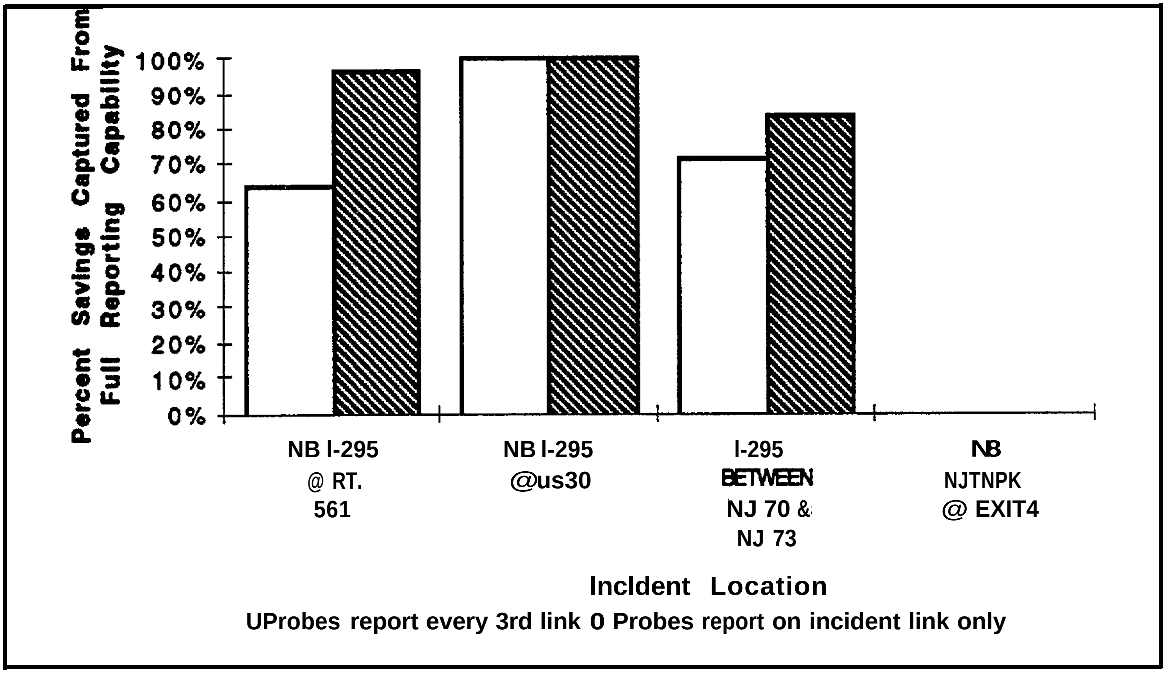

Figure 4-15. Percent Savings Captured for Northbound Guided Vehicles Varying Incident Locations

4.7 Experiment 6: Sensitivity to Tolerance Levels

The final experiment examines the effect of probes reporting link travel times only if the link travel time is at least 20% higher than the expected time. As a consequence of the reduced information input, the route guidance algorithm must use expected (historic) link travel times except for those links experiencing at least a 20% increase in travel time.

There are at least two ways this restriction could be implemented. One is for each probe vehicle to carry a database of expected times and to check the database to determine whether to transmit a link travel time to the TMC. Another is for the TMC to collect all reported travel times, but to transmit to guided vehicles only those times that exceed expected values. Either implementation could place a far smaller demand on the supporting communication system than scenarios previously described.

4.7.1 Experiment Design

In this experiment, guided vehicles receive updated information every ten minutes of simulation time and do not transmit any data to the TMC. The incident blocks one lane of I-295 at the Route 561 interchange for a duration of 30 minutes beginning at time 25 minutes and ending at time 55 minutes.

The procedure for modeling this case is more complex than the other experiments. No probes or stationary link detectors exist in this case. Instead, guided vehicles arc routed using the link travel times from a pm-calculated file, not real time information transmitted from the TMC.

The time-varying link travel time file was created by combining the results of two INTEGRATION output files from prior runs. The first file consisted of link travel times for the non-incident case and the second file consisted of link travel times for the incident case. The combined file uses the link travel time from the non-incident case for all links except those that experienced more than an increase of 20% in travel time in the incident case, in which the case the higher value is used. Thus the case represents guided vehicles not diverting to alternate routes until the projected time savings crosses a threshold.

4.7.2 Experiment Results

Table 4-7 and figure 4-16 indicate that there is little change in average travel times over all northbound vehicles. There is approximately 45 minutes more travel tune delay for the 2,533 northbound vehicles (1.1 seconds per vehicle) for the threshold level case than for the full surveillance case. However, if individual O-D pairs are examined, the effect on travel time of guided vehicles becomes more evident.

O-D pair 1-18 has an alternate route with a low cost of diversion from the preferred route. Guided vehicles on that O-D pair take the alternate route in the base case and save tune. The delay on several links along the preferred route is less than 20% of normal link travel time though, so the delay for those links is not reported to the TMC in the 20% tolerance case. Guided vehicles in that case stay on the original route, because they never get the information about the delay. Therefore their average trip time is higher for the second case. The situation is the same for O-D pair 2-6.

Table 4-7. Change in Guided Vehicle Travel Between Full Surveillance and a 20% Tolerance Level

	Guided Travel Time Full Surv. (seconds)	Guided Travel Time 20% tolerance (seconds)	Increased Delay (seconds/veh.)
All Northbound corridor trips	727.39	728.45	1.06
O-D = 1-18	871 12	930 41	59 29
O-D=2-6	816.69	830.06	1337
O-D = 2-3	864.99	854.08	-10.91

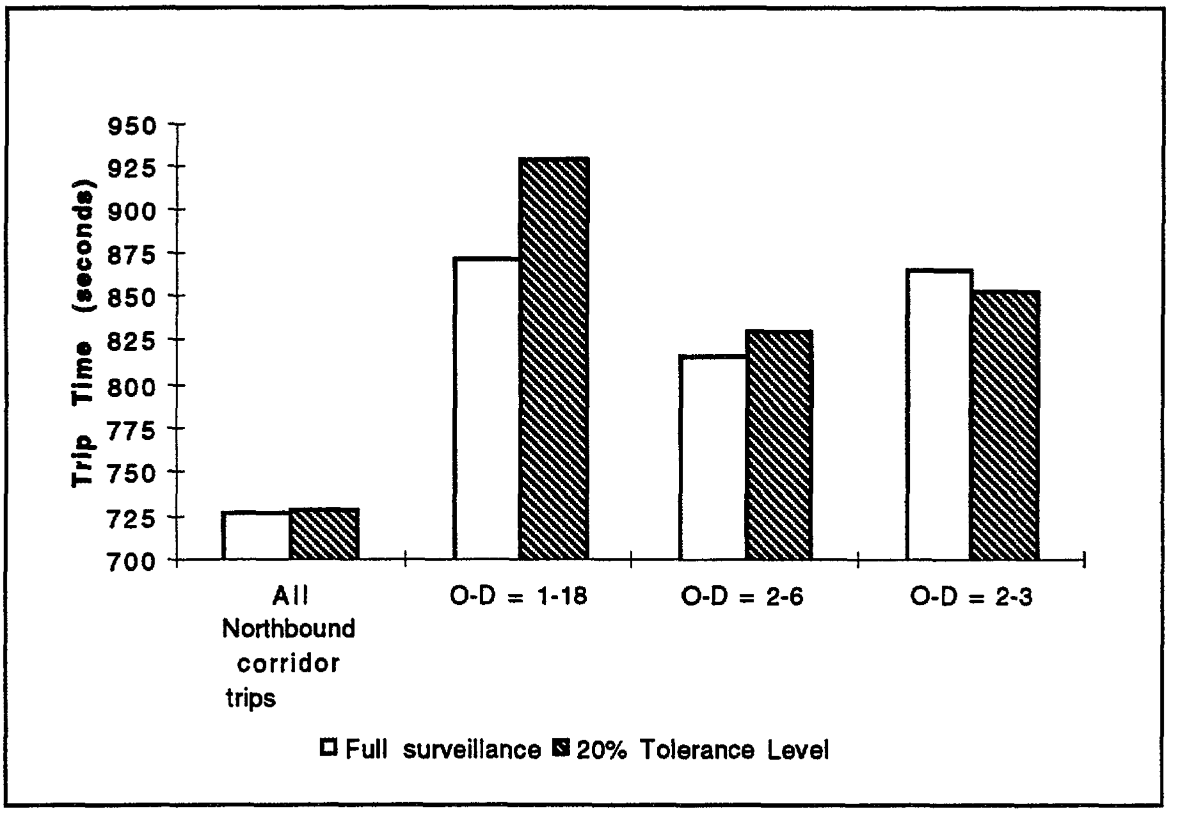

Figure 4-16. Change in Guided Vehicle Travel Times Between Full Surveillance and a 20% Tolerance Level

O-D pairs whose only alternate routes have a high cost of diversion have nearly the same results for the two cases. In the 20% Tolerance case, when the delay on the preferred route is low, those vehicles do not hear about it, but they would not have rerouted anyway. When the delay on the preferred route is high enough to cause rerouting, it is over the 20% level so the information is transmitted to the guided vehicles.

A few O-D pairs experience lower trip times in the 20% Tolerance case. In the case of O-D pair 2-3, the reason is that guided vehicles for that O-D pair take an alternate path, but other O-D pairs with different costs of diversion do not. There is less congestion on the alternate path so the travel times are less.

4.8 Summary of Results and Discussion

The major theme of this study is to examine the effects of limiting the amount of link travel time information collected by detectors or probes. A secondary theme is to examine the effects of changing the frequency with which updated information is transmitted to the TMC or to guided vehicles.

