

A System-wide Evaluation of a Traffic Control System using Microscopic Simulation

by

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE IN TRANSPORTATION

at the
Massachusetts Institute of Technology
May 1998

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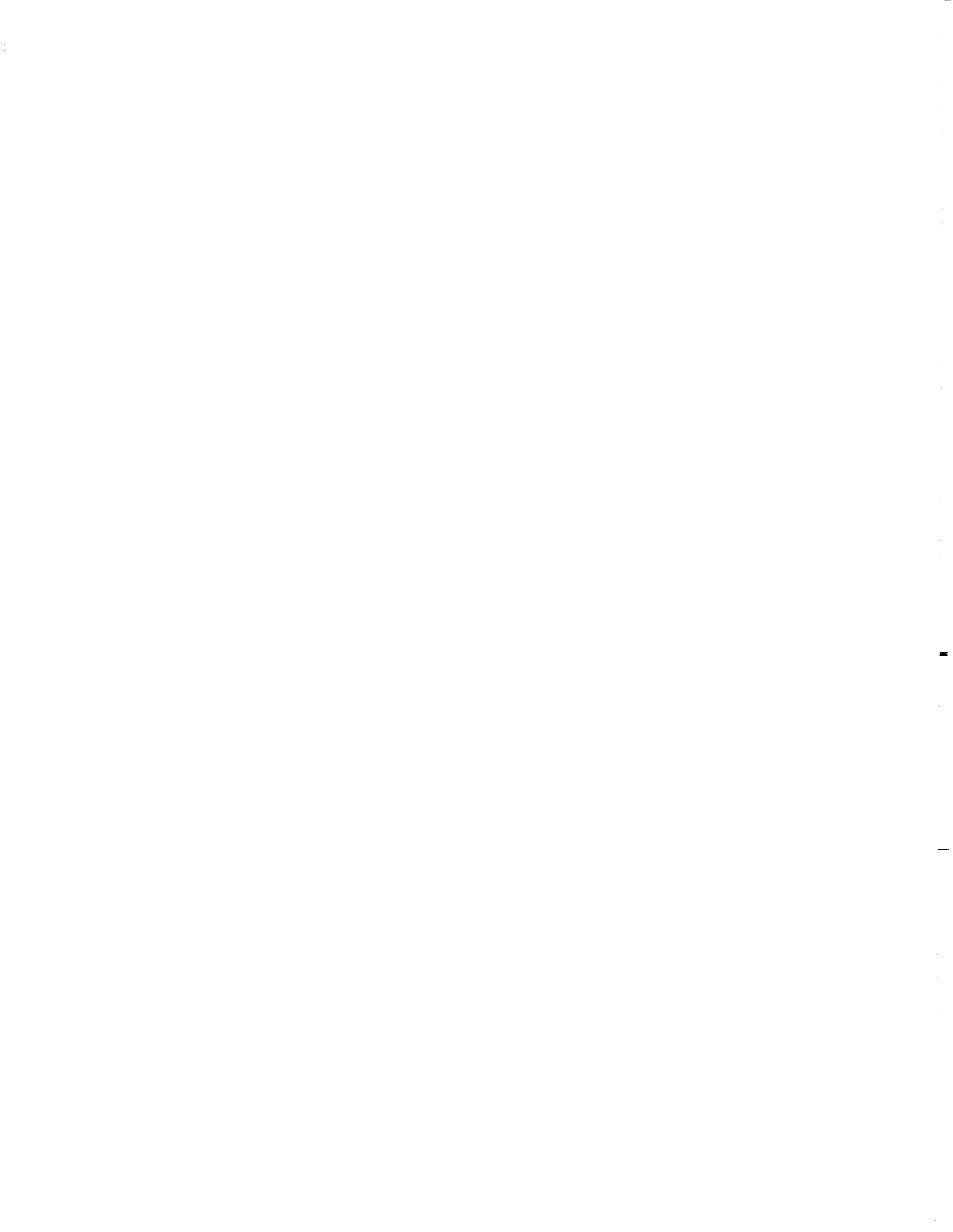
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Abstract

Dynamic Traffic Management Systems (DTMS) are being developed as part of the Intelligent Transportation Systems (ITS) initiative to reduce congestion growth. DTMS are responsible for traffic monitoring, implementation of traffic control, and providing traveler information. The development of DTMS is a new advancement, and evaluation of the traffic control system is essential to ensure a successful implementation. A simulation approach has been shown to be an appropriate method for performing this evaluation.

The simulation evaluation is applied to the Central Artery/Tunnel (CA/T) project network. MITSIM microscopic traffic simulator laboratory is used to test and evaluate the traffic control design. The advantage of this microscopic simulation laboratory is that it simulates the interaction of individual vehicles with other vehicles, network geometry, and traffic control devices, thus providing a detailed analysis of the impact of traffic control.

This thesis presents a framework and simulation experiments for system-wide evaluation of DTMS implementation for the CA/T network. Previous simulation studies have investigated the performance of individual control components for the CA/T network. This evaluation study considers the integration of these controls. It evaluates control designs on both a local and system-wide level in order to fully identify the impact of a design strategy. Two case studies are presented. One places an incident in a weaving section and uses control designs comprised of lane control signs (LCS), variable speed limit signs (VSLS), ramp meters, and route diversion for incident management. The other case places an incident in a tunnel, and uses controls comprised of LCS, VSLS, and route diversion to a parallel tunnel. For each case study, the results of various demand scenarios are presented and analyzed based upon multiple measures of effectiveness (MOEs).

The experiments demonstrated that the simulation laboratory can be used as an evaluation tool. The case study results indicate a marginal improvement due to DTMS. They identify the need for more advanced DTMS designs which consider the interactions of control components.

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Acknowledgments

I take this opportunity to thank my advisors, Prof. Moshe Ben-Akiva and Dr. Mithilesh Jha, for their advice and guidance throughout this research. They provided me with many insights, both applicable to this research and otherwise. Their perception astonishes me. I learned much from them and consider myself very fortunate for having this opportunity.

Many thanks go to the crew at "3CC". From the researchers: Michel Bierlaire, Didier Burton, Alan Chachich, and Qi Yang, to my fellow students: Kazi Ahmed, Owen Chen, Sridevi Ganugapati, Masroor Hasan, Mark Chang, and Sreeram Thirukkonda, everyone helped create a wonderful environment, that made it easy to go to work in the morning and be productive. I thank you all for your insights and support.

I would like to thank Bechtel/Parsons Brinckerhoff for their financial support of the Central Artery/Tunnel project at MIT, without which this research would not have been possible.

I would also like to thank the transportation program at MIT, especially my fellow students, who almost made it fun to work on the weekend.

To all my friends at MIT and in Boston, who have made my stay here very enjoyable and difficult to end, I would like to offer my thanks. They kept me sane by offering exciting diversions.

Finally, I would like to express my appreciation for the constant support of my family.

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Chapter 1 Introduction

Traffic congestion is growing in urban areas with detrimental effects to the transportation system and society. Dynamic Traffic Management Systems (DTMS) are being developed as a potential solution to this growing congestion. DTMS seek to alleviate congestion by improving capacity utilization through traffic control and information. The development of DTMS is a new advancement, and its evaluation is necessary to ensure that systems are not poorly operated with disrupted travel conditions. Evaluation of DTMS investigates the performance of its components in response to different situations, and offers insights into when and how those components should be used.

An implementation of a system-wide evaluation for the design and operation of a DTMS is presented. This evaluation uses microscopic traffic simulation to test the DTMS design for a real-world transportation network, the Central Artery/Tunnel (CA/T) network. This chapter provides the motivation for the research and its organization.

1.1 Congestion

The transportation roadway system in the United States and throughout the world is currently confronted by a large obstacle: congestion. Traffic congestion in urban areas has been growing rapidly for the past few decades and is not expected to stop. In fact, travel demand is expected to grow by about 30% over the next 10 years, implying that unless there is a corresponding 30% increase in capacity, the congestion level will further increase [Proper, 1997]. This congestion has led to lost productivity. ITS America valued the lost productivity due to congestion at \$100 billion a year in the United States alone [IVHS America, 1992].

Congestion also deteriorates safety of the roadways. Accident rates have been found to be 2 to 28% greater in congested conditions [Sandhu, 1996]. The cost of accidents in the US was valued at \$70 billion a year, a numeric value which cannot fully recognize the comprehensive effects of accidents [IVHS America, 1992]. Additionally, there are concerns about added energy consumption and the environmental impact of congestion. All of these concerns make congestion alleviation a major transportation priority.

The traditional way to combat congestion was to build capacity to existing roads. But due to scarcity of land and environmental concerns, roadway capacity cannot be built to keep up with demand growth. A new method for increasing capacity must be developed. Intelligent Transportation Systems (ITS) has been perceived as a measure to address this congestion problem.

1.2 Intelligent Transportation Systems

ITS, formerly known as Intelligent Vehicle/Highway Systems (IVHS), is the application of advanced technologies such as information systems, electronics, communications, and automatic control to transportation. These technologies are used for a wide-range of tasks, ranging from automatic vehicle identification, roadway monitoring, incident detection, electronic toll collection, ramp metering, route guidance, collision avoidance, and many more. ITS is subdivided into six functional areas [Sussman, 1996]:

- **Advanced Traffic Management Systems (ATMS)** - ATMS integrates management of roadway functions. It uses traffic surveillance, communication, and traffic control to manage the operations, demand and safety of the transportation system. A traffic management center (TMC) receives real-time traffic information from multiple sources: loop detectors, video images, probe vehicles, and cellular phone calls from drivers. The TMC then uses this information to implement an appropriate control strategy. The strategy can include combinations of routing information, control-specific information (such as adjusting traffic signals or changing a ramp metering rate), or even alerting the transit agency. In the future, ATMS systems will be able to use these data to predict future traffic conditions and respond in real-time.
- **Advanced Traveler Information Systems (ATIS)** - ATIS is closely related to ATMS. ATIS provides information to travelers of both automobiles and transit. It can provide information on incidents, weather, road conditions, routing, and lane restrictions to travelers. The purpose of ATIS is to provide information in a way which helps improve capacity utilization.
- **Advanced Vehicle Control Systems (AVCS)** - AVCS aims to improve the driver's control of the vehicle, resulting in increased safety and efficiency. In the near future, advanced warning and collision avoidance systems will assist drivers in preventing accidents and reducing congestion caused by accidents. Full implementation will lead to the development of the Automated Highway Systems (AHS), which will control the movement of platoons of vehicles traveling at normal highway speeds with very small headways (~1ft).
- **Commercial Vehicle Operations (CVO)** - CVO is the application of ITS technologies towards the operations of fleets of trucks, vans, and taxis. The result is greater fleet productivity.
- **Advanced Public Transportation Systems (APTS)** - APTS uses ITS technologies to improve the efficiency of the public transit fleet, and to provide real-time information to transit users.

- **Advanced Rural Transportation Systems (ARTS)** - ARTS applies ITS technologies in rural areas, considering the economic constraints of low-density roads.

These six functional areas of ITS will work in an integrated manner when ITS is fully implemented.

The research presented will focus on the ATMS and ATIS areas of ITS, and consider how they can be used to reduce congestion in roadways.

1.3 Dynamic Traffic Management Systems

Dynamic Traffic Management Systems (DTMS) are responsible for traffic monitoring, implementation of traffic control, and communication of traveler information, thus they operate within the ATMS and ATIS functional areas of ITS. TMCs are responsible for implementation of DTMS. They can operate statically or dynamically. For static operations, traffic controls are run at a constant setting, while dynamic operations change the settings for different time intervals. DTMS operate dynamically based upon the relationship with traffic, specified in Figure I-1. Traffic data is collected by the surveillance system and fed into the TMC to determine the control to implement, which in turn impacts the traffic flow [Ben-Akiva, 1994]. Dynamic Traffic Management System (DTMS) is the term used to describe this process.

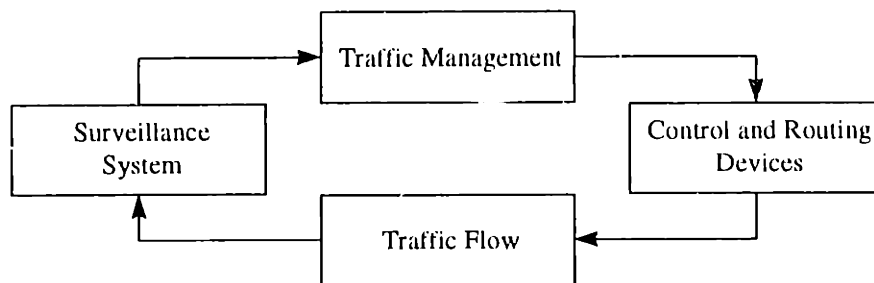


Figure I-1 Dynamic Traffic Management System Overview

Figure I-2 displays how users of the transportation system interact in this loop. The TMC receives surveillance information and uses it to determine the control and information to convey to the users. Aggregate network conditions evolve from users' responses to the control, and information.