The study focuses on information collection on an inter-urban roadway network that contains a sub-population of vehicles with dynamic route guidance. These guided vehicles are provided with updated route guidance information periodically during the simulation run. The routes provided for equipped vehicles are calculated based on the most current estimates of link travel times throughout the network The simulation generates these link travel time estimates by sampling a set of vehicles traversing links in the network By adjusting parameters in the simulation control files, the percentage of vehicles that contribute to the generation of the link travel time estimates can be varied. The key measure of effectiveness for this study is the amount of time saved by guided vehicles compared to non-guided vehicles with the same origin and destination.

This section presents a summary of the results of each of the six experiments and discusses the implications of those results in the context of ITS deployment.

4.8.1 Summary of Findings, Experiment 1

In the case where there is no incident in the freeway network, there is little congestion and little benefit of route guidance. When there is a congestion-creating incident, guided vehicles routed around the congestion achieve shorter trip times.

In an incident case, guided vehicles receive the maximum amount of benefit (savings compared to non-guided vehicles) if the network is under full surveillance. Full surveillance requires either detectors on all links or probe capability for every vehicle. However, a network surveillance system based on 20 to 25 percent uniformly distributed probe vehicles provides enough information for guided vehicles to obtain virtually all of the benefit of a fully detectorized network More than 80% of the maximum benefit of a route guidance user service can be provided by introducing five to ten percent probe vehicles. More than half of the benefit is achieved with one percent of the vehicles uniformly distributed as probes.

The percentage of probes required to determine the best route for a particular O-D pair is a function of the difference in travel time between preferred and alternate diversion paths available in the network. If the cost of diversion is high, more information is required to route vehicles accurately.

4.8.2 Summary of Findings, Experiment 2

If the percentage of probes on the network is small, guided vehicles are able to capture a greater percentage of the maximum benefit if the frequency of network condition reports is increased. If guided vehicles receive network condition reports every one minute, approximately 2% to 5% unguided vehicle probes are required to obtain more than 95% of the maximum possible travel time savings for this network.

4.8.3 Summary of Findings, Experiment 3

If a network surveillance system relies only on guided vehicles, it may not recognize when link travel times return to normal after incident-caused congestion has dissipated. Guided vehicles under these conditions may be unable to obtain a significant percentage of the benefit possible, and in fact may experience additional delay beyond that caused by the incident itself.

For near term deployment with only guided probes in a network, there is a potential risk of not detecting the full impact of non-recurrent delay. This may be alleviated if a small proportion of the guided probes do not comply to routing strategies and choose to remain on paths with the non-recurrent delay, or by guiding probes into the congested area. In these cases, enough information about the dissipation of delay can be collected to provide the benefit of accurate routing for the remaining guided vehicles. However, this results in longer travel times for these probes.

4.8.4 Summary of Findings, Experiment 4

As reporting opportunity decreases, guided vehicles do not capture all the time savings possible under full reporting. Since the system does not know about congestion on links that are not reported, guided vehicles may be routed onto those congested links. Information about delay occurring on the network is only required from those links on which the delay exists. If probes are capable of reporting this delay, guided vehicles are able to capture most of the potential benefit. One way of doing so is probe vehicles to use exception reporting, reporting only for links on which they experience unexpected delay. With that information, guided vehicles are able to capture most of the potential benefit.

4.8.5 Summary of Findings, Experiment 5

Experiment 5 confirmed the results of Experiment 4 for several different incident locations. Incidents located on links that were reported were avoided by routed guided vehicles, while incidents located on links that were not reported caused delay for all vehicles including guided vehicles. Exception reporting is one way to ensure that atypically congested links are reported to the system.

4.8.6 Summary of Findings, Experiment 6

Using a tolerance level is one way of implementing exception reporting, reducing data collection and communications cost. Exception reporting requires higher in-vehicle functionality, however. When link travel times are reported only when they exceed normal times by more than 20%, guided vehicles are able to realize almost 100% of the benefit obtainable under full surveillance. However, the benefit varies by O-D pair, primarily as a function of the cost of diversion.

4.8.7 Discussion

Route guided vehicles can benefit from relatively limited probe-based surveillance systems. For an inter-urban corridor it is unlikely that a state or regional highway agency would want to install and maintain detectors on every link. Study results indicate that it may be significantly more cost-effective to obtain this information from guided or unguided vehicle probes than by adding these devices. The public or private sector may find it advantageous to subsidize travelers to be probes to provide a more uniform distribution of these vehicles.

This study has also shown that if probes are equipped for exception reporting only, most of the potential benefit to guided vehicles can be obtained. Exception reporting can reduce the loads on the communication network connecting the probe vehicle to the TMC. However, it also requires higher in-vehicle functionality. The vehicle must know the current travel time average. A higher level of probe functionality could be used by a guided probe population in the network.

An important assumption made throughout this study is the uniform generation of probe vehicles across the network. Under this assumption relatively few vehicles are required to realize the majority of the benefits of route guidance. This assumption may be valid for an Inter-urban scenario. However, this assumption may not always be valid in other implementations. For example, urban traffic might contain a probe population in only subsections of the network. This situation could arise from socioeconomic factors, or from an early deployment of probe capability to fleet vehicles which operate primarily in areas such as business districts, airports or higher income neighborhoods. The concentration of probes in certain areas of the city would cause poor estimates of link travel time on other portions of the network.

A related assumption concerns the role of guided vehicles acting as probes. It is likely that guided vehicles will act as network probes in near-term deployments. In fact, guided vehicles may represent the entire probe population. That case would pose a problem for a probe-based surveillance system, since congestion information is only collected for segments of the roadway network where guided probes vehicles have traveled. One way of collecting information about congested areas is to direct guided vehicles onto routes affected by incident. This policy could cause a serious reduction in compliance and goodwill, however, if drivers felt they were being steered onto longer paths. Unless a sufficient number of drivers ignored the guidance on their own, the TMC may have to use other forms of surveillance to obtain data on congested links once diversion has started.

The risk involved in supporting a route guidance user service with low numbers of probes in portions of the network could be reduced by installing a system of link detectors in those areas to be used in combination with a developing guided or unguided probe population. In this case not every link must have a detector. Guided vehicles traversing these areas would find an increase in benefit as the probe population develops. In these portions of the network, link detectors providing information could also be used for other forms of ATIS, such as providing vehicle counts and speeds for adaptive signal controls in urban areas. Thus, even if in near term deployment the number of guided vehicles in these areas is low, traffic will receive a visible benefit from the surveillance of the detectors.

Section 5

Pre-Trip Mode Shift Benefits Assessment

This study examines the impact of real-time information on the traveler pre-trip planning process. Specifically, the purpose of the study is to identify conditions for, and quantify ranges of, the potential benefit of real-time mode shift, a key aspect of a trip planning user service. This benefit is then compared to other congestion reduction strategies related either to traveler information user services or short-term increases in roadway capacity.

5.1 Introduction

This study examines the effect of one aspect of a potential trip planning user service: mode choice. Although a sophisticated trip planning service might have other attributes, this study specifically addresses the benefit of the mode choice aspects of real-time pre-trip planning activity. The study was originally documented by Wunderlich (1995b).

A trip planning user service delivers information about the predicted state of the transportation network (including both roadway and transit) to the traveler's home before the trip begins. For transit, this information may take the form of transit schedules, fares, and predicted travel times. For the auto mode, the user service might provide an estimated highway travel time by origin, destination, and time-of-departure from the home. The user service might be supported either by home computer terminal access or through a specialized cable television service. Based on the information, the traveler might make a decision to change destinations, modes, time of departure, or even possibly to cancel the trip. On an intuitive level, the capability to adapt individual traveler nip choice should result in a more balanced overall transportation network load than the case when no information is provided to the traveler. This more balanced network load results in a reduction in trip delay, both to the travelers using the trip planning service and to the system as a whole.

This section presents the Smart-Shift framework for the evaluation of the mode choice aspects of a trip planning user service. This framework is described in section 5.2. Section 5.3 describes the test network employed in the study, including a discussion overall transportation demand Section 5.4 examines the convergence of the iterative Smart-Shift method and establishes properties of an equilibrium solution. The convergent solution is critical to the study since it establishes a baseline set of for average travel times on each mode and an expected steady-state mode split in the test network Section 5.5 presents a range of results employing the Smart-Shift method in the evaluation of real-time mode shift under a range of network conditions, or scenarios. These scenarios ("rainstorm", "construction", and "incident") describe peak travel periods in which roadway network capacity has been reduced from the baseline value. Section 5.6 summarizes the key fmdings and implications of the study.

5.1.1 Approach

This study assumes every traveler may choose from two modes: "on-roadway" and "off-roadway." On-roadway corresponds to a traveler choosing to use a car for the trip. On-roadway trip duration can be computed from traffic simulation output, and may vary significantly as a function of time during the rush period. Off-roadway trip time, representing generalized rail transit or other alternative mode choice, is computed for each origin and destination pair in the demand pattern. Off-roadway trip time is assumed to be constant throughout the peak period. Further, off-roadway trip time is considered inelastic with respect to demand Smart-Shift allows for time-variant mode choice across the network. For example, fewer travelers might choose an off-roadway trip very early in the rush period since travel demand is light at that time.

Mitretek has developed a new analytical framework for this study, dubbed Smart-Shift. The general approach of the study differs from the other studies in this report in that additional models in conjunction with traffic simulation are employed as evaluation tools. Traffic simulation alone cannot be employed to evaluate benefits of mode choice or trip planning. A mode choice must also be included that can model the impact of a trip planning user service on traveler behavior and travel demand patterns.

In this study, real-time mode choice is examined as a part of a trip planning user service. Altered demand patterns, corresponding to the aggregated impact of the provision of traveler information, can then be provided as input to a traffic simulation, in this case the INTEGRATION traffic simulation. The effect of all of these individual mode shifts on overall network congestion can then be quantified through the use of the traffic simulation. Thus, the approach of this model is to employ INTEGRATION and a mode shift model in tandem (Smart-Shift) to evaluate the mode shift impacts of a trip planning user service.