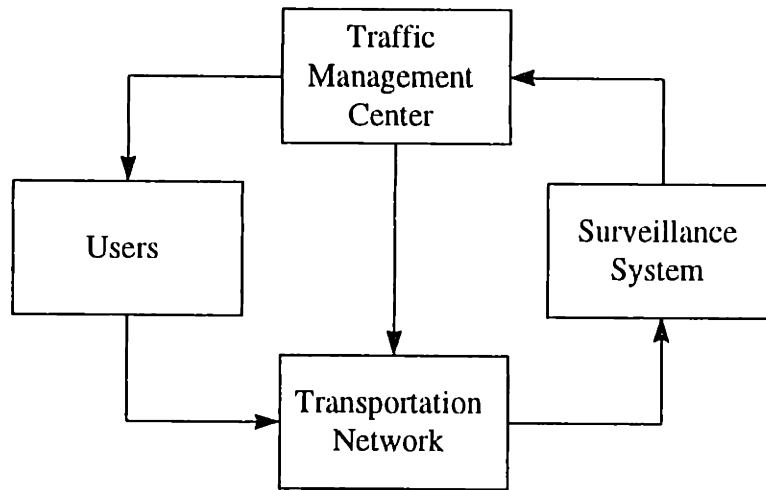


Figure I-2 User Interface with Dynamic Traffic Management System

Figure I-3 represents a more detailed view of this process. It shows how traffic control and information affects the travel conditions by impacting the travel demand and network supply. The following sections describe the three elements of DTMS: traffic surveillance, traveler information, and traffic control.

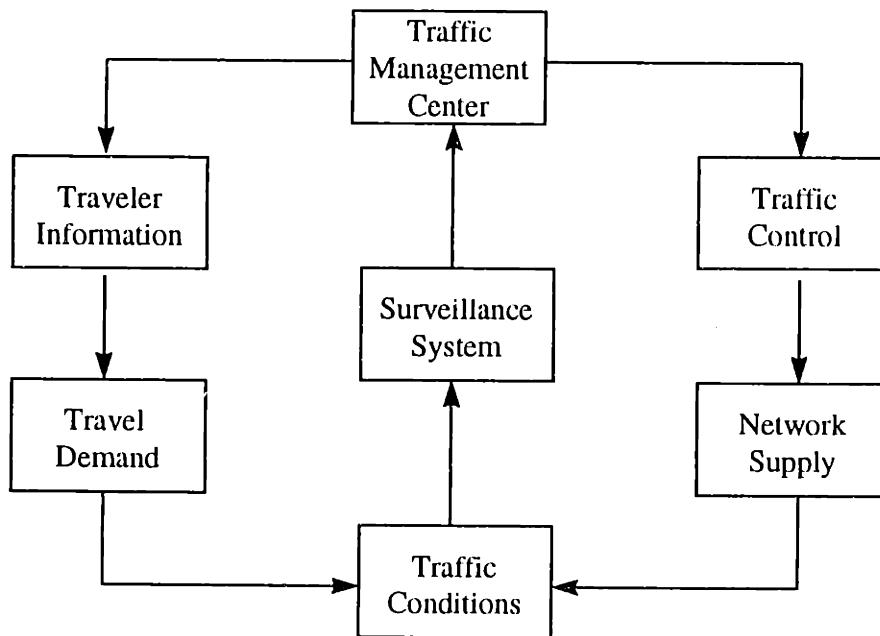


Figure I-3 Components of Dynamic Traffic Management

1.3.1 Traffic Surveillance

The surveillance system is responsible for identifying the state of the roadway network. Inductive loop detectors, video surveillance, and probe vehicles provide this real-time information to the TMC. The TMC then evaluates this information to estimate the current network state, possibly predict future network conditions, and determine the control plan to implement.

1.3.2 Traveler Information

Traffic information helps travelers make travel decisions based upon current or predicted conditions. There are three major methods for the TMC to provide this information:

- **Variable Message Signs (VMS):** VMS are signs located over the roadway or on the side of the road, and provide information to travelers as they drive. This information can be descriptive or prescriptive. A descriptive message provides travel time information, while a prescriptive message suggests a specific route. Although VMS are an effective device, their use may be limited due to space restrictions. VMS have limited capacity due to sign space.
- **Highway Advisory Radio (HAR):** HAR are similar to VMS in that they can provide descriptive or prescriptive information, but use radio frequency to communicate the information. The advantage of HAR is that it can communicate more detailed information than VMS but the message may not reach as large of an audience since all drivers may not tune to HAR.
- **In-Vehicle Units:** Electronic devices located in vehicles can communicate with the TMC or traffic information provider to receive traffic information. This information can be very detailed and of the descriptive or prescriptive kind. Two-way communication units are being developed which will allow the TMC to obtain data from vehicles.

Additionally, traveler information is being communicated through radio, television, phone, and internet by both TMCs and private information providers.

1.3.3 Traffic Control

The TMC uses the surveillance information to determine an efficient strategy. The following are some of the control components available to the TMC: Lane Control Signals (LCS), ramp control, VMS, route diversion, mainline metering, and Variable Speed Limit Signs (VSLs). Components can be used independently or in combination. A more detailed description of these components will be presented in Chapter 2.

1.4 Literature Review

Research has been undertaken to ascertain the impact of traffic control on congestion. Much of the early research considered pre-timed control of individual components (i.e. not adjusting to current traffic conditions). Technological improvements have led to investigation of how these components can be used to respond to real-time traffic information, and how they can be used together. Traffic control research can be divided into three areas: 1) design, 2) field operational testing, and 3) simulation studies. Much research has been done in algorithm development for design of these controls, but more realistic evaluation is required to analyze the impact of these designs.

1.4.1 Design of Traffic Control Systems

The first step towards the successful use of a new technology requires careful planning of how the technology will work and interact with other technologies. During this stage, the requirements for successful implementation of the technology are considered.

A number of projects have considered the design of for the use of individual components or combinations of components. For part of the PRIMAVERA project of the European DRIVE II program, a manual is being developed to provide guidelines for the development and implementation of integrated traffic management. It considers the development and evaluation of integrated strategies, concerned with both field implementation and simulation [Montgomery, 1995]. Maxwell and Beck [1996] discuss the use of VMS to implement route guidance on English roadways. In their plan, real-time traffic data will be fed into the MCONTRM macroscopic model and its output used to prepare VMS to redistribute traffic. Pooran and Lieu [1994] present guidelines to select and implement strategies to integrate ramp metering and traffic signal control. The guidelines are based upon decision matrices and parameters which quantify traffic conditions. Rindt et al [1997] describe the CART (California Advanced Research Testbed) project, which combines VMS for route guidance, ramp metering and traffic signal control for a multi-jurisdictional area in California. They present a methodology for the coordination of data collection and control implementation, and preparation of a simulation platform for testing. Diakaki et al. [1998] present the application of the IN-TUC (Integrated - Traffic responsive Urban corridor Control) in Glasgow. This system uses traffic control and VMS for route diversion. The route diversion messages are prescriptive, determined to split travel patterns amongst routes. The components are integrated by communicating measurements and control decisions.

The development of complete control designs has also been considered at the planning level. Van Schuppen [1997] presents an approach to integrated control developed for the DACCORD

project. He presents a hierarchical model to consider a motorway at the network, link, and point levels. He defines coordination as ensuring that the same controller in different locations coordinate their actions, and defines integration as requiring that different types of control devices all share the same objective. These definitions serve as the basis for the design of these types of systems. Brewer et al [1994] give an account of the system designed for the Interstate H-3 and Trans-Koolau Tunnel in Honolulu. The management system of this project includes tunnel portals, LCS, traffic signals, ramp metering, VSLS, VMS, HAR, and public radio. The system design includes a knowledge-based expert system to determine the incident management response from a traffic control strategy matrix.

Tsavachidis et al. [1998] describe the COMFORT (Cooperative Management For Urban and Regional Transport) project in Munich. It integrates incident detection, urban traffic control, and route diversion. The system receives real-time traffic data, detection of incidents, and current traffic cycle times. It uses this information as input into a routing algorithm, VARIA, which uses the macroscopic simulator METANET for on-line simulation of routing alternatives. The output is used to determine the operation of the routing control. The use of simulation in this project is different than other projects due to its on-line nature.

1.4.2 Field Operational Testing

After designing for a new technology, operational tests allow for the advancement of the technology from the research phase into implementation. A number of field operational studies have been completed to demonstrate the benefits of ATMS/ATIS control designs. Several field tests have investigated the success of ramp meters and traffic signal control improvements. Proper and Cheslow [1997] report speed increases in the range of 16% to 62% and travel times savings up to 48% for North American traffic management centers using ramp metering. They also report that traffic signal control improvement decreased travel times between 8% and 18% for three test implementations.

Operational tests have also been performed for integrated controls. The INFORM (Information for Motorist) evaluation in Long Island, New York used ramp metering, traffic signal control, and route diversion. This system was found to increase speeds by 13% despite a VMT increase of 5% [Smith, 1992]. The FAST-TRAC project in Oakland County, Michigan includes traffic signal control and route guidance. It resulted in increases of peak hour speeds up to 19% [ITS America, 1997]. The Minnesota Guidestar project includes ramp metering, traffic signal control, and VMS. It has increased average speeds by 35% during the peak periods, and increased the freeway capacity by 22% [ITS America, 1997; Wright, 1997].

Outside the United States, Papageorgiou et al. [1997] investigated field implementation of ramp metering. In two separate tests, the ALINEA control algorithm was implemented on three ramps of the Boulevard Périphérique in Paris, and on four ramps of A10 West in Amsterdam. ALINEA was found to reduce the total travel time by 15.9% and 6.3% for these locations respectively.

1.4.3 Simulation Studies

Operational tests provide a real-world evaluation of traffic control. However, they are very expensive, time consuming, and sometimes infeasible. Simulation is an off-line tool for testing system designs before implementation. Simulation studies can be used to analyze how robust a design is by evaluating a range of scenarios. Simulation studies can also be used for calibration of control parameters.

A number of studies have simulated the use of individual traffic controls. Smulders [1990] simulated VSL control and found that their most significant impact was in creating more uniform speed distributions with a reduction in the fraction of small headways. Hardman [1996] modified the SISTM microscopic simulator to model VSL control and also found VSL to result in a more uniform speed distribution. These studies considered only the use of VSL and not their integration with other control components.

Messemer and Papageorgiou [1995] simulated route diversion via VMS using METANET macroscopic simulator. They compared route guidance developed by off-line and on-line optimization with a no control case. In their simulation, VMS messages directed vehicles to a specific route based upon an optimization solution. The VMS messages were specified for time intervals, and route information could be changed from one time interval to the next. Thus, when the route guidance control recommended a different route, the VMS was switched. It was found that the on-line optimization resulted in only slightly less improvement, but with fewer number of VMS switches, meaning a more constant diversion strategy were offered to travelers. A pre-specified fraction of vehicles divert in this simulation, instead of simulating a driver's route choice behavior. Van Aerde and Yagar [1990] also simulated route guidance, using INTEGRATION. In their simulation, portions of vehicles receive updated link travel times, which are used to determine these vehicles' routes. They found the benefit of route guidance to range from 11% to 33% depending on the duration of the incident and if traffic signals were re-timed. The traffic signal re-timing was performed independent of the route guidance, and thus the controls were not integrated.

Hellinga and Van Aerde [1995] simulated ramp metering in INTEGRATION. They used a time of day fixed metering rate for a test network, and found a slight reduction (0.39%) in total network travel time. In order to gain a better insight into these minimal improvements, they performed

sensitivity analysis on the ramp metering implementation and network conditions. They discovered that the timing of implementation and metering rate had an impact on travel conditions, suggesting benefit to metering strategies which use real-time traffic data. Papageorgiou et al. [1990] simulated local (ALINEA) and coordinated (METALINE) ramp metering for the Boulevard Périphérique in Paris using METANET macroscopic traffic simulator. Both types of metering control were found to decrease the total travel time, with METALINE resulting in slightly better performance for non-recurring congestion. Zhang et al. [1995] used INTRAS microscopic traffic simulator to evaluate the impact of ramp metering strategies using different metering rates on a stretch of freeway in Pasadena, California. They found the strategies to have little mainline impact, but potentially disadvantageous impacts on ramps and surface streets.

Integration of individual components has been considered using simulation experiments. Reis et al. [1991] presented simulation experiments for the Integrated Motorist Information Systems (IMIS) project in Long Island, New York. A corridor was simulated using the SCOT macroscopic model. This corridor included the following traffic components: traffic detectors, ramp metering, traffic signals, and VMS. Nine typical scenarios were simulated using control and no control. These scenarios represented a range of demands and incidents that the corridor is likely to experience. The output of the control and no control designs were then compared for selected performance measures: travel time, vehicle miles traveled, maximum queue length, and congestion clearance after incident. The study found that the control design resulted in improvement in delay for all but one of the scenarios. This simulation study only considered the use of all controls or no controls, instead of also partial combinations of controls.

Another integrated control simulation study was performed by Gardes et al. [1993], investigating ATMS and ATIS control for the Smart Corridor in Los Angeles. There were three types of ATMS/ATIS controls used: ramp metering, traffic signal control, and route diversion. A no control case and five groupings of controls were simulated for the base condition using the INTEGRATION macroscopic model. The results compared total travel distance, total trip time, and average speed, and showed that the controls were synergistic, i.e. the scenario which used all control resulted in performance improvements greater than the sum of the performance improvements of the individual controls. This study considered control for recurring congestion, and did not investigate control modifications required for incident management.

1.5 Objective

The purpose of this thesis is to use a microscopic simulation laboratory for evaluation of integrated traffic control designs on a system-wide level. The MITSIM laboratory will be used for

this analysis. This laboratory was designed to evaluate DTMS over a range of circumstances, while taking into account the dynamic and variable nature of transportation systems. It integrates traffic control and vehicle routing with driver behavior models, providing an explicit consideration of the effects of DTMS on traffic flow [Ben-Akiva, 1997].

The interaction between individual vehicles and traffic control is the distinguishing feature of this laboratory. In the real world, traffic control affects driver behavior, which in turn impacts traffic flow. The same is true in this laboratory. MITSIM can mimic the traffic control being evaluated, both static and dynamic (including pre-specified and traffic responsive) control. The reactions of drivers to this control are explicitly modeled on a detailed network representation, capturing the sensitivities of traffic flow. To the best of our knowledge, MITSIM laboratory is a unique tool to perform an evaluation study for DTMS.

As the literature survey described, a number of studies have considered the use of various individual control components of traffic management. However, there has been little investigation into the integration of these components, none with a detailed simulation laboratory like MITSIM. This research will investigate the performance of an integrated traffic control design. It will also consider the effect of these controls at both the local and network levels, in order to fully evaluate the impact of traffic control. This is an important consideration, since a control device could potentially improve the conditions of the control area at the expense of other portions of the network, resulting in an overall increase in travel time.

This thesis will apply MITSIM laboratory for analysis of the traffic control for a real transportation network, the Central Artery/Tunnel (CA/T) Project network. The TMC of the CA/T, includes the following ATMS components which are used in the simulation study: LCS, VSLS, ramp metering, and route guidance. The uniqueness of this research arises from its elaborate experimental design applied to a real network, demand, and controls through the use of a realistic simulation laboratory, demonstrating how simulation can be used to evaluate DTMS designs and to derive insights for design refinement.

1.6 Organization of Thesis

This chapter provided the motivation for the need of ATMS and ATIS, how they operate, and research towards their design and implementation. Chapter 2 describes the evaluation methodology for DTMS evaluation. It also provides the background of the transportation project which is used for the simulation experiments. The third chapter presents two case studies for system-wide evaluation of DTMS. Chapter 4 summarizes the findings and lessons learned from the case studies, and Chapter 5 presents a summary, conclusion and future work in this area.

Chapter 2 - Evaluation Framework

Evaluation of DTMS design is important to identify its performance over a range of circumstances before the it implemented. Evaluation also helps refine the design by identifying shortcomings or conditions under which the design does not perform satisfactory. This chapter describes the microscopic traffic simulation laboratory used for evaluation, specifies the evaluation methodology, and provides background of a real project used in this investigation.

2.1 MITSIM Simulation Laboratory

The MITSIM traffic simulation laboratory is used for performing the simulation evaluation. This simulation laboratory consists of a Microscopic Traffic SIMulator (MITSIM) and a Traffic Management Simulator (TMS). MITSIM is a microscopic traffic simulator which models the behavior of individual vehicles. These vehicle movements are based on: their desired speeds, their lane changing behavior, their car-following behavior, and their responses to control. The interactions of individual vehicles with other vehicles and traffic control is explicitly modeled in MITSIM laboratory which allows MITSIM laboratory to be used for several types of applications. MITSIM laboratory can be used as a tool for transportation planning to forecast changes in traffic conditions due to level of demand. It can analyze the effect of adding a lane to a roadway section, changing the geometry, or adding a new road. However, MITSIM is developed to establish a laboratory environment for testing and evaluating the design of DTMS controls and strategies.

Additionally, MITSIM can be run in a graphical mode, visually displaying individual vehicle movements. This offers the advantage of being able to observe how vehicles behave in certain situations. For instance, one can see the impact of a ramp meter, by observing how vehicles merge from the on-ramp with and without the ramp metering. This can provide insights that simulation output alone cannot.

The next sections will describe the two components of the MITSIM laboratory. For a detailed description of the MITSIM laboratory, see Yang [1996].

2.1.1 MITSIM Traffic Simulator

MITSIM is responsible for the movement of vehicles in the network. It is comprised of three elements: the transportation network, the vehicles, and the driver behavior models.

Transportation Network

Networks in MITSIM are represented by nodes, links, segments, and lanes. Segments are portions of links which have uniform geometry, including the number of lanes. These lanes can be specified for high occupancy vehicles (HOV) or electronic toll collection (ETC) only. Lane level controls (LCS), toll booths, and surveillance devices are also presented.

Vehicles

Vehicles are stochastically generated from the travel demand. Travel demand is specified in MITSIM as time-dependent origin to destination (OD) trip tables which is in the form of the hourly demand for every O-D pair of each vehicle type. For each of these specified periods, vehicles are generated and enter the network with randomly distributed inter-departure headways based upon the traffic conditions.

Each vehicle possess the following attributes: vehicle type, vehicle class, information availability, and lane use. Vehicle type indicates if a vehicle is an old car, new car, bus, or truck. This classification affects the acceleration and emission parameters of the simulator's models. Vehicle class segments the vehicles by driver aggressiveness, which describes a driver's desired speed, acceleration, gap acceptance, and lane changing. The information availability attribute indicates if a vehicle can receive real-time traffic information (used for route guidance). The vehicles which are classified as informed, are able to communicate with the TMC, and may change their route based on the information they receive. The lane use privilege indicates if a vehicle is allowed to use special lanes, such as ETC and HOV lanes.

Driver Behavior Models

There are basically four driver behavior models: car following, event responding, lane changing, and vehicle routing. These models are based on the statistical distributions of behaviors among real drivers. Some of these driver behavior models have components. Table II-1 displays the driver behavior models and their individual components. The free flowing regime of the car following model is used to model a vehicle whose speed is not affected by the vehicle in front of it, while the car following regime models those vehicles which are affected by the lead vehicle. The emergency regime determines the vehicle's behavior when it is confronted by a situation which requires immediate deceleration.

The event responding model describes how vehicles behave under special circumstances, such as traffic signals and signs, incidents, connection to the next link of the vehicle's path, and courtesy yielding to another vehicle changing lanes or merging.

There are three components in the lane changing model. The first component determines if a lane change is necessary based the travel speed and destination, and if it's a mandatory or discretionary; the next component determines the target lane; and the final component is the gap acceptance model, which determines if the gap in the destination lane is acceptable to the driver. For a detailed description on the lane changing model in MITSIM please see Ahmed [1996].

Table II-1 Driver behavior models and components of MITSIM

Model	Component
Car Following	Free flowing regime
	Car following regime
	Emergency regime
Event Responding	Traffic signals and signs
	Incidents
	Connection to downstream link
	Courtesy yielding
Lane Changing	Checking if a change is necessary and define type of change (discretionary or mandatory)
	Selecting the desired lane
	Gap acceptance
Vehicle Routing	

The vehicle routing model is responsible for simulating drivers' route choice decisions and responses to traffic information. A C-Logit model is used for predicting drivers' route choice behavior [Cascetta, 1996]. The variables used by the model are the expected link travel times and freeway bias. Freeway bias represents drivers preference for using freeways instead of urban roads. These expected link travel times are based upon historical travel times for uninformed drivers and correct a predicted travel time for informed drivers [Yang, 1996].

2.1.2 Traffic Management System

TMS is responsible for simulating the operations of the TMC. It receives information about traffic conditions and recommends the state of the control devices. Surveillance systems in MITSIM collect traffic data from the network and communicate them to TMS. For example, a ramp metering algorithm may use a target occupancy level to determine when the meter should be activated. TMS receives occupancy data from a sensor and recommends an appropriate metering rate which is implemented in MITSIM. It should be noted that we use more sensors in our study than included in the real-world network. This is done to analyze traffic flow at a desired level of detail.

MITSIM supports the control of the following traffic and route guidance devices: traffic signals, stop signs, ramp meters, lane control signals (LCS), variable speed limit signs (VSLs), variable message signs (VMS), portal signals at tunnels, and electronic route guidance devices. These controls can be segment-wide (e.g. VMS) or lane specific (e.g. LCS) and they are characterized by their location, initial state, and visibility.

2.2 Evaluation Methodology

In order for proper evaluation of DTMS, an established methodology must be followed. This section describes the methodology used for this research. A detailed description of an evaluation framework and methodology can be found in Jonnalagadda [1992].

There are three major components in an evaluation project: 1.) the input scenario, 2.) the control design, and 3.) the measures of effectiveness. The following sections will describe each of these components and their role in the evaluation.

2.2.1 Scenarios

The scenario is the input which drives the evaluation and represents the real-world conditions which could occur. It is designed to challenge the control system. Therefore, it is necessary to design scenarios which provide a wide-range of conditions to test the robustness of the control system. Three types of scenarios should be designed for a complete evaluation:

1. the free-flow traffic condition
2. moderate congestion - resulting from an increased level of demand or capacity reduction
3. severe congestion - typically resulting from very high demand levels, severe incidents, or both.

A scenario has two inputs: the travel demand and the network supply.

Demand

The demand is typically specified in the form of origin-destination (OD) matrices, which vary depending on the time of day and vehicle class. Vehicles are classified based upon vehicle occupancy and vehicle type (trucks and buses, etc.). In planning work, demand is typically considered at the traffic analysis zone level. Depending on the level of detail of the network, origins and destinations can represent groups of zones, zones, or sub-zones. The network used in this research is very detailed, and thus origins and destinations are treated at a sub-zone level.

Demand for transportation systems are typically determined for the peak and off-peak periods. The demand for a scenario can be specified as a fraction of the peak or off-peak period demand. For example, a 70% of the PM peak period demand level represents 70% of the number of trips for the PM peak for all OD pairs and vehicle classes.

Supply

The supply of a transportation network is described as its capacity. It can be varied in scenario design by events, such as incidents, which alter the capacity. Extent of capacity reduction depends on the type of incident which may include: an accident, vehicle breakdown, debris spillage, equipment failure, or weather conditions. An incident typically disrupts traffic flow, resulting in capacity reduction.

The severity, number of lanes, location, and duration of an incident have an impact on the resulting lost capacity. The severity describes whether the incident causes a lane to be closed or if it only results in a speed reduction. The location of the incident is also important. Identical incidents placed in different locations may result in different capacity losses. The incident duration plays an obvious role in the reduction of capacity, with longer incidents resulting in capacity reduction of longer periods.

2.2.2 Control Design

For a given scenario, control strategies are designed and tested. In this study, each control strategy can be formed as combinations of the following DTMS components:

Lane Control Signals (LCS): The primary purpose of LCS is to provide advance warning to drivers about lane specific traffic conditions. They are typically used to facilitate a smooth lane changing by informing drivers about an impending bottleneck. The bottleneck can be either due to the geometry (for example a heavy merge or weaving) or a lane closure.