A key aspect of the modeling approach in this study is the distinction between knowledge of long-term average (base case) conditions and knowledge of reliably predicted, pre-trip conditions. In a network with no trip planning user service, commuters are assumed to make mode choices based on their own experience with network congestion and mode preference. To establish base case conditions, the traffic simulation and the mode choice model are used iteratively until equilibrium is reached. Travelers with a trip planning service have access to a current prediction of peak period roadway delay and may choose to shift modes (either from on-roadway to off-roadway or vice versa). Travelers without the trip planning service follow the same mode split as in the base case.

Base case congestion conditions are established for average trip demand under a non-incident case, i.e., expected values for both travel demand and network capacity. For an individual day, however, demand or capacity may be higher or lower than expected. Capacity reductions may be characterized in two ways. System capacity may be reduced locally (as in the case of an incident) or globally (as in the case of rain or other precipitation). From the perspective of the trip planning service provider, system capacity reductions may be predictable (as in the case of lane closure for construction) or unpredictable (accidents). Travelers with the trip planning option can expect to gain highest benefits under network conditions that do not conform directly with the expected long-term average conditions. Under base case conditions, the trip planning user service would not provide any additional benefit, since long-term average roadway congestion conditions are assumed known by all travelers.

The framework uses both traffic simulation and the mode shift model to model the base case and non-recurrent cases. Since a trip-based traffic simulation is employed (INTEGRATION), a range of ATMS and ATIS user services may be modeled in isolation or in conjunction with real-time mode choice.

5.2 Smart-Shift Mode Choice/Assignment Method

This section provides detail on the two primary components of the Smart-Shift evaluation framework: the mode choice model and the traffic simulation. Several aspects of the mode choice model employed in Smart-Shift extend the analytic approach of traditional long-term mode choice models. The interaction between the two components is described and the nature of an equilibrium solution is discussed.

5.2.1 Overview of the Iterative Method

Data processing programs within Smart-Shift control the interaction between the two primary components (mode choice model and traffic simulation). The iterative process involves the exchange of data between the mode choice model and the traffic simulation. The traffic simulation reports roadway travel times for all vehicles in the network. These data are then aggregated to provide an average travel time for each origin-destination pair and time of departure $\tau_{o,d}(t)$. These data are the key input to the mode choice model, which compares the roadway travel time to a table of constant off-roadway travel times. Based on the ratio of on-roadway to off-roadway travel times, the mode choice model generates a demand pattern based on a new set of mode splits for input to the traffic simulation.

This new pattern may contain fewer or greater vehicles over the course of the modeled time period for each origin-destination pair and time of departure, $\Delta_{o,d}(t)$. Figure 5-1 illustrates the iterative aspect of the Smart-Shift framework. If, in two consecutive iterations of Smart-Shift, the time-variant mode splits are sufficiently close, Smart-Shift is considered to be at equilibrium. Section 5.2.4 discusses the properties of equilibrated solutions in the Smart-Shift framework.

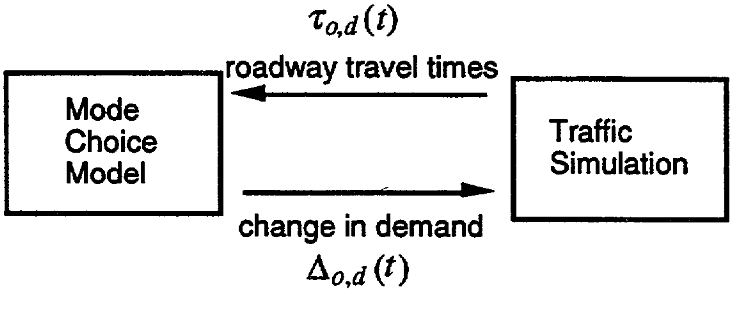

Figure 5-1. Iterative Approach in the Smart-Shift Evaluation Framework

5.2.2 Mode Choice Model

Over the last 30 years a large body of research and application experience has developed regarding the mode choice decision. These efforts deal with expected or perceived characteristics of different modes of travel between an origin and destination. However, these past efforts assume steady state conditions over the particular time period under study -- typically the peak hour, peak period, or average weekday. Network planning models have been developed to represent the different modes within the transportation system for a particular time period. Static minimum impedances combining both time and cost are then estimated using the networks for each mode between each origin and destination. The impedances are used as inputs to a mode choice model to determine the probability that a mode will be selected given the differences between modes and the traveler preferences. A common mode choice model form is the Logit formulation (Horowitz et al, 1986):

$$m = \frac{e^{(-bI_t)}}{e^{(-bI_t)} + e^{(-bI_a)}} \qquad \textit{(Eq. 5-1)}$$

where m = the fraction of trips choosing transit
I_t = the impedance (cost plus travel time) for transit mode
I_a = the impedance (cost plus travel time) for auto mode
b = a constant

Another simpler formulation based on the ratio of impedences is provided in the NCHRP 187 Quick Response guide (Transportation Research Board 1978):

$$m = \frac{1}{1 + \left(I_t / I_a \right)^b} \qquad \text{(Eq. 5-2)}$$

where m, I_a, I_t are defined as in Eq. 5-1, and
b = the impedance exponent, typically having a value between 2.0 and 3.0.

The Quick Response formulation was chosen for modification and extension for the Smart Shift framework. First, it is computationally efficient and does not require exponentiation of the utility functions. This made it a good model formulation for use during Smart-Shift development. A complex mode choice model stucture would have created undue complexities and potential errors. Second, the Quick Response formulation bases mode shift calculations on the ratio of impedances and not the absolute differences in impedance as in the Logit formulation. For the decisions and the range of values an impedance ratio was considered a more appropriate indicator of mode shift

Neither the Quick Response nor the Logit fommlations may be applied directly within Smart-Shift. First, the formulations are for static or steady-state conditions and cannot consider time-of-departure effects. Second, the formulations assume that all travelers have access to either mode. At the extreme points of the model, where transit becomes either very attractive or very unattractive, travelers will choose one mode completely to the exclusion of the other mode. In the real world, it is unlikely that the population as a whole will have such flexibility. Some travelers may not have a vehicle and are transit-captive. Likewise, other travelers may be unwilling or unable to use transit. A recent study of suburban commuters in Nassau County, NY found that more than 50% of respondents are highly averse to the use of public transportation for commuting (Meagher, 1995).

Because of these limitations, Mitretek extended the model in two important ways. First, the model considers the ratio of roadway trip times to off-roadway trip times on a time-variant basis. Second, the Quick Response curve has been constrained at its extreme points to allow for a subpopulation of transit-captive travelers (5%) and a subpopulation of travelers who will not consider a transit-based commute (30%). The remaining group of commuters are willing to consider alternative modes for their trips. If the non-travel time elements (cost, comfort, etc.) of the static impedance model are considered constant, the impedance relationship may be replaced with a travel time relationship. This assumption is not limiting for this study since changes to parking, transit costs or other factors are not considered.

A time-variant constrained mode choice model can then be defined as:

$$m_{o,d}(t) = \breve{m} + (\hat{m} - \breve{m})\left[\frac{(r_{o,d}(t))^b}{1+(r_{o,d}(t))^b}\right] \qquad \text{(Eq. 5-3)}$$

where $m_{o,d}(t) =$ fraction of trips choosing transit from origin o to destination d at time t
$\breve{m} =$ fraction of trips that must choose transit (off-roadway mode)
$\hat{m} =$ 1 - the fraction of trips that never choose transit (off-roadway mode)
$b =$ the impedance exponent (value 3.0); and
$r_{o,d}(t) = \dfrac{\tau^A_{o,d}(t)}{\tau^T_{o,d}}$, the ratio of expected roadway to off-roadway travel time.

Constrained and unconstrained mode choice models are graphically illustrated in figure 5-2.

Values for $\breve{m}$ and $\hat{m}$ have been selected to be consistent with empirical data from a study of Seattle commuters (Barfield et al., 1991). Thirty percent of respondents said they would never alter their commuting behavior based on pre-trip planning information. The remaining group (70%) indicated they might change some aspects of their commute based on pre-trip information. Other figures from the Barfield study are used to provide more optimistic or pessimistic impacts for mode shift based on trip planning information and are detailed in section 5.5.2. One impact of the selection of these parameters is that, when travel times are equivalent for roadway and off-roadway travel, roadway travel is slightly preferred. This effect can be seen in figure 5-2 where the ratio of trip times is equal to 1. In addition, the endpoint constraints on the Quick Response model restricts the subpopulation of commuters who are sensitive to mode travel time information. The result is that the constrained model is more conservative than the Quick Response model in determining the impact of a real-time mode choice.

5.2.3 Traffic Simulation: INTEGRATION

Any simulation model that can calculate individual trip statistics by origin and destination can be used in the framework. INTEGRATION was selected because of its capability to model a range of ATIS and ATMS user services at the desired regional or sub-regional level. INTEGRATION simulation output is used in conjunction with the Cohort15 data post-processor developed at Mitretek to compute roadway trip times for vehicles entering the network at various times during a simulated peak period. Each set of vehicles departing an origin within the same time period (called a cohort) is tracked throughout the simulation. The trip statistics for these vehicles are computed and an average is found for each origin-destination pair by time of departure. These values are then provided directly to the mode choice model.

A change in mode splits affects on-roadway travel time because the on-roadway system is sensitive to level of demand When travel demand is shifted to the off-roadway facility, congestion is reduced in the on-roadway network. Conversely, higher demand generates longer trip times in the on-roadway network because of higher congestion levels.