Variable Message Signs (VMS): VMS are probably the most diverse component of ATMS. It can be used in a variety of circumstances: lane closure situation, delay warning, route advisory and so on. Typically, VMS are used to supplement other advisory/control signals and as a result, it is often very difficult to separate their impact from other devices on driver behavior.

Variable Speed Limit Signs (VSLs): VSLs are changeable displays of the speed limit of a roadway section. Unlike a typical speed limit sign, VSLs can be varied depending on the traffic conditions.

Ramp control: Ramp meters are traffic signals placed at on-ramps to limit the flow entering the highway from a ramp. There are many algorithms for ramp control. The purpose of ramp control is to achieve a maximum mainline flow by restricting the entry from ramps.

Route diversion: There are two characteristics which describe route diversion: the type of information provided, and the basis of that information. The type of information provided can either be descriptive (it provides information about current network conditions) or prescriptive (it suggests an alternative route). The information can be based upon existing or predicted conditions.

It may be beneficial to design the control strategy in stages. An initial design can be developed and tested. After the results are analyzed, design refinements can be developed based on the insights gained from the initial design. This process can be completed as many times as necessary to develop a satisfactory control design.

2.2.3 Measures of Effectiveness

The measures of effectiveness (MOEs) are used to evaluate the performance of a control design. It is useful to consider multiple measures of effectiveness to evaluate the designs on several levels. This could be very important in situations when a design performs well with respect to one MOE, but poorly for other MOEs. Consideration of all of these MOEs allows the decision-makers to fully understand the impact of the implemented design. A multi MOE based evaluation allows for control designs to be re-evaluated if the objective changes without re-running the simulation experiments. There are a number of different criteria goals and measures which can be used for the evaluation, see Ben-Akiva [1995] for a comprehensive list. Some of the more important measures are:

Total System Travel Time. This measure considers the total amount of time experienced by all vehicles in the network. Thus, it is a good measure to evaluate system performance of the control design for the entire network.

OD Travel Time. OD travel times consider the amount of travel time incurred by vehicles traveling between specific OD pairs. This measure can be used to consider the effect of control on certain groups of vehicles. For instance, it can consider a group which includes all vehicles that pass through the incident location.

Variability of Travel Time Savings. It is important to consider the impact of control on specific groups of vehicles. In economics, Lorenz Curves are used to show the distribution of benefits [Eckert, 1988]. Similar curves can be created by plotting the

cumulative travel time savings versus number of vehicles to provide insight into the uniformity of travel time savings for different groups of vehicles. The closer the curve is to a straight line, the more uniform the travel time change. This measure should not be used alone for evaluation, but rather as a secondary measure to indicate the control's effect on different groups.

Speed. Speed is a good indication of how smoothly traffic is moving. It can be expressed in several ways. It can consider how speed varies with time for a given location, how speed varies with location for a given time, or even how speed varies across lanes of a roadway section. Speed variability can also be considered to determine which control design results in uniform speeds at different locations. This indicates the amount of accelerations and decelerations in the network.

Throughput. Throughput is the number of vehicles which pass a given section during a specified time period. It is often a good measure to be used in conjunction with other measures to verify that a design has not caused a bottleneck upstream. For example, speeds in a section may improve since controls restrict flow upstream of this section. This can be identified by a reduction in throughput of that section.

2.3 Application to the Central Artery/Tunnel Project

The Central Artery/Tunnel (CA/T) Project in Boston is used as the test network for the evaluation study presented in this thesis. An overview of the CA/T project is given, followed by a description of previous evaluations of the control design for this project.

2.3.1 Central Artery/Tunnel Project

The CA/T Project is the largest highway project in the United States. The project will replace the existing Central Artery (I-93) and connect the Massachusetts Turnpike (I-90) to Logan International Airport, completing the final link of the Interstate Highway System. It is a 7.5 mile interstate highway, approximately half of which will be built as a tunnel. Figure II-1 displays the CA/T network. The tunnel design makes the CA/T network unique and creates a number of challenges to drivers and designers of the network. In addition, the network is expected to carry a large demand of 250,000 daily trips through the Central Artery and 100,000 daily trips through the Ted Williams Tunnel by the year 2010. For a more detailed description of the CA/T project, see Hotz, et al. [1994].

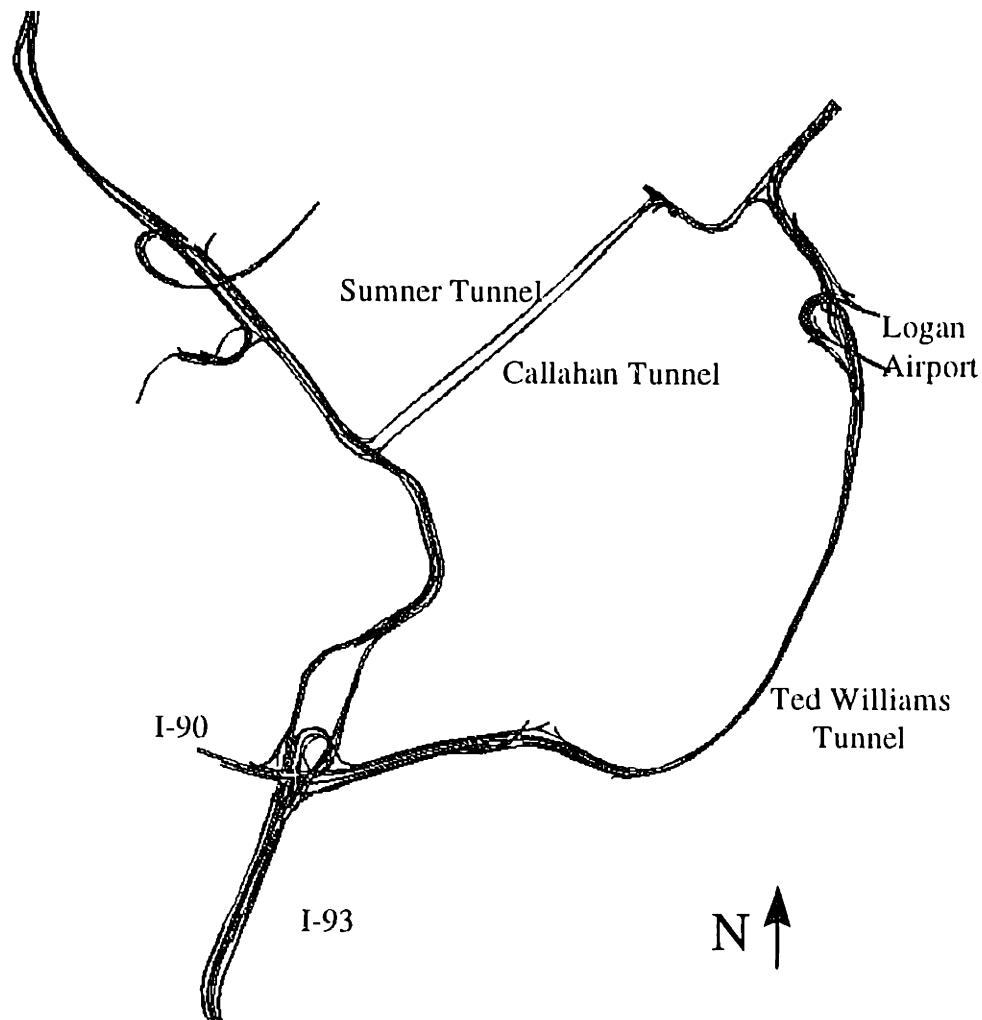


Figure II-1 The Central Artery/Tunnel network

2.3.2 Integrated Project Control System (IPCS) of the CA/T Project

The Integrated Project Control System (IPCS) is responsible for the dynamic control operations of the CA/T. Its primary purpose is to collect and manage information needed to support CA/T operations. Its design needs to address the following two concerns in the CA/T's tunnel design:

1. From a driver's perspective, this road system will pose an extra burden in terms of comfort, safety and familiarity with the driving conditions due to its unique tunnel construction, thus requiring a more effective and efficient traffic control system.
2. From a traffic flow perspective, it is highly desirable to maintain a level of service in the tunnel which is able to prevent drivers from being exposed to Carbon Monoxide (CO) for an extended duration.

The IPCS will be located at the operational control center for the Central Artery. It will integrate traffic surveillance, incident detection, control devices, and fire and safety systems. The following is a list of components which will be controlled at the CA/T's TMC:

- video traffic surveillance
- loop detector surveillance
- emissions monitors - these will be used to track the levels of different vehicle emissions, such as CO.
- fire monitors - will be able to identify when there is a fire in any of the tunnels
- overheight vehicle detection - will check all points of entry into tunnels to make sure that vehicles which are too tall for the tunnel do not enter the tunnel.
- lane control signals (LCS)
- variable message signs (VMS)
- variable speed limit signs (VSLS)
- ramp meters
- route guidance
- highway advisory radio (HAR) - the tunnel is equipped to provide local radio stations of the Boston area. This will allow the control center to preempt the local signal with any necessary messages.
- ventilation system - this system will be operated to keep exhaust levels below the threshold.
- electronic toll collection system

A number of studies have already considered evaluation of portions of the IPCS design. Gua, et al. [1995] investigated electronic toll collection. Jha et al. [1997] studied the usage of ramp meters, while Jha et al. [1998(a)] evaluated the design of LCS and VMS for incident management. By evaluating the use of multiple IPCS components, this study will consider a wider range of the IPCS. It will also increase the scope of evaluation by considering a larger portion of the CA/T network than previous studies.

Chapter 3 presents two case study evaluations using the MITSIM laboratory and CA/T network.

Chapter 3 Case Studies

This chapter presents two integrated DTMS simulation evaluations. Chapter 2 described the evaluation process, and this chapter presents its implementation. The first section of this chapter depicts the control designs which will be evaluated by MITSIM. This is followed by a presentation of the output measures that this evaluation is based upon. Then simulation results from the two case studies are presented. The first case study simulates the use of control in response to an incident in the Central Artery (I-93 northbound), while the second case study evaluation simulates an incident in the Ted Williams Tunnel. For each case studies, first the scenarios are described, then the results are presented and analyzed.

3.1 Control Designs

Case studies presented in this thesis evaluate various control designs for the CA/T network. The control designs are developed from a bottom-up approach, i.e. the most basic components are used first, and additional components are added later. Finally, a complete design using all control is constructed. Coordination refers to control of different devices of the same type, while integration is concerned with the use of different types of controls. For example, ramp meters in different portions of the network should have their implementation *coordinated*, while the control of ramp metering and route diversion need to be *integrated* to ensure that they have the same objectives. The following devices are used to form the control designs:

Local Controls

LCS - This is a local control which is used upstream of the incident to improve the lane changing of vehicles. The proposed spacing between LCSs in portions of the CA/T network is 300 feet, much closer than other roadway networks, where LCS spacing is typically more than 1500 feet. The effect of lane control has previously been studied by Jha et al. [Jha, 1998(a)].

VSLs - These controls are used for 2 reasons: 1.) to increase speed uniformity, which should increase safety, and 2.) to reduce waiting time in the incident queue by delaying vehicles' arrival at the incident site. When the demand is too low, this control could result in an increase in travel time, since the VSLs may unnecessarily delay vehicles.

Area-wide Controls

Route Diversion - Route diversion helps vehicles divert from the affected area to another route. It is more effective when attractive alternate routes exist. In MITSIM route diversion is descriptive, providing vehicles with updated link travel times. This differs from other types of route diversion which are prescriptive, instructing vehicles to use an alternate route.

Ramp Metering - The goal of using ramp metering for incident management is to allow the optimal number of vehicles to enter into the incident area by controlling the on-ramp flow. The ALINEA ramp metering algorithm is used. The advantages of this algorithm are its simplicity, data requirements, and its proven performance through both simulation and field tests [Papageorgiou, 1997]. For detailed microscopic simulation results see Jha [1998(b)].

These devices will be combined to form the following control designs used in the evaluation:

No Control: For each demand level, we simulate a scenario without using any control. Together with no incident, it forms the basis of evaluation for the other control designs.

Design 0: This is called the base design. It uses LCS (with VMS to reinforce the message) and VSLS as an operator's response to the incident. These controls are used regardless of their effect on system performance due to safety considerations. The LCS design consists of one red "X" and four yellow "X"s upstream of the incident. The LCSs indicates that a lane is closed ahead and that drivers should change lanes. In addition, two upstream VMS are used to identify the location of the incident and advise drivers of closed lanes. This design was found to perform best for local incident management [Jha, 1998(a)].

VSLS is used to further reduce the safety risk associated with an incident. VSLS reduce speed variability amongst drivers in a given location, creating a more uniform speed distribution [Smulders, 1990]. A more uniform speed distribution reduces the occurrence of accidents, thus lowering the potential of a secondary accident. In these case studies, the VSLS reduce the speed limit from 50 mph to 30 mph upstream of the incident is response to an incident.

Design 1: This is an advanced control design which adds route diversion to Design 0. Information about current travel conditions are provided to help drivers change routes. This travel time information is estimated from sensor data, thus route diversion acts as a traffic responsive control.

Design 2: For this design, ramp metering is added to Design 0. The ALINEA algorithm with a 19% target occupancy and a queue constraint is used to control the ramp metering. These parameters were selected based on the previous work in this area. [Jha, 1998(b)]. The ALINEA algorithm tries to maintain an occupancy which maximizes the throughput across the downstream section. For a more detailed description of the ALINEA algorithm, please see Papageorgiou [1997]

Design 3: This design combines all of the control devices. It adds both route diversion and ramp metering to Design 0. The route diversion is used in the same manner as in Design 1. Likewise, the ramp metering uses the ALINEA algorithm in the same way as Design 2. Thus,

Design 3 is a naively integrated design which does not attempt to jointly optimize the independent control algorithms. This could be a useful area of future research.

Case Study 1 simulates the use of all of these control designs, while Case Study 2 only uses no control, Design 0 and Design 1 due to the incident location, which is described in Case Study 2. Additional details of the control usage in each case study is described in later sections.

3.2 Output Measures

Output measures are used to evaluate control design performance. The following measures of effectiveness (MOEs) are used for evaluation in these case studies: Total Travel Time, Mainline Travel Time, Travel Time Savings Across OD Pairs, and Speed. This chapter presents analysis of the effectiveness of control designs based upon these measures, providing policy-makers the information needed to select a control design.

3.2.1 Total Network Travel Time

The total travel time indicates the impact of control designs on the system performance for all vehicles. For this analysis, the total travel time represents the summation of the individual travel times experienced by all vehicles in the network which departed between 4:40 and 5:30 PM of a simulation which begins at 4:30 PM. For each case study, one table presents the total travel times for control designs in each scenario, and another table presents for each design the incident delay and the travel time savings as a percentage change in incident delay.

3.2.2 OD Specific Travel Time

A traffic control's impact may vary across OD pairs. This MOE considers the travel times of specific OD pairs which are of particular concern. For example, the travel time of all vehicles which use the mainline of a roadway may be considered to demonstrate the control design's impact on the vehicles who are directly affected. Policy decisions about the operation of roadways are often concerned with the impact on the mainline operations, and this measure can be used to support these decisions. Similar to total travel time, two tables are also presented for OD specific travel time: one table with travel time values of controls for each scenario, and one table presenting incident delay and travel time savings as a percentage change in incident delay.

3.2.3 Travel Time Savings Across OD Pairs

When designing a control strategy, it is important to not only consider the impact of the design on total travel time, but also the variation of impact across OD pairs. Analysis of individual OD travel times can

provide this insight. This measure considers the travel time change for both vehicles which are directly affected by the incident and control and vehicles subject to secondary impacts of the incident.

An effective control design should decrease the overall travel time without severely penalizing individual OD pairs. In order to identify the distribution of the travel time savings, the cumulative travel time savings is plotted against the number of vehicles. In economics, Lorenz Curves are used to show distribution of benefits [Eckert, 1988]. This cumulative travel time savings plot attempts to identify the distribution of travel time savings. The travel time savings is the decrease in travel time due to a control design, compared to no control. The vehicles are plotted by increasing value of travel time savings per vehicle. Thus, the vehicles plotted nearest to the y-axis have the smallest travel time savings. A negative travel time savings indicates additional delay due to control.

The ideal control design will equally improve travel time for all vehicles. Thus the cumulative travel time savings plot would be a straight line from 0 to 100% of the total travel time savings. When comparing designs, the closer the cumulative travel time savings plot is to a straight-line, the more evenly distributed the benefits are. It is important to use this as a secondary measure of effectiveness, since it is possible for a design to have a straight cumulative travel time savings plot, but little network improvement. The use of this measure together with travel time provides more insight into the effectiveness of a control design than each measure independently.

3.2.4 Speed Plots

Speed plots in the vicinity of the incident may also provide additional insights into the use of controls. These plots show the spatial speed profile of a roadway section and can thus identify acceleration and deceleration patterns. A good control design should not cause large accelerations and/or decelerations. These plots also provide some insights which travel time alone can not. For example, the travel time measures can identify when a control design improves conditions, but the speed profile can identify the location specific improvements.

3.3 Case Study 1 - Incident in the Central Artery

This case study investigates the use of traffic controls to improve the overall network conditions when there is an incident in a weaving section. The primary purpose of this case study is to evaluate the effectiveness of combinations of traffic control. It identifies control combinations that improve traffic conditions for different scenarios. It also identifies when a control needs refinement of design. Another significant purpose of this case study is to analyze control designs on a network level, instead of only at a local level. By considering the entire network, control strategies which may deteriorate total travel conditions despite improving the local area can be identified.

Control devices used in this case study are: LCS, VMS, VLS, route diversion, and ramp metering. The case study is comprised of multiple scenarios, representing different demand levels. It uses an identical incident for each scenario.

3.3.1 Incident Location

The incident is placed in northbound I-93, in the tunnel portion of the section known as the Central Artery, as seen in Figure III-1. It is located in the right lane downstream of Ramp-C and upstream of an exit to city streets (see Figure III-2). Ramp-C is an on-ramp from I-90, eastbound and westbound. The exit to city streets is located about 500 ft. south of the Callahan Tunnel.

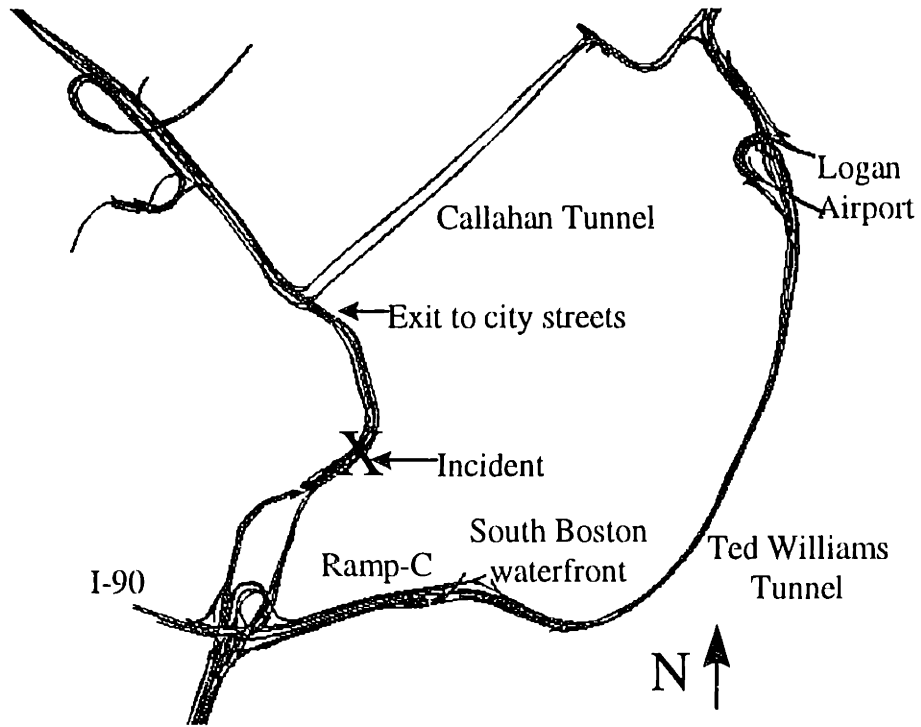


Figure III-1 Case Study 1 - Incident location

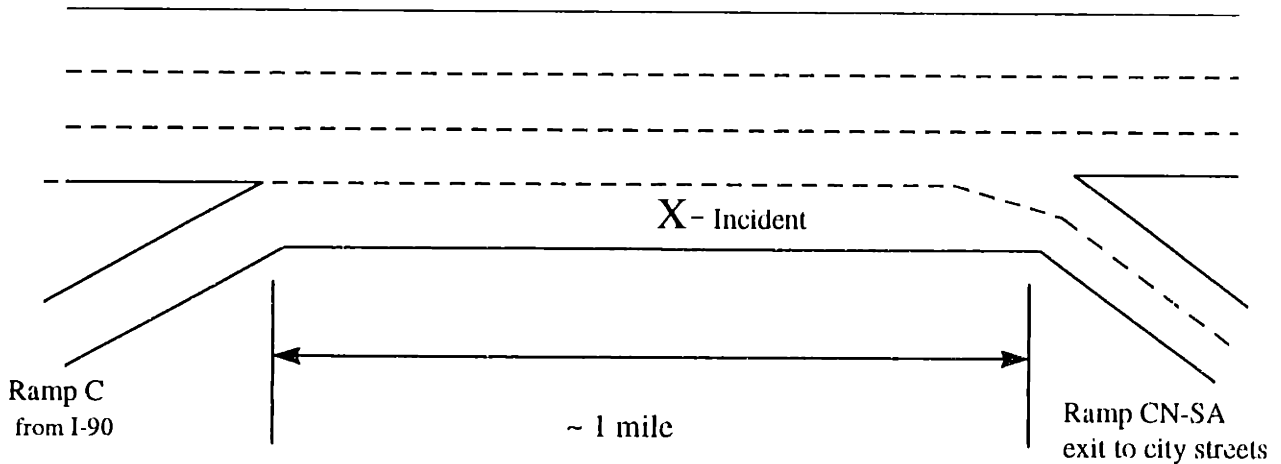


Figure III-2 I-93 northbound configuration near incident

Simulations are run during the 4:30-6:30 PM peak period, and the incident occurs between 4:50 and 5:10 PM. The first 10 minutes of simulation are used to load the network. The control is activated at 4:55 PM. Thus, the total time for incident detection, confirmation and activation of the control system is assumed to be 5 minutes. At 5:10 PM the blockage is removed. The simulations continue until all vehicles departing by 5:30 PM reach their destinations (typically by 6:00 PM). This period is required since results are presented for vehicles departing between 4:40 and 5:30PM.

3.3.2 Scenarios

Chapter 2 described a range of scenarios which should be used for an evaluation: free-flow conditions, moderate congestion, and severe congestion. In order to obtain the effectiveness of design over this full spectrum, six scenarios are used. In this study, a scenario is defined by an incident and a demand level. Six demand levels are used: 60%, 70%, 80%, 90%, 100%, and 110% of the 2004 PM peak period demand tables provided by the Bechtel / Parsons-Brinckerhoff CAT project management with assistance from the Metropolitan Planning Organization of Boston. Demand lower than 60% is not used since a one-lane incident at this demand does not cause enough congestion to warrant the use of traffic control for any reason other than safety. It is unlikely to observe a demand higher than 110%, and the network is also almost in a gridlock situation at this demand. Therefore, we did not simulate higher demand. However, there may be a potential for system improvement through incident management at higher demands, which should be investigated in future work.

Additionally the demand for the two OD pairs has been increased:

- From the South Boston waterfront origin, located just west of the Ted Williams Tunnel, to the destination represented by the exit to the city streets, located downstream of the incident
- From Logan Airport to the same exit to the city streets.

These origins and destinations are identified in Figure III-1. The airport demand is increased to represent a large air travel period, for example, a Thanksgiving weekend. The South Boston waterfront origin is an industrial/commercial area which is subject to fluctuations in demand.

Additionally, a no incident case is simulated for comparison. This case is actually a separate scenario since it uses a different network supply. It is necessary to simulate this case in order to identify the effect of the incident, before distinguishing the effect of the control design.

Section 3.1 described the control designs used in the evaluation. In this case study, all control designs (no control and Designs 0 through 3) are simulated for each scenario, along with the no incident case. Two sets of simulations are also required for each scenario to develop historical link travel times of the no incident and incident situations. Thus, eight sets of simulations are performed for each of the six scenarios. Ten replications are performed for each set of simulations. Therefore, a total of 480 replications of simulation are performed in this case study.