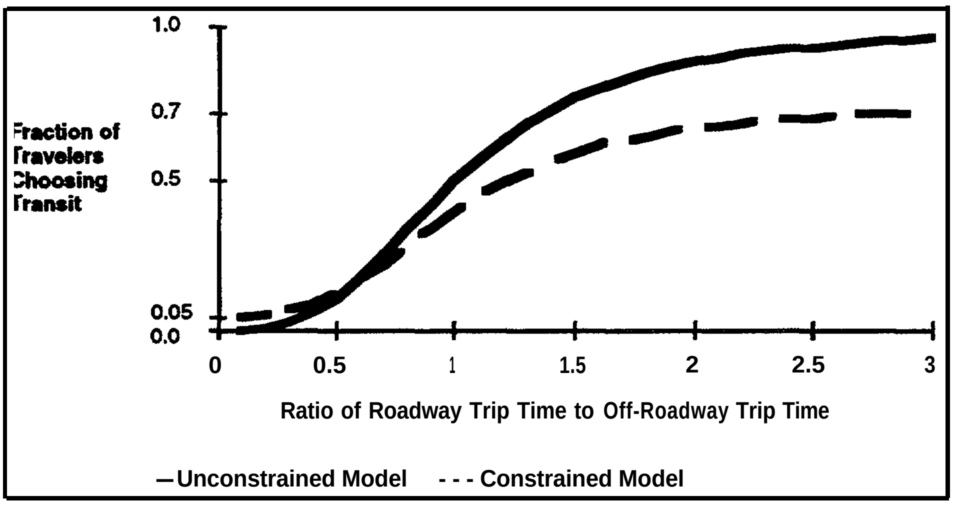

Figure 5-2. Constrained and Unconstrained Mode Choice Models

5.2.4 Properties of Smart-Shift Equilibration

If the Smart-Shift framework is allowed to iterate from some initial point, it may eventually converge to a consistent set of on-roadway trip times and corresponding mode split. If the simulation were replaced with a continuous function, mapping mode splits into resultant roadway trip times, then it would likely be possible to prove convergence of such a method under some non-restrictive conditions. However, such a function is likely to be too crude a tool to estimate impacts of ITS, particularly in comparison with a detailed traffic simulation like INTEGRATION.

Since INTEGRATION is a component of Smart-Shift, it is very difficult to prove that the procedure is absolutely convergent. The fractional shifts generated by the mode choice model are converted into discrete vehicle counts. This characteristic complicates any claim that such an interactive framework represents an absolutely convergent method. Smart-Shift may demonstrate relative convergence, however, Wunderlich (1994) demonstrated that a two-module iterative procedure employing a route choice model and a traffic simulation for predictive route guidance can be convergent under conditions relating to the accuracy of information provided. Smart-Shift, a theoretically similar approach, is likely to have similar convergent properties. The study's expectation is that the system will equilibrate within a certain range of values.

Smart-Shift is considered a priori to converge when no more than 1% of the population of travelers associated with any time-variant origin-destination pair in the demand pattern change mode in two consecutive iterations. A convergent solution in Smart-Shift can be interpreted as a condition analogous to a long-term average wherein travelers possess complete, accurate travel time estimates for all trips in the network in all modes. Therefore, at equilibrium, travel demand is distributed across both modes based on the preference curve established in the mode choice model. Travelers are assumed to have complete information on long-term average travel times for their trip by mode and time of departure.

5.3 Test Network Description

Although the Smart-Shift approach has been constructed with the flexibility to handle large networks like the Urbansville scenario case study network, initial analyses applied the framework against a small test network (figure 5-3). The test network provides a proof-of-concept for the approach.

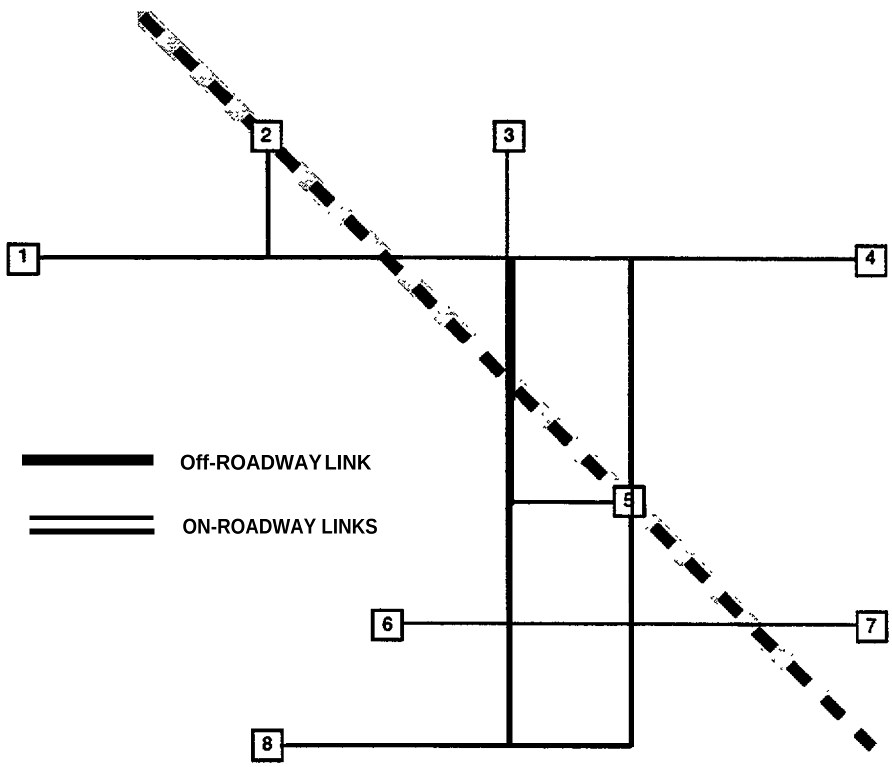

Figure 5-3. Test Transportation Network

5.3.1 Network On-Roadway Topology and Characteristics

The test network is a two-mode transportation network. The roadway facilities in the test network compose a 36-link, 16-node network with four origins and four destinations. The average trip length in the network is almost 8 km (5 miles). The longest trip in the network is 12 km (7.5 miles) and the shortest trip is 4 km (2.5 miles).

The roadway facilities are multi-lane facilities of varying capacity. Capacity ranges from 1,600 to 2,200 vehicles per hour per lane. Facilities range from two- to five-lane widths. The recurrent bottleneck in the network occurs on the two parallel links leading from the group of four origins in the direction of destination node 5. The thicker link in the bottleneck area is a freeway link of 8,800 vehicles per hour (vph) capacity, while the parallel lower capacity link may carry a maximum of 3,200 vph. Therefore, total bottleneck capacity is 12,000 vph in the test network.

Travel times are determined on the roadway network through a run of INTEGRATION. Average peak period travel times and congestion conditions in the test network are detailed in section 5.4.3.

5.3.2 Network Off-Roadway Topology and Characteristics

An off-roadway facility also runs through the network, representing a fixed rail transit facility. "Off-roadway" and "transit" are used as interchangeable terms in this report with respect to the test network. The off-roadway facility runs through origin 2 and destination 5. Travel on the off-roadway network occurs either on the rail line or perpendicular to the rail line. A traveler on the rail line moves at a constant 80.5 kph (50 mph). Travelers gain access to the rail line by moving perpendicular to the line at a constant 16 kph (10 mph). This access may be a combination of modes such as walking, biking, or even a car trip which does not utilize the designated major on-roadway facilities. Access speed also includes wait time at the rail facility. Thus, the convenience of the off-roadway option is highly dependent on the location of a trip start and trip end. For a trip from origin 2 to destination 5, for example, transit is a highly competitive option. In comparison, a trip from origin 4 to destination 8 is likely to be heavily weighted towards the roadway option since the off-roadway facility poorly serves this origin-destination pair.

off-roadway travel times are calculated for each origin-destination pair. They are time-invariant and inelastic with respect to travel demand. Travelers are not allowed to use both the major roadway network and a rail trip together to complete a trip. Trips are completed either on or off the roadway network from start to finish. off-roadway travel times are tabulated in table 5- 1.

Table 5-l. Off-Roadway Trip Times in Test Network (minutes)

Origins	Destinations			
	5	6	7	8
1	11.67	19.08	15.90	24.40
2	3.18	10.60	7.42	15.90
3	7.42	14.85	11.67	20.15
4	10.60	19.08	14.83	24.38

5.3.3 Travel Demand Characteristics

Eight-thousand trips arc modeled in the network over a 60 minute study period. The study period is composed of three time periods, designated Early, Middle and Late. Each period is 10 minutes long, with trips entering the network until the 30 minute mark. In the last 30 minutes of the study period, demand drops and congestion dissipates while the vehicles that have entered the network in the Early, Middle and Late time periods complete their trips. There are sixteen origin-destination pairs linking the four origins with each of the four destinations. Total demand (all modes) for each origin-destination pair is 1,000 vehicles per hour. Thus, a sustained travel demand rate of 16,000 vph is introduced onto the test network. This level of demand exceeds the bottleneck capacity of the roadway system by 4,000 vph.

5.4 Convergence of Smart-Shift

This section describes the convergence of the Smart-Shift model in the test network. The convergent solution is described with respect to aggregate stability of solution as well as the stability of individual time-variant origin-destination mode splits. Expected time-variant roadway trip times are established, along with the mode split associated with the average day. The convergence of the Smart-Shift process is critical in the establishment of base case conditions. The evaluation of effectiveness for any delay mitigation strategy will be measured against conditions in the base case.

5.4.1 Convergence Criterion

As outlined in section 52.4, Smart-Shift is considered to converge when no more than 1% mode shift is registered for any origin-destination pair in the demand pattern in two consecutive iterations. This 1% shift is measured in relation to total traffic demand. This convergent solution is employed as the steady-state or average travel pattern. The mode shift for any time-variant origin-destination pair is designated $m_{o,d}(t)$.

An initial point for the Smart-Shift iterative method is obtained by using a demand pattern based on a 0% transit use assumption. This initial guess is then provided to the traffic simulation to begin the iterative process. An iteration counter is set to increment each time a new mode split was generated from the mode choice model. In the test network, Smart-Shift is convergent after 40 iterations.