Use of Route Diversion

In this case study, only two OD pairs have alternative routes. One of these OD pairs is from the South Boston waterfront to the exit to local streets. These vehicles normally use westbound I-90 and northbound I-93 to reach their destination. The incident is located in this section of I-93 northbound. In the real-world, there are urban streets which offer an alternative route for these vehicles. But the CA/T network used in MITSIM does not include these urban roads. In order to simulate this alternative, it is necessary to add an additional link to the CA/T network to represent these local streets, as seen in Figure III-3.

The other OD pair with alternative routes is from the airport to the exit to the local streets. It is important to understand the representation of this destination in MITSIM. The destination in the simulation network is an exit ramp to local streets. To an individual making a trip, the destination is a location accessed from the highway by that exit ramp. There is another exit in the CA/T simulation network which serves the same real-world destinations. This exit is shown in Figure III-3 as the Sumner Tunnel city street exit. When the demand matrix was prepared for simulation, the number of vehicles traveling from the airport to these real-world destinations was split into two OD pairs: one representing travel via the Ted Williams Tunnel, and the other for travel through the Sumner Tunnel. This split was based upon the forecasted split during typical conditions. In order to represent a realistic route diversion scenario, the opportunity must be provided for these vehicles to determine their route independent of the pre-specified split. Therefore an additional link was placed in the CA/T network connecting the Sumner Tunnel to the local street exit.

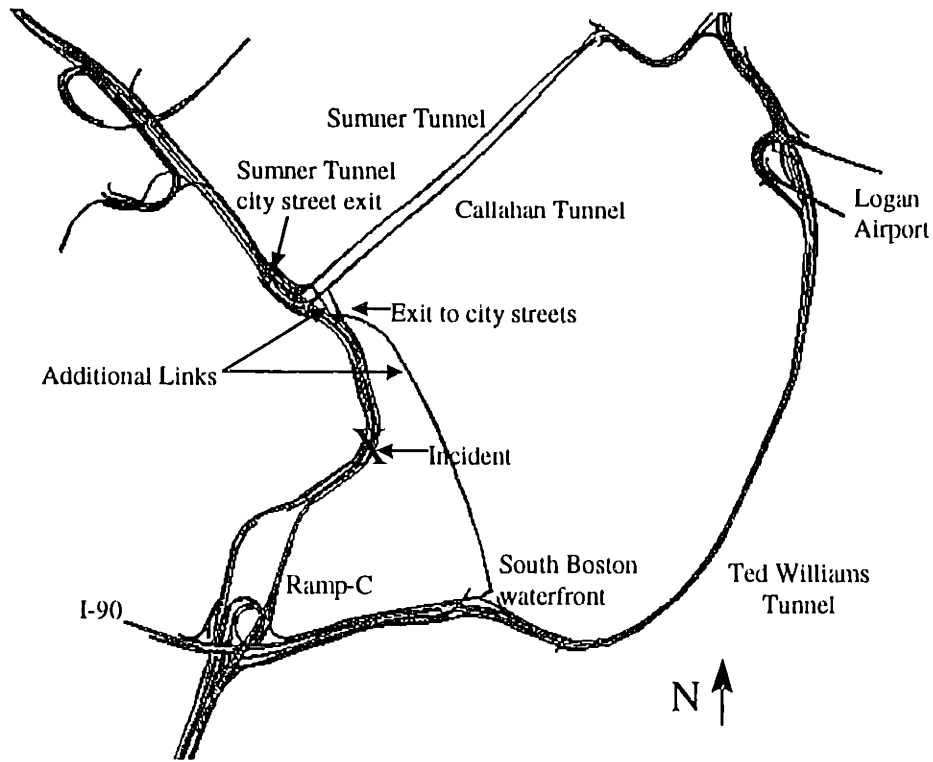


Figure III-3 Modified CAVT network for Case Study 1

Use of Ramp Metering

In this case study, Ramp-C, the entrance ramp to northbound I-93 from I-90, is metered during the duration of the incident and the recovery period. Once the incident congestion is over, the ramp metering is shut off.

3.3.3 Results

The results of Case Study are presented in this section. This section begins by showing the travel time tables which include the results of all scenarios and is followed by the results and analysis for each scenario.

The total network travel times for each design and scenario combination are shown in Table III-1. As mentioned previously, these travel time values indicate total travel time experienced by all vehicles which departed between 4:40 and 5:30 PM. Table III-2 presents the travel time savings as a percentage of incident delay for all vehicles, and the total network incident delay for each scenario. For this case study, OD specific travel times are considered only for the mainline vehicles passing through the incident. These vehicles originate from the southbound limit of I-93, Ramp-II and Ramp-LL. Ramp-II and Ramp-LL are upstream of Ramp-C and are shown in Figure III-1. Table III-3 shows these mainline travel times for all designs and scenarios. Table III-4 shows the travel time savings as a percentage of

incident delay for these vehicles. The accuracy of travel times was found to be within 2% of the mean at the 95% confidence level using 10 replications of simulation.

Table III-1 Total network travel time (in minutes) -Case Study 1

Demand	no inc	no control	Design 0	Design 1	Design 2	Design 3
60%	54395	54896	55504	55505	55559	55491
70%	65915	68857	68412	68390	68654	68490
80%	78846	92431	90886	89660	91178	89329
90%	90069	126667	124836	123050	126574	122019
100%	145638	179476	179480	175762	177932	175491
110%	232742	276216	274981	272384	273954	272721

Table III-2 Travel time savings as % of incident delay for all vehicles -Case Study 1

Demand	Inc Delay	Design 0	Design 1	Design 2	Design 3
60%	501	-122%	-122%	-133%	-119%
70%	2942	15%	16%	7%	12%
80%	13585	11%	20%	9%	23%
90%	36597	5%	10%	0%	13%
100%	33838	0%	11%	5%	12%
110%	43474	3%	9%	5%	8%

Table III-3 Mainline travel time (in minutes) -Case Study 1

Demand	no inc	no control	Design 0	Design 1	Design 2	Design 3
60%	10900	11258	11796	11802	11788	11801
70%	13737	15934	15883	15838	15514	15431
80%	17356	28666	27598	27443	26560	26035
90%	25296	47880	46490	48144	47855	47085
100%	52612	76688	75790	78311	74503	78301
110%	82516	111136	110623	116337	110362	115859

Table III-4 Travel time savings as % of incident delay for mainline vehicles -Case Study 1

Demand	Inc Delay	Design 0	Design 1	Design 2	Design 3
60%	358	-150%	-152%	-148%	-152%
70%	2197	2%	4%	19%	23%
80%	11309	9%	11%	19%	23%
90%	22584	6%	-1%	0%	4%
100%	24077	4%	-7%	9%	-7%
110%	28619	2%	-18%	3%	-17%

The speed profile plots for Case Study 1 are displayed in Appendix B in Figures B-1 through B-30. A set of five time dependent speed profile plots are presented for each scenario - one each for the incident periods of 4:55-5:00 PM, 5:00-5:05 PM, and 5:05-5:10 PM, and the recovery periods of 5:10-5:20 PM and 5:20- 5:30 PM. Each plot shows the speed along ten sensor (loop detectors) stations upstream of the incident. Figure B-31 shows the locations of these sensor stations, with Sensor Station 1 immediately upstream of the incident, and the sensor station numbers increasing opposite the direction of the flow.

Scenario - 60% Demand

Travel Time

Table III-2 shows that the incident delay at 60% demand was only 501 minutes for the entire network. It also shows that all of the control designs increased the travel time compared to no control. Designs 0 through 3 resulted in delay increases of 122%, 122%, 133%, and 119% of incident delay respectively.

The additional delay due to control was primarily due to a low traffic volume on the network. The incident does not cause substantial delay at this demand level. The VSLs slowed vehicles as they pass through this section to obtain a more uniform speed distribution. Since the incident congestion did not otherwise slow vehicles, the control designs increased travel time through this section. Design 2, which used ramp metering, performed slightly worse than the other designs. This indicates that the ramp metering algorithm may not be effective at this demand level. Similar results have been found by Jha et al. [1998(b)].

Table III-4 shows that all of the control designs also increased mainline travel time compared to a no control case. Results are similar to total travel time, indicating that the demand was too low to cause substantial incident delay. Without substantial incident delay, the local control increased travel time.

Figure III-4 shows graphically that all control designs resulted in similar travel time increases for both total and mainline travel times, with Design 2 causing slightly more delay to the entire network, but slightly less delay to the mainline. In order to avoid additional delay, controlling the designs in a traffic responsive manner should be investigated.

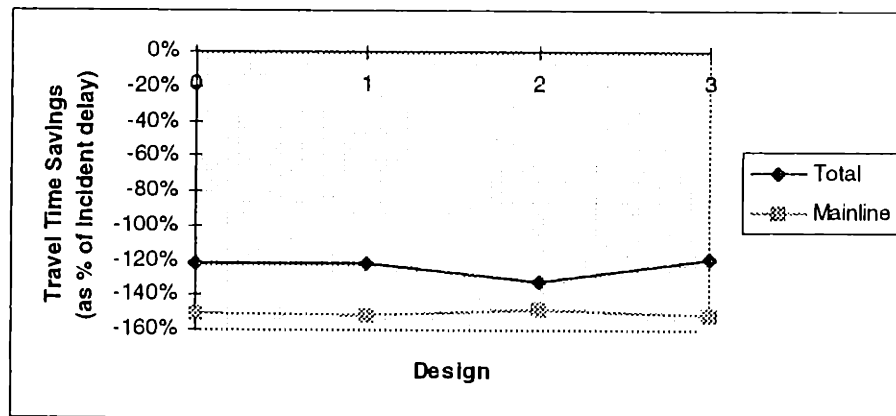


Figure III-4 Travel time savings for 60% demand -Case Study 1

Travel Time Savings Across OD Pairs

The total network travel times and mainline travel times indicated that the incident delay was not large, and all designs resulted in increases in travel time. Therefore, the cumulative travel time savings plots for all control designs resulted in curves with negative values. Figure III-5 shows that these curves are similar for all control designs. Thus, these plots do not provide much insight at this demand level.

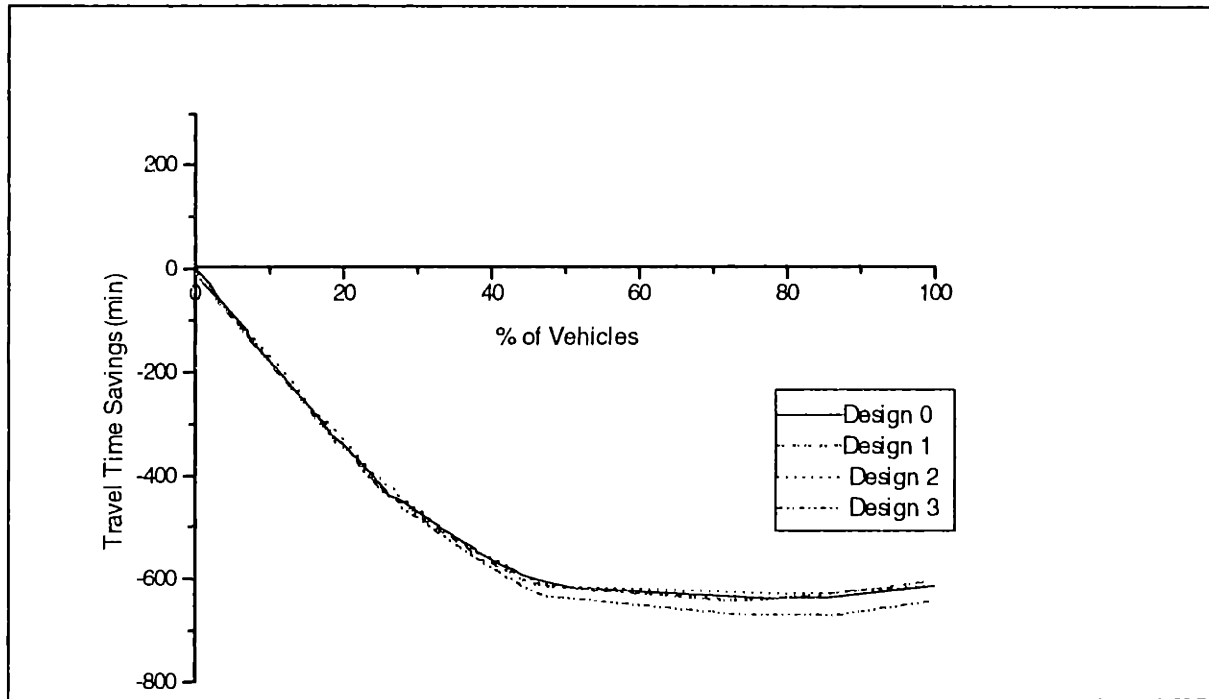


Figure III-5 Travel time savings distribution for 60% demand -Case Study 1

Speed Plots

From Figures B-1 through B-5, it is clear that all control designs resulted in similar decreases in speeds upstream of the incident for 60% demand. It is understandable that the designs had similar speeds since the VSLS have the most effect on speed at this demand level.