After each iteration the average and maximum differential across the set of 48 time-variant origin-destination pairs (3 time periods x 16 origin-destination pairs) in the travel demand pattern are determined. The average differential over all $m_{o,d}(t)$ between iteration 9 and iteration 10 is less than 1%. The maximum differential comparing any $m_{o,d}(t)$ between iteration 9 and iteration 10 is 3%. The maximum differential of $m_{o,d}(t)$ values obtained at 39 iterations and those at 40 iterations is less than 1%.

However, when Smart-Shift is allowed to continue iterating, the solution does not continue to converge beyond the point established at iteration 40. This point appears to be the limit of the approach as defined in establishing conditions close to steady-state. Smart-Shift, as expected, is not an absolutely convergent method, but does eventually reach conditions close to steady-state.

5.4.2 Stability of Solution

When individual time-variant origin-destination mode splits are examined, Smart-Shift eventually reaches a point at which splits vary narrowly around a stable value. Figure 5-4 illustrates some typical time-variant origin-destination splits as well as the overall average mode split in the network. As expected, trips from origin 2 to destination 5, a route well-served by the off-roadway option, are predominantly off-roadway trips. However, a greater fraction of travelers choose to take transit in the later time periods after congestion has begun to build on the roadway network. In contrast, trips from origin 4 to destination 8, a route poorly served by the off-roadway option, remain at the minimum transit-captive population throughout the period. The network average mode shift is very stable from sixth iteration, remaining within 0.5% of the convergent value.

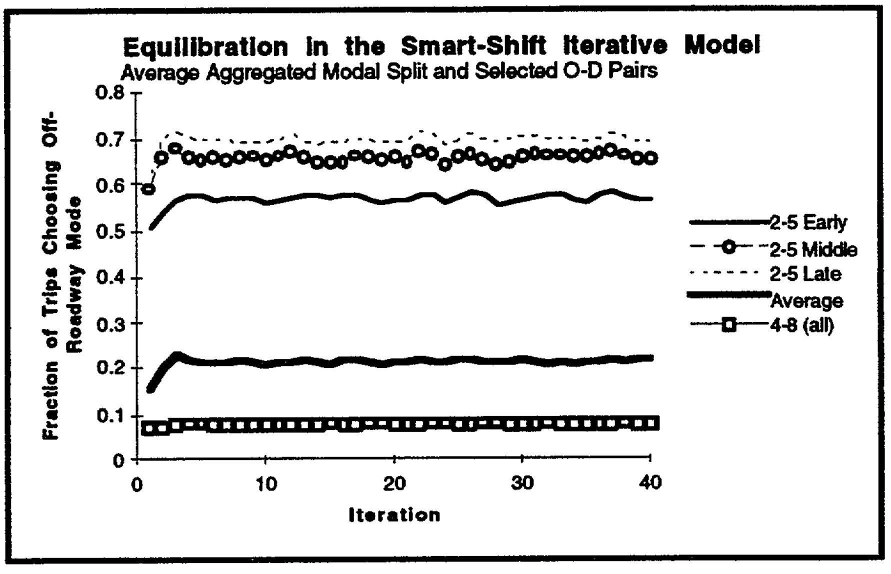

Figure 5-4. Selected Time-Variant Origin-Destination Mode Split Values

Not all time-variant mode splits are as stable as the values shown in figure 5-4. The splits shown are taken from flatter parts of the constrained Urban Transportation Planning System (UTPS) mode choice curve near its extreme points. These points are where mode choice is relatively clear, either for the on-roadway or off-roadway mode. Trips from origin 3 to destination 5, for example, have a different dynamic since the ratio of on-roadway to off-roadway trip times falls near 1.0. In this part of the constrained UTPS mode choice model there is a steeper reaction to marginal changes in trip time. Figure 5-5 illustrates the behavior of this origin-destination pair in the three time periods (Early, Middle, and Late).

Figure 5-5 also illustrates that there can be a dramatic difference in mode shift based on the time-of-departure for the traveler. Off-roadway ridership more than doubles from the early to the middle peak period. This reflects the sensitivity of the constrained UTPS curve for mode choice when travel times for both modes are relatively close to one another. These time-variant origin-destination pairs have higher variability than the convergence criterion allows, although for the 39th and 40th iteration, the criterion is met. Despite the presence of some time-variant origin-destination pairs with higher variability in the approximate steady state condition, the average network mode split remains almost constant. Maximum differential between mode splits is bounded by 3% beyond the 40 iterations mark. In other words, no individual time-variant origin-destination pair varies by more than 3% under long-term average conditions.

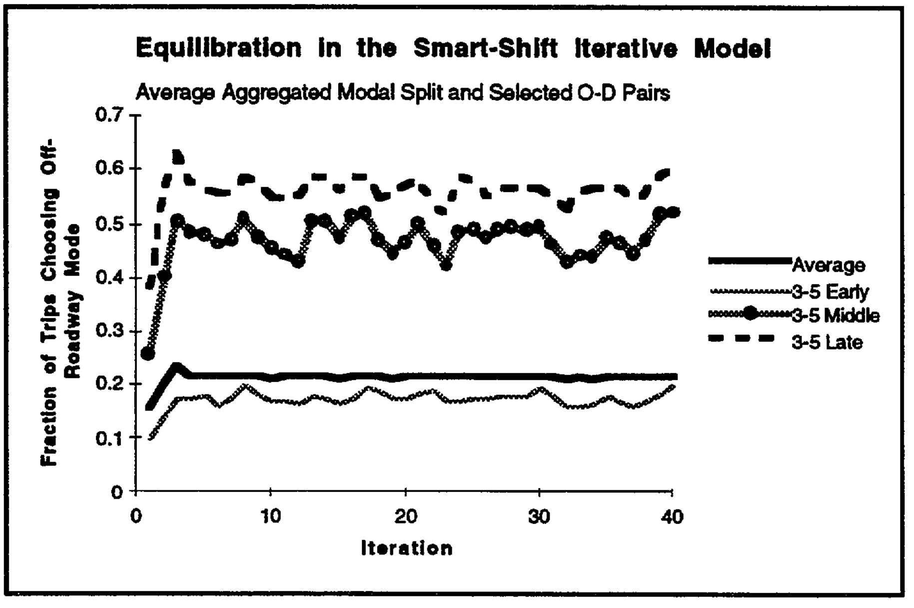

Figure 5-5. Examples of Higher Variance Mode Split Values

5.4.3 Baseline Time-Variant Mode Splits in the Test Network

This section details the base case roadway travel times obtained at the convergence with the Smart-Shift framework. These values represent the long-term average travel times on the roadway network in the test network. Long-term average trip time in the network across both roadway and off-roadway trips is roughly 8 minutes. Just over 22% of all travelers choose the off-roadway facility in the baseline day. The fraction of travelers choosing the off-roadway facility varies significantly among the time-variant origin-destination pairs.

Table 5-2 details the on-roadway trip time (in minutes) between each of the origins in the network and each destination. For each time-variant origin-destination triple, the baseline roadway travel time is given for the time of the trip start, either in the Early, Middle, or Late time periods.

Table 5-2 Roadway Travel Times Under Baseline Conditions (minutes)

	Dest. 5	Dest. 6	Dest. 7	Dest. 8
EARLY				
Origin 1	5.38	6.42	7.77	8.05
Origin 2	4.40	5.30	6.70	7.05
Origin 3	4.57	5.60	6.78	7.27
Origin 4	3.87	5.67	6.37	7.73
MIDDLE				
Origin 1	6.53	7.93	9.23	10.38
Origin 2	5.57	6.93	8.20	9.37
Origin 3	8.52	9.93	11.40	12.42
Origin 4	3.73	6.75	6.30	8.53
LATE				
Origin 1	8.08	9.50	10.87	11.32
Origin 2	7.07	8.47	9.78	10.37
Origin 3	10.52	11.82	13.23	13.52
Origin 4	3.43	7.37	5.97	8.52

These travel times are consistent with the mode shift obtained at Smart-Shift convergence. The mode shift associated with the average day is provided in table 5-3. The entries in the table are the fraction of trips choosing the off-roadway facility in each time-variant origin-destination pair.

5.5 Evaluating Impacts of Real-Time Mode Shift

If the established long-term average or base case conditions are perturbed, either through a reduction in capacity or change in demand, then a mode choice made under the assumption of baseline congestion conditions will no longer be completely accurate. This perturbation of the system provides an opportunity for a trip planning service to provide travelers with a more accurate prediction of network conditions. Travelers with the service may make more informed mode choice decisions. These choices or changes in behavior may reduce travel time for travelers in the network

Table 5-3. Baseline Off-Roadway Mode Splits

	Dest. 5	Dest. 6	Dest. 7	Dest. 8
EARLY				
Origin 1	0.116	0.077	0.126	0.075
Origin 2	0.567	0.133	0.356	0.108
Origin 3	0.196	0.090	0.173	0.083
Origin 4	0.076	0.067	0.094	0.070
MIDDLE				
Origin 1	0.163	0.099	0.167	0.100
Origin 2	0.650	0.209	0.460	0.168
Origin 3	0.521	0.244	0.421	0.198
Origin 4	0.076	0.079	0.096	0.076
LATE				
Origin 1	0.217	0.123	0.211	0.111
Origin 2	0.688	0.278	0.531	0.195
Origin 3	0.596	0.317	0.491	0.234
Origin 4	0.073	0.085	0.092	0.077

Using Smart-Shift, the impact of pre-trip mode choice planning under a range of scenarios and market penetrations can be evaluated. At the same time, other ATMS or ATIS impacts can be evaluated using the features of INTEGRATION. Section 5.5 describes the application of the Smart-Shift framework in an evaluation of real-time mode shift with respect to three scenarios. The first, "rainstorm," considers a predictable, global reduction in roadway system capacity. The second, "construction," considers a predictable, localized reduction in roadway capacity. The third, "incident," considers an unpredictable, localized reduction in roadway capacity.