Scenario - 70% Demand

Travel Time

All control designs outperformed the no control case for 70% demand when considering total network travel time, as seen in Table III-2. The incident delay experienced by the total network was 2,942 minutes. Design 1 performed the best, followed by Designs 0, 3 and 2 with delay reductions of 16%, 15%, 12%, and 7% respectively. The small improvements for Designs 2 and 3 indicate that the ramp

metering algorithm was not beneficial for the system at this demand level. This indicates the need for better integration of ramp metering, which considers its interactions with the other controls.

Table III-4 shows that all control designs decreased mainline travel time at 70% demand. The mainline incident delay was 2,197 minutes, and Design 0 reduced this by 2%. Each subsequent addition of a control component resulted in further improvement. Designs 1 and 2, reduced the incident delay by 4% and 19% respectively. The most incident delay, 23%, was caused by the full integration of controls in Design 3. This shows that the integration of all controls resulted in the best condition for mainline vehicles at this demand.

The graphical representation of the total network and mainline travel time savings are shown in Figure III-6. This figure illustrates how Designs 2 and 3 which used ramp metering caused a larger reduction in delay for mainline vehicles, but not as large of a travel time savings for the entire network.

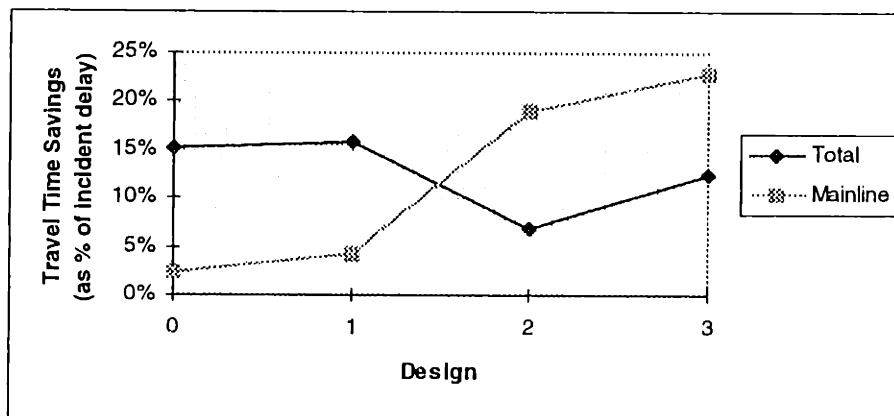


Figure III-6 Travel time savings for 70% demand -Case Study 1

Travel Time Variance

Figure III-7 displays the cumulative travel time savings for 70% demand. It indicates that Designs 2 and 3 result in less uniform travel time savings than Designs 0 and 1. The curves of Designs 2 and 3 reach a larger negative cumulative travel time savings value and stay negative longer, indicating that a larger number of vehicles' travel times were adversely affected by the control design. This uneven benefit of Designs 2 and 3 can be attributed to ramp metering.

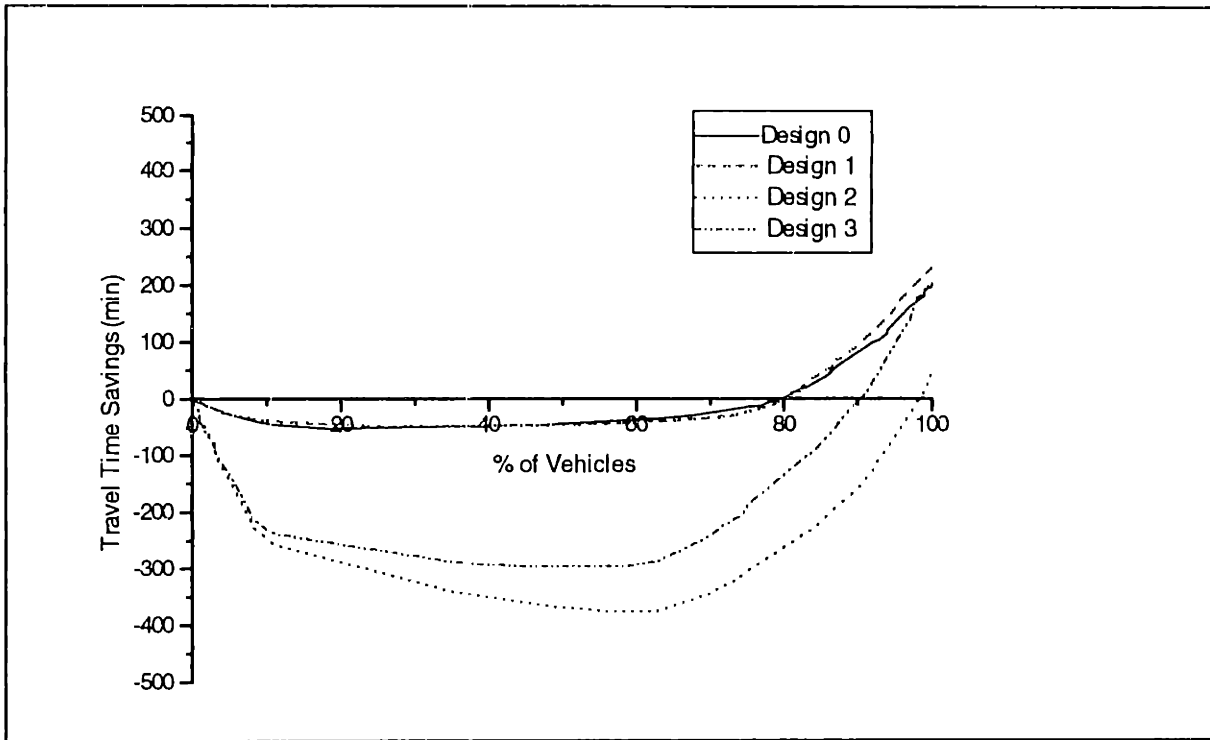


Figure III-7 Travel time savings distribution for 70% demand -Case Study 1

Speed Plots

The speed profiles for 70% demand are displayed in Figures B-6 through B-10. During the incident (4:55- 5:10 PM), the control designs typically resulted in faster speeds than no control, except beyond the incident congestion. This occurred at Sensor Station 8 in Figure B-6 and Sensor Station 10 in Figure B-7. Designs 2 and 3 resulted in the highest speeds, demonstrating the impact of ramp metering. The speed improvements from Designs 0 and 1 indicate that the local control (LCS and VSLS) alone were able to improve speeds in the vicinity of the incident.

Scenario - 80% Demand

Travel Time

At the 80% demand level, all control designs outperformed the no control case when considering total network travel time, as seen in Table III-2. The incident resulted in total network delay of 13,585 minutes which was reduced by Designs 0, 1, 2, and 3 by 11%, 20%, 9%, and 23% respectively. Addition of ramp metering alone (Design 2) to Design 0 did not result in further improvement, but when used in conjunction with route diversion (Design 3) it did cause further improvement. Ramp metering may not have worked without route diversion due to a high ramp demand. When some of the ramp vehicles were diverted with a resulting lower ramp demand, the metering had a positive impact. This indicates that the

ramp metering implementation needs refinement either in terms of algorithmic enhancement, parameter calibration, or a better integration. The fully integrated design (Design 3) resulted in the largest delay reduction, indicating that use of all controls resulted in the best network travel times at this demand level.

Table III-4 shows that all control designs also improved the mainline travel times at 80% demand. The incident delay was 11,309 minutes in this case, and Designs 0, 1, 2, and 3 reduced this delay by 9%, 11%, 19%, and 23% respectively. The delay reduction due to Design 0 shows that local control alone improved travel time for mainline vehicles. The additional delay reductions due to Designs 1 and 2, indicate that route control and ramp metering each further reduced mainline congestion. Design 3's performance indicates that a full design resulted in the least travel time for the mainline vehicles at 80% demand, similar to the case of total network travel time.

Figure III-8 graphically presents the total network and mainline travel time savings. This figure illustrates how the controls which use ramp metering, Designs 2 and 3, caused the largest reductions in delay for mainline vehicles. It also shows how the controls which use route diversion, Designs 1 and 3, resulted in the largest travel time savings for the entire network. The figure also identifies the relatively poor network performance of ramp metering in Design 2.

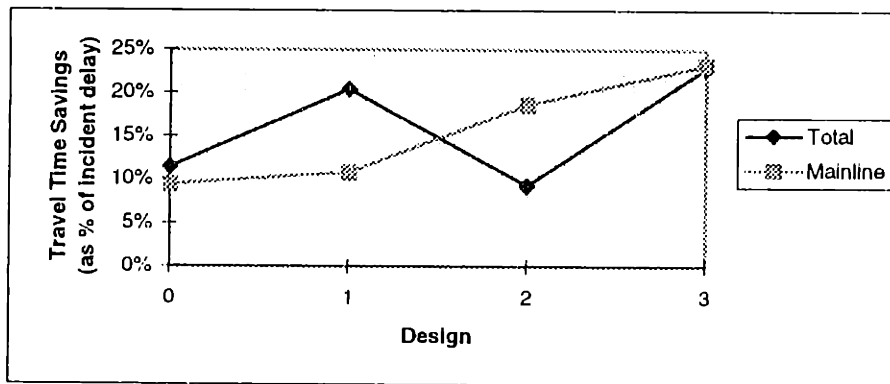


Figure III-8 Travel time savings for 80% demand -Case Study 1

Travel Time Savings Across OD Pairs

The cumulative travel time savings plots for 80% demand are shown in Figure III-9. The curve of Design 2 indicates that it had the worst cumulative travel time savings performance. It shows that the majority of the vehicles were delayed, and only a small portion experienced savings. The curves for Designs 1 and 3 show that most of the vehicles experience a positive travel time savings. Design 3's curve has a slightly higher slope at the end of the curve, indicating that the vehicles who receive the most benefit receive a greater portion of the total travel time savings. The difference of the curves of Designs 2 and 3 indicate that route diversion reduce the adverse impact of ramp metering on on-ramp traffic.

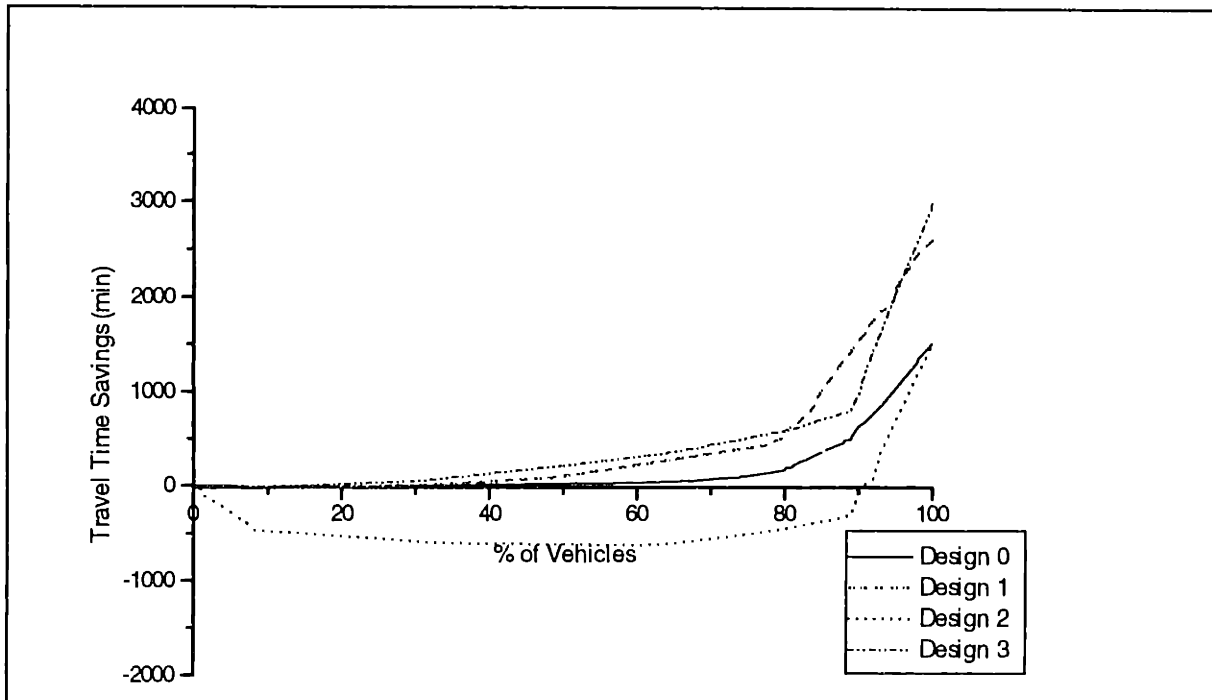


Figure III-9 Travel time savings distribution for 80% demand -Case Study 1

Speed Plots

Figures B-11 through B-15 show the speed profiles for 80% demand. Figures B-11 through B-13 show that the control designs always resulted in similar or higher speeds than no control. The designs result in faster speeds than no control during the recovery period (Figures B-14 and B-15). Design 2 resulted in higher speed from 5:10 to 5:20 PM, and Design 1 slightly outperforms the others from 5:20 to 5:30 PM.