5.5.1 Rainstorm Scenario Description

Heavy rain causes a network-wide reduction in capacity of a roadway system since drivers maintain wider spacing and slower speeds than under dry pavement conditions. According to a study in Houston, precipitation in the form of rain reduces overall effective system capacity by 16-19% (Highway Capacity Manual, 1994). For this study, a 25% global reduction in network roadway capacity was chosen, which might reflect a heavier than average rainstorm during the morning travel period. Off-roadway capacity and trip times are not affected. Changes to roadway capacity are accomplished by changing capacity values in input files for INTEGRATlON.

5.5.2 Congestion Reduction Strategies

Six responses to congestion are modeled as cases with the test network: a base case, three levels of pre-trip planning, route guidance, and additional lane. The cases are described as follows:

1. The simplest strategy is to do nothing. This reflects a pre- or non-ITS network. It also establishes a worst case for delay in the network. In this scenario, travelers choose on-roadway and off-roadway trips at the same rate as on the baseline day.

2. The second strategy is to introduce a trip planning user service. This strategy is broken into three levels of penetration for the user service: LOW, MED, and HIGH. The three levels represent decreasingly optimistic predictions of the acceptance and availability of pre-trip travel information.

   2a. The HIGH trip planning case assumes the highest impact and availability of pre-trip information. If the constrained UTPS model is applied directly to measure the impact of pie-trip planning information, there is a potential audience of 70% of the total traveling population. In the HIGH trip planning case, it is assumed that information is provided to all of the travelers who might make a shift based on real-time roadway congestion information.

   2b. The MED trip planning case assumes a more pessimistic view consistent with the results of the Barfield study. In that study, only 15% of the respondents indicated a willingness to change mode based on real-time information. The MED case, then, models the impact of providing this information to the 15% of the population willing to change modes in real-time before a trip begins. Steady-state mode choice still follows the constrained UTPS model, but only a fraction of the population responds in real-time. All other travelers are assumed to remain on the travel mode associated with the expected day.

   2c. The LOW trip planning case is the worst-case impact for trip planning. Again, steady-state mode choice remains consistent with the constrained UTPS model. However, only 3% of the traveling population make a mode choice based on real-time information. This reflects either a situation where acceptance is even lower than the 15% estimate from Barfield, or a case where only 1 in 5 potential mode changers (based on the Barfield estimate) are equipped with the trip planning user service.

3. Another congestion reduction strategy evaluated is the impact of a 20% sub-population of route guided vehicles in the network There is no change to expected demand and expected mode splits in this case, but one-fifth of all the vehicles in the network navigate the network based on real-time estimates of network congestion. Transit riders are unaffected. This feature is part of the INTEGRATION traffic simulation. Updated routes are provided every 10 minutes during a trip on the network, which is assumed to be under complete surveillance. Unguided vehicles remain on routes identified for the expected day.

4. The last congestion reduction strategy modeled is the establishment of an additional lane of freeway in the network bottleneck. This could reflect the presence of a reversible lane, the opening up to general access of a shoulder or HOV lane, or some

other real-time localized increase in network capacity. Demand in this case follows the expected day (no rainstorm) with expected mode splits.

5.5.3 Experimental Results: Rainstorm Scenario

The results of the experiment are tabulated in table 5-4. First a non-rainstorm “average day” case was generated to provide a baseline for delay calculation. To model the “do nothing” strategy case, the expected demand file was simply run in INTEGRATION with the reduced network capacity. Average trip times in the on-roadway network increased by over 7.5 minutes. Average trip time across all modes (which includes off-roadway trip time) increased roughly 6 minutes.

Table 5-4. Average Trip Times (All Modes)

Strategy	Average Trip Time (minutes)
Baseline Case (No Rainstorm)	8.51
Rainstorm: Do Nothlng	14.51
Rainstorm LOW Trip Planning	14.29
Rainstorm: MED trip Planning	13.62
Rainstorm: HIGH Trip Planning	11.46
Rainstorm: 20% Route Guidance	14.22
Rainstorm: Add Lane	14.04

Modeling the trip planning case involved the use of the mode choice model. The “do nothing” run of INTEGRATION establishes an prediction of roadway trip times that is input to the mode choice model for all trip planning cases. The HIGH trip planning case supplies these new roadway values and lets the mode choice model establish a new mode split for the rainstorm case. Since the roadway travel times are generally higher in the rainstorm case than in the average day case, a higher proportion of travelers will select the unaffected off-roadway facility.

Note that not all the population of potential mode changers do, in fact, change mode. The shift of modes is still based on the constrained UTPS model, so the amount of mode shift is a factor of how competitive the off-roadway facility is for a particular origin-destination pair and time of departure. Travel times across both modes are computed by tallying total trip times. In the case of the off-roadway facility, there is no change to average trip time since by assumption this facility is not sensitive to level of demand. For the roadway facility, a new demand file provided to INTEGRATION reflects a reduced mode split for the roadway option. Trip times are calculated from simulation outputs. Smart-Shift is not iterated in this case, to measure the impact of the information in a real-time situation which does not correspond to a long-term steady-state condition.

To model the LOW and MEDIUM cases, a weighted sum of the expected day mode splits and the HIGH case are ma& to reflect reduced impact. This approach ensures that travelers who do not have the trip planning service still employ the travel mode associated with the expected day. These combinations are made by computing the ratio of expected population (3% or 15%) and the maximum level of acceptance (70%). The result is a set of splits reflecting a smaller mode shift than was realized in the HIGH case.

As illustrated in figure 5-6, the three trip planning cases provide delay reduction (DR) from the do-nothing worst case. The HIGH trip planning strategy cuts the delay introduced by the rainstorm by 51%. The MED and LOW cases are less effective, reducing delay by 15% and 4%, respectively. The effectiveness of the HIGH option in reducing system delay is related to the number of travelers shifting mode. Under the HIGH option, 21% of all travelers switch from the roadway mode to the off-roadway mode. Under MED and LOW cases, only 4% and 1% of the traveling population respectively make a mode shift.

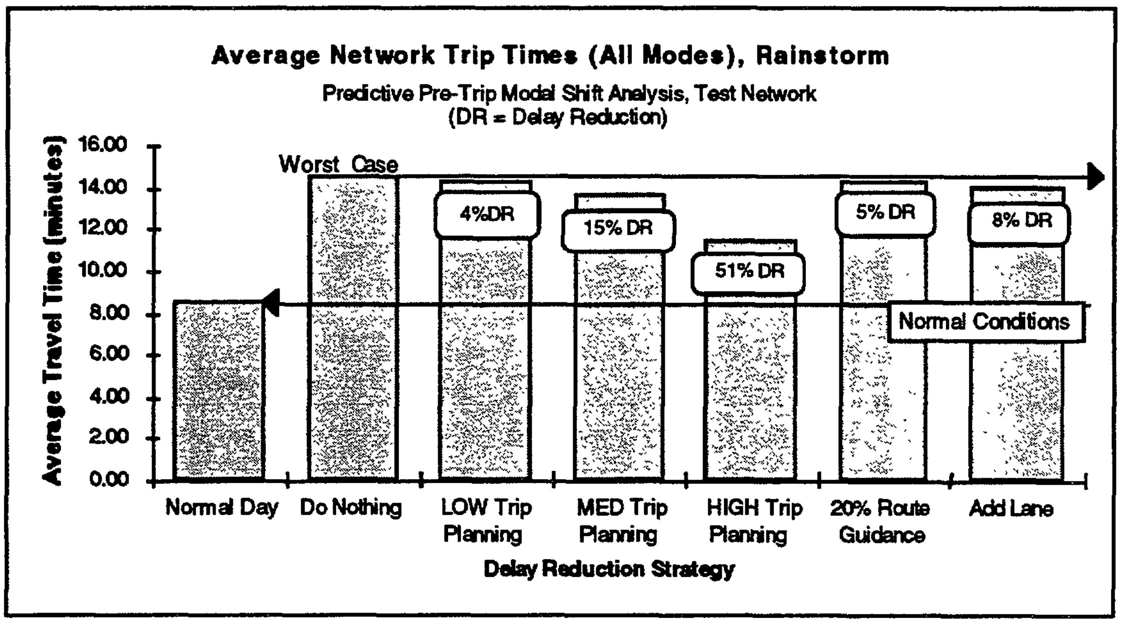

Figure 5-6. Delay Reduction, Rainstorm Scenario

Route guidance and the Add Lane strategies are evaluated in INTEGRATION. Route guidance provides a reduction of delay in the rainstorm scenario of 5%, while the Add Lane option reduces delay roughly 8%. The nature of rainstorm scenario limited the effectiveness of these two strategies. Route guidance was relatively ineffective because the reduction in capacity was global, not localized. The uniform reduction in roadway capacity did not create localized congestion that could be avoided by choosing a diversion route. Lane-adding added some capacity to the network at the bottleneck, but (as with route guidance) its effectiveness was limited by the global nature of the capacity reduction. There may have been additional capacity at the bottleneck but access to the bottleneck was impeded because those access roads were congested.

User benefits for real-time mode shifting individuals can also be tabulated from Smart-Shift outputs and are illustrated in table 5-5. The subpopulation of travelers shifting mode have different trip characteristics than average travelers. For example, mode shifters tend to have longer trips and leave later in the period rather than earlier. User benefit for mode shifters decreases as participation increases in the rainstorm scenario. In the HIGH trip planning case, mode shifters experience 31% higher travel times than competing non-shifters. This case represents an over-shift situation, wherein so many travelers shift mode that the predicted roadway congestion never materialized.

Table 5-5. Rainstorm Scenario User Benefit Analysis

TRAVEL TIME (minutes)	LOW Trip Planning	MED Trip Planning	HIGH Trip Planning	Anticipatory Trip Planning
Mode Shifters	14.5	14.5	14.5	14.1
Competing Non-Shifters	17.4	16.3	11.1	13.5
Predicted Roadway Trip Under No Mode Shift	17.7	17.7	17.7	17.7
Shifter Savings vs. Non-Shifters	17%	11%	-31%	-4%
Shifter Savings vs. No Mode Shift Case	18%	18%	18%	21%
Non-Shifter Savings vs. No Mode Shift Case	2%	6%	37%	24%
System Travel Time Savings	2%	6%	21%	17%
Pct. Travelers Shifting	0.8%	4%	21%	13%

The Smart-Shift framework can be employed to evaluate a trip planning service that can compensate for overshift conditions, however. If the Smart-Shift system is allowed to equilibrate under the rainstorm conditions (rather than the single pass employed above), one can estimate the effectiveness of a trip planning system that predicts not only time-of-departure trip time relationships, but also anticipates the effect of information dissemination on the network. In this case, mode shifters have travel times slightly worse than non-shifters (-4% benefit), but system travel time is still significantly reduced (17% system travel time savings).

The anticipatory aspect of this kind of real-time mode shift reduces overall mode shift from 21% to 13%, reallocating the 8% of travelers who were experiencing the least benefit from shifting mode. The increase in system travel time is a result of the implicit preference for travelers in the mode choice model for slightly longer duration roadway trips over off-roadway trips.

5.5.4 Construction Scenario

The construction scenario represents a predictable reduction in localized roadway effective capacity. The effect is predictable in the sense that the trip planning service provider knows from the outset of the rush period the location and severity of the link capacity reduction. Travelers in the network without access to the trip planning service are assumed to be unaware of the capacity reduction. For this reason, the construction scenario is not intended to represent the impact of a construction site weeks after it has been introduced. Rather the construction represents a short-term constrictions such as emergency work or late-lifting night repairs, or even the first day of an unpublicized construction project.

The bottleneck freeway link in the test network is the localized area affected in the construction scenario. A reduction of 40% in link capacity for the peak period is modeled through changes to INTEGRATION simulation input parameters. Off-roadway capacity is not reduced. The same set of congestion reduction strategies tested in the rainstorm scenario are employed in the construction scenario.

System impacts of the various strategies are illustrated in figure 5-7. Delay in the worst-case (Do Nothing) causes an increase in average traveler trip time of just under 6 minutes. Thus, the level of total delay in the construction scenario is comparable to the total delay introduced in the rainstorm scenario, although the nature of the capacity reduction is different.

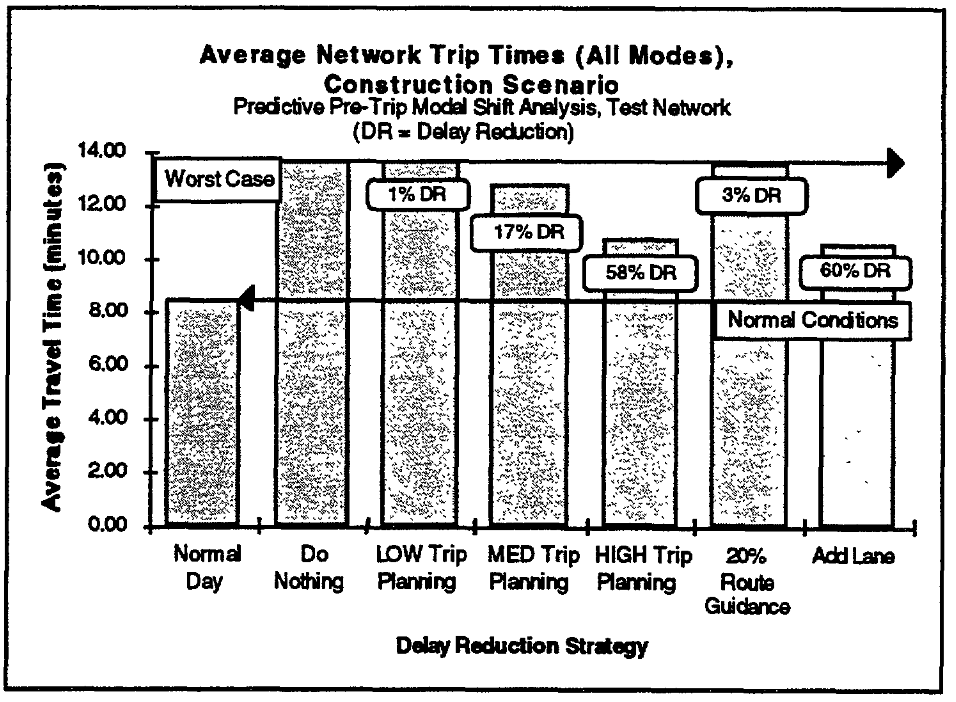

Figure 5-7. Delay Reduction, Construction Scenario

The trip planning strategies (LOW, MED, HIGH) reduce system delay by 1%, 17%, and 58% respectively. The route guidance strategy, in which 20% of all vehicles are equipped with en route guidance, reduces system delay 3%. The real-time addition of a lane on the freeway bottleneck (also the location of the construction site) reduces delay 60%. The effectiveness of the Add Lane strategy implies a capability to add capacity in real-time to the affected link with no interference to opposing flow.

User benefits for real-time mode shifters are presented in table 5-6. As in the rainstorm scenario, user benefits decrease with increasing mode shift participation. However, unlike the rainstorm scenario, mode shifters do not have worse travel time performance at the HIGH trip planning response level. Slightly higher system benefits are obtained in the construction scenario than in the rainstorm scenario (22% vs. 21%) even though a smaller subset of travelers shift mode (16% vs. 21%). Note that the set of competing non-shifters (the set of travelers who continue to make roadway trips and do not shift mode) almost always gain proportionally higher benefit than the system as a whole from real-time mode shift, This implies that even those travelers who ignore roadway travel time prediction gain benefit from the provision of a trip planning user service.

Table 5-6. Construction Scenario Pre-Trip Mode Shift User Benefit Summary

TRAVEL TIME (minutes]	LOW Trip Planning	MED Trip Planning	HIGH Trip Planning
Mode S h ifterr	14.2	14.2	14.2
Competing Non-Shifters	22.5	20.3	14.3
Predicted Roadway Trip Under No Mode Shift	22.2	22.2	22.2
Shifter Savings vs. Non-Shifters	37%	30%	1%
Shifter Savings vs. No Mode Shift Case	36%	36%	36%
Non-Shifter Savings vs No Mode Shift Case	-1%	9%	36%
System Savings	0.3%	7%	22%
Pct. Travelers Shiftina	0.6%	3%	16%

5.5.5 Incident Scenario

The incident scenario represents an unpredictable, localized reduction in system capacity. Unlike the forecast of rain or the scheduling of construction work, incident location, severity and impact cannot be predicted. Until the incident is detected, a trip planning service provider cannot disseminate information on the impact of the incident on trip times in the network Travelers who begin their trips after the incident has been detected and reported may utilize information about the incident in their mode choice decision.

An incident is modeled on the same freeway bottleneck link used for the construction zone in the construction scenario. The capacity restriction is more severe (45%) than in the construction scenario, but occurs midway through the first of the three time travel start periods (Early, Middle, Late). The incident occurs in the Early time period, but information is not passed to travelers until the Middle departure period begins. This reflects delay in the detection of the incident, determination of the severity, and the time the trip planning user service provider spends to calculate a new prediction of roadway congestion. As a result, the travelers beginning their trip in the Early time frame, representing one-third of the total traveling population, do not have the opportunity to shift mode. This limitation of information flow to groups of travelers is modeled through the manipulation of both the demand input files in INTEGRATION and the set of predicted travel times input to the Smart-Shift mode choice model.

As in the rainstorm and construction scenarios, no reduction is made to off-roadway capacity. The impact of the incident causes average trip time in the network to increase by just over 6 minutes, roughly the same level of total delay as the rainstorm and construction scenarios. Delay reduction under the various control strategies is illustrated in figure 5-8. As expected, real-time mode choice has a more limited impact on system travel performance than in the rainstorm or construction case. Delay for the three trip planning cases (LOW, MED, HIGH) reduced system delay 3%, 6% and 32%, respectively. Quipping 20% of roadway drivers with a dynamic route guidance system reduced delay 19%.

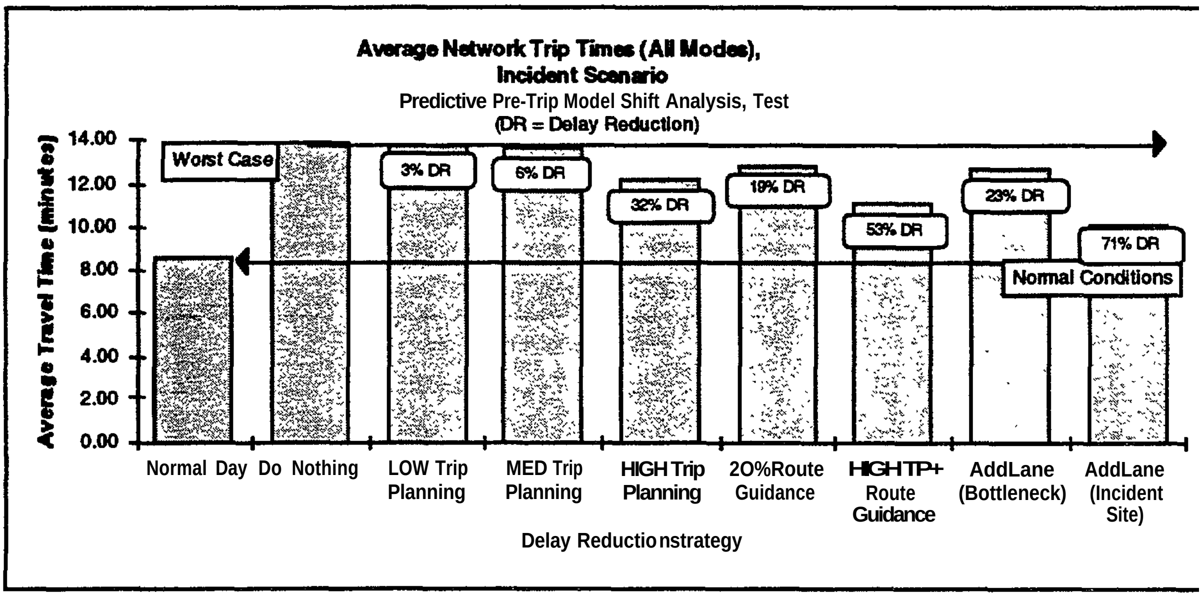

Figure 5-8. Incident Scenario Delay Reduction

Two new congestion reduction strategies were also considered. The first was the concurrent effects of HIGH trip planning together with 20% route guided roadway travelers. Route guided travelers were considered a component of the subpopulation of travelers who never consider the off-roadway mode in the Smart-Shift mode choice model. The impact of combining the two user services was at least additive, reducing delay by 53%. Although this single case is far from conclusive, it may also hint at potential (albeit small) synergies between the two user services. An additive relationship would have provided a (19% + 32%) 51% delay reduction.

The second additional congestion reduction strategy considers the location of the incident relative to where capacity might be added in real time. Two cases were considered, one in which a additional capacity is added along the affected link (as in the construction scenario) and the second along a parallel link. Adding a lane near the incident site reduced delay by 7l%, an additional link along a parallel bottleneck link reduced delay 23%. Adding capacity elsewhere in the link (on a non-parallel link, for example) did not reduce delay.

User (mode shifter) benefits are summarized in table 5-7. One interesting observation is that even though only two-thirds of the population can be potentially reached by the service because of the incident detection delay, the percent of travelers shifting is roughly the same as in the construction scenario. Clearly, since there is no mode shift in the frost trip start period, a higher percentage of travelers are shifting mode in the later two periods. This is a reflection of the increased congestion resulting in the incident scenario for the last two periods. In the construction case, some early drivers were shifted onto the off-roadway network, so delays in the later periods were partially reduced. In the incident case, them is no early shift, and increased roadway congestion results after the incident occurs.

Table 5-7. Incident Scenario Pre-Trip Mode Shift User Benefit Summary

TRAVEL TIME (minutes)	LOW Trip Planning	MED Trip Planning	HIGH Trip Planning
Mode Shifters	14.6	14.6	14.8
Competing Non-Shifters	22.7	22.7	18.4
Predicted Roadway Trip Under No Mode Shift	23.3	23.3	23.3
Shifter Savings vs. Non-Shifters	35%	35%	20%
Shifter Savings vs. No Mode Shift Case	36%	36%	36%
Non-Shifter Savings vs. No Mode Shift Case	3 %	3 %	21%
System Savings	1.0%	2.3%	12%
Pct. Travelers Shifting	0.6%	3 %	15%

System delay reduction for the trip planning user service are not as high in the incident scenario compared to the construction scenario. However, user benefits are either the same or higher than in the construction scenario. This result stems from a concentration of delay among a smaller set of travelers. In the rainstorm scenario, total delay is borne relatively equally among all travelers. In the construction scenario, total delay is borne primarily by subset of travelers who have paths crossing the construction zone. In the incident scenario, total delay is borne by an even smaller subset of travelers with paths and times of departures resulting in interaction with the incident site. When delay is concentrated among a smaller set of trips, roadway delay dwarfs off-roadway trip time. Travelers considering real-time mode choice who receive a prediction of this extensive roadway delay are not only more likely to shift modes, but also realize significant trip tune savings. Travelers with trips that see little change in the current prediction from expected conditions do not shift mode. Thus, the aggregate user benefit figure is dominated by the smaller group of high-benefit mode shifters.

5.6 Conclusions

The results obtained in this study demonstrate that the Smart-Shift framework can be an effective tool in the evaluation of a real-time mode shift. There are currently no other modeling approaches with the capabilities of the Smart-Shift approach. Mitretek plans to continue development of Smart-Shift to include other aspects of real-time trip planning beyond mode choice. The results indicate large potential benefits for a trip planning user service, both for the system as a whole and the travelers using the service.

5.6.1 Analysis of Results

In several cases, real-time mode shift proved more effective than other strategies at reducing overall travel delay. The results demonstrate how valuable trip information may be when the effective capacity of the transportation system has been reduced.

System benefit realized by real-time mode shift in all cases studied is positive. In addition, system benefit increased with increased participation. User travel tune benefit, i.e. the travel time benefits for mode shifters, was generally positive, but not in all cases. In all test cases with Smart-Shift, user benefit decreased with increased participation. As demonstrated in the rainstorm scenario, a drop in user benefits at the highest participation levels can be mitigated to some extent by the provision of anticipatory roadway congestion predictions.

Real-time mode shift can be an effective method of redistributing travelers under both localized and global capacity restrictions. Under conditions of roughly the same total delay, real-time mode shift provided a 22% reduction in system travel time in both the rainstorm and construction scenarios.

System benefit of real-time mode choice is higher for predictable events than unpredictable (or random) events. Although the construction and the incident scenarios generated roughly the same total delay, the inability to predict the occurrence of the incident cut maximum system travel time savings from real-time mode choice from 22% to 12%. Travelers who are wamed of the effects of newly-detected incidents are able to realize significant travel time reductions, however.

User benefit was demonstrated to be high when the size of the responding population is low. This indicates that the first user benefits of such a service are likely to be high.

5.6.2 Caveats

Several attributes of the test network and the scenarios tested make the trip planning options particularly effective. First, the test network contained capacity in the off-roadway network available for shifted demand. Many large urban areas have rail transit systems, but this is not a general&able feature for all urban areas in the nation. The Smart-Shift framework may be extended to include other travel modes and choices beyond a shift-to-rail, however.

In addition, the off-roadway system absorbed a doubling in ridership in the HIGH trip planning case without an increase in travel time. It is more likely that delays would accrue to a transit system that experienced such a surge of ridership on a one-time basis.

The rainstorm scenario has been characterized as predictable. One might argue that weather is a self-evident phenomenon, and that some mode shift is likely to occur without the provision of a trip planning user service. While this is likely to be true, the effect of the trip planning service is to give some certainty and specificity to the mode decision making process. In this way, the allocation of travel between the two modes is efficiently allocated based on a (hopefully) accurate prediction, and not on previous experience under rainy conditions.

In a case corresponding to a invariant demand and full capacity, none of the trip planning techniques can reduce overall system travel time. This is because all information about relative travel times in both modes are considered known by the traveling population. Permanent lane construction would be the only effective congestion reduction strategy in this case. Modern urban travel rarely conforms to this concept of rigid predictability, however. In addition, permanent lane construction may influence the underlying travel patterns, clouding any comparison to real-time congestion-reduction strategies.

Finally, the test network depicted a network with significant recurrent roadway congestion and limited alternative roadway routes. In a network with lower recurrent congestion and a larger number of path options, the real-time mode choice strategy would likely demonstrate lower benefits relative to a route guidance user service. The test network also tests sensitivity in a morning rush period. A reduction in mode choice flexibility would have to be modeled in the consideration of an evening peak period.

5.6.3 Implications

An important implication of the results obtained so far is that the value of pre-trip mode choice information in certain circumstances can far exceed the value of other congestion mitigation strategies. Mode choice is one aspect of pre-trip planning, a user service which may include other choices such as trip deferral, trip chaining, or trip cancellation. In many circumstances, the dissemination of traveler information may be the only viable real-time strategy. For example, one cannot simply add capacity in real-time (with the exception of reversible or shoulder lanes).

The accuracy of trip time forecasts under high (70%) market penetration is critical to user service viability. The high-delay that is forecast for roadway conditions in the HIGH trip planning case caused an overshift of travelers to the off-roadway mode, resulting in significant increase in delay for mode shifters in comparison to non-shifting competitors. When a more accurate, anticipatory forecast was distributed to travelers, however, mode shifters experienced much better performance. At lower levels of trip planning market penetration (3-15%) anticipatory accuracy of trip time forecasts was not found to be critical.

Another interesting result from the study is that the lane-addition strategy is evaluated under steady state using Smart-Shift. In this case, ridership is drawn away from the off-roadway facility to the roadway facility, thereby reducing some of the system benefit of lane-addition. In fact, in some cases using the framework, aggregate travel time actually increases when capacity is added to the roadway system. This is because the mode choice model inherently prefers slightly longer roadway trips to off-roadway trips. New roadway users abandon the transit facility to take longer trips on the roadway system. In the equilibrated lane-building case, aggregate traveler utility may increase even though aggregate travel time also increases. With the addition of a function relating travel tune and traveler utility, travel tune benefit figures identified under the various congestion reduction strategies could be converted into utility or mobility benefit measures.

5.6.4 Extensions

The current Smart-Shift formulation considers only travel time in mode choice. In the next phase of analysis a number of additional issues will be explored including: incorporation of more complex Logit and nested Logit formulations; addition of additional variables including parking costs, tolls, transit fares; and inclusion of time-of-departure, new modes, and other decisions in the travel process. Travel time for the transit mode may also be modeled in greater detail, including explicit modeling of rail station location and transit access modes.

Variability in network demand or capacity provides the opportunity for trip planning to provide both user and system benefits. Although only roadway capacity reductions have been examined so far, the results of localized or global increases in demand can also be evaluated in Smart-Shift. A demand-increase scenario is likely to produce similar results to a capacity-decrease scenario, as long as the two scenarios are similar in terms of total delay, local/global effect, and predictability. In general, the greater the variability in the transportation system, the higher the benefit of real-time congestion reduction strategies.