Scenario - 90% Demand

Travel Time

Table III-2 shows that all the control designs decreased the total network travel time at 90% demand, except for Design 2 which has a similar travel time with no control. The incident increased the network travel time by 36,597 minutes, and Design 0 decreased this incident delay by 5%. Adding route diversion (Design 1) further decreased the incident delay, by 10% of the initial incident delay. The addition of ramp metering (Design 2) caused a residual delay equivalent to the incident delay, which is a larger delay than Design 0. This indicates that refinement of ramp metering implementation is required for this demand. Adding route diversion and ramp metering (Design 3) resulted in the largest incident delay reduction of 13%. This implies that the full design results in the best travel times for the entire network.

Table III-4 shows that the control designs resulted in mixed performance at 90% demand when considering mainline travel time. A mainline incident delay of 22,584 minutes was found. Design 0 decreased this incident delay by 6%. But Design 1 increased delay by 1%, Design 2 caused similar delay as no control, and Design 3 reduced the delay by 4%.

Intuitively, a diversion of traffic away from the mainline should decrease mainline travel times. However, it was found in this case that diversion (Designs 1 and 3) resulted in an increase in travel times. Appendix A presents a detailed investigation of this phenomenon. It presents the conditions under which this situation can occur. Basically, a high demand level for the on-ramp caused a bottleneck on the ramp upstream of its merge with the mainline. The bottleneck acted like a natural meter and determined the headways of vehicles as they merge from this ramp onto the mainline. These headways in turn determined the extent of disturbance in the mainline merge area. In other words, the ramp bottleneck caused a situation which results in less mainline disturbance. When vehicles were diverted from this ramp, this bottleneck formed later, meaning a longer duration of the higher pre-bottleneck mainline disturbances.

The addition of ramp metering did not result in as large of a delay reduction as use of local control only for the mainline vehicles. This was only found to happen at 90% demand. Design 2 also did not reduce total network delay at 90% demand. This again shows the adverse impact of ramp metering.

It is also interesting that the addition of both route diversion and ramp metering to local control reduced mainline delay while the addition of each independently did not. This may be explained by considering the problems these controls encountered independently. The ramp metering of Design 2 was not working due to too high ramp demand, and the route diversion of Design 1 was increasing mainline travel times since the natural metering occurred later. The combination of these controls partially eliminated the problem that the other encountered. The route diversion lowered the ramp demand so that ramp metering could work better, and the ramp metering compensated for the natural metering not occurring with route diversion. This substantiates the need for a better integration approach.

Figure III-10 graphically presents the total network and mainline travel time savings. This figure shows how the route diversion in Designs 1 and 3 improved travel time for the entire network, but not for the mainline vehicles. This finding indicates that route diversion provided benefit to some at the expense of the mainline. This figure also illustrates the poor performance of ramp metering for both total network and mainline travel times.

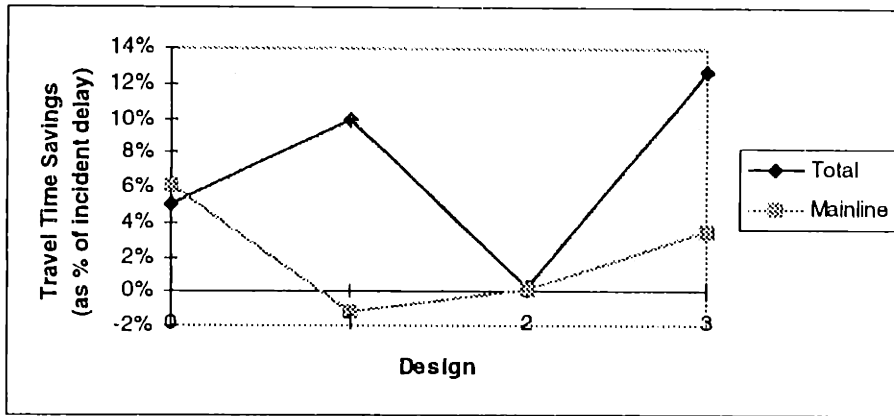


Figure III-10 Travel time savings for 90% demand -Case Study 1

Travel Time Savings Across OD Pairs

Figure III-11 displays the cumulative travel time savings plots for 90% demand. Design 0 caused little travel time change to about half of the vehicles, and improved the conditions for the other half. Design 1's curve shows a negative travel time change for about 25% of the vehicles, and travel time savings for the rest, with substantial savings of about 5%. Design 2's curve indicates that the travel time savings was evenly distributed amongst vehicles, but that savings was small. The curve for Design 3 shows that about half of the vehicles experienced little travel time change, 25% experienced moderate travel time savings, and 25% had substantial travel time savings. This curve indicates that Design 3 improves travel conditions for some vehicles without causing much disruption to others.

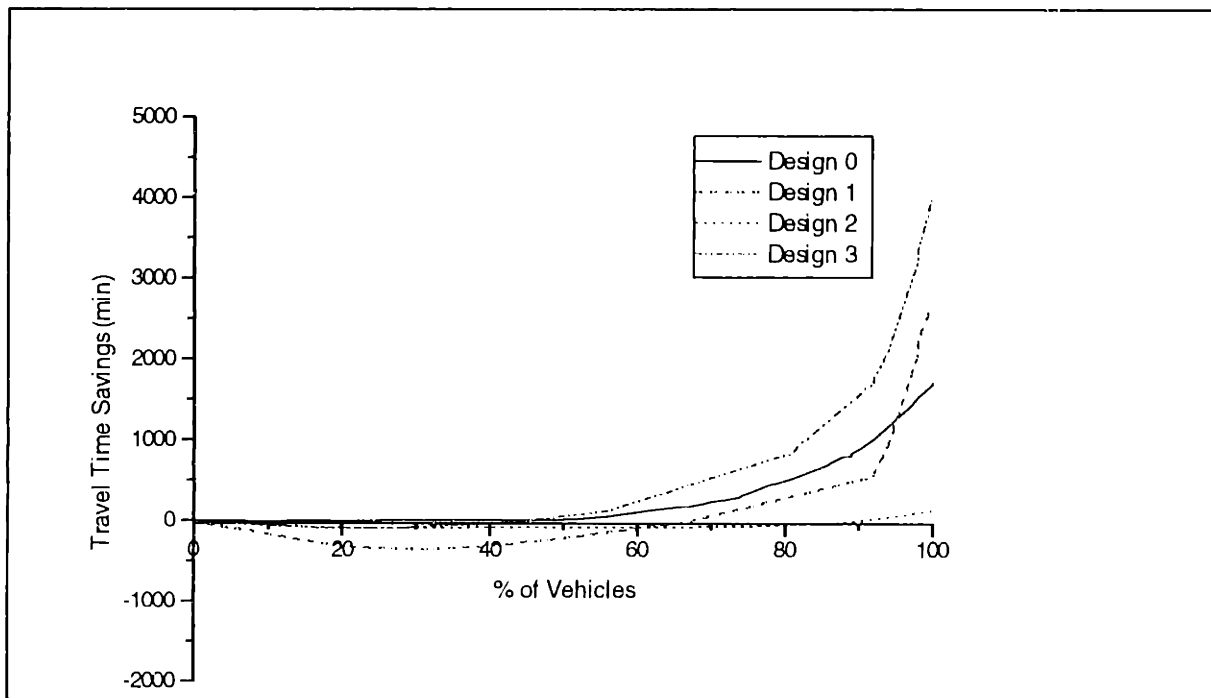


Figure III-11 Travel time savings distribution for 90% demand -Case Study 1

Speed Plots

The speed profiles for 90% demand is presented in Figures B-16 through B-20. The control designs had higher speeds at the first two sensor stations than no control during the incident (Figures B-16 - B-18). Design 0 consistently resulted in the fastest speed at Sensor Station 1. During the beginning of the recovery period (Figure B-19), all control designs outperformed no control, with Design 2 producing the best speeds. At the end of the recovery period (Figure B-20), Designs 0 and 2 resulted in speeds similar to no control, but Designs 1 and 3 had slower speeds. This indicates that route diversion away from the mainline caused slower speeds on the mainline. This is because of a higher mainline merging disturbance by traffic due to route diversion.

Scenario - 100% Demand

Travel Time

Table III-2 shows that all control designs, except Design 0, reduced total network delay at the 100% demand level. The incident alone caused 33,838 minutes of delay to the total network. Design 0 resulted in delay equivalent with the incident delay. Both Designs 1 and 2 reduced the incident delays by 11% and 5% respectively, demonstrating the benefit of adding route diversion and ramp metering independently to local control. Design 3 reduced the incident delay the most, by 12%. Design 3's superior performance implies that this integration of all controls improved the total network travel conditions for 100% demand.

When considering mainline travel time, the control designs generated mixed results at 100% demand, as presented in Table III-4. The mainline incident delay was 24,077 minutes, and Design 0 decreased this delay by 4%. But both route diversion designs, Designs 1 and 3, resulted in 7% mainline incident delay increases. The delay increases by Designs 1 and 3 were due to diversion of vehicles from the mainline resulted in mainline travel time increases. This is due to the similar phenomenon as in the 90% case, and is fully explained in Appendix A. Design 2 decreased delay by 9%. This is a larger decrease than local control only, indicating that ramp metering worked correctly at this demand level.

The graphically presentation of the total network and mainline travel time savings is seen in Figure III-12. This figure shows how the route diversion in Designs 1 and 3 improved travel time for the entire network, but not for the mainline vehicles. This indicates that although the total network travel time was reduced, the travel times of the mainline vehicles who pass through the incident were increased. Operators of the control center need to be aware of this tradeoff when determining if route diversion should be used. This figure also illustrates that ramp metering resulted in an increase in both total network and mainline travel time savings compared with the base control.

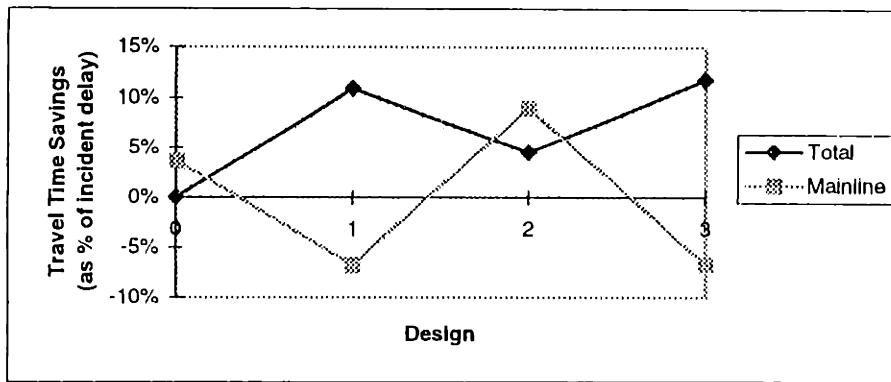


Figure III-12 Travel time savings for 100% demand -Case Study 1

Travel Time Savings Across OD Pairs

There are large differences in the cumulative travel time savings amongst the designs for 100% demand, as seen in Figure III-13. The curves of Designs 1 and 3 indicate that the majority of the vehicles did not benefit from control. In Designs 0 and 2, few vehicles had increased delay, but few also received savings. Design 2 had the most uniform cumulative travel time savings since it resulted in the largest portion of vehicles which experienced travel time savings while few vehicles experienced travel time increases. The large number of vehicles experiencing the travel time increases in Designs 1 and 3 is because of an increase in mainline travel time due to route diversion, as described earlier.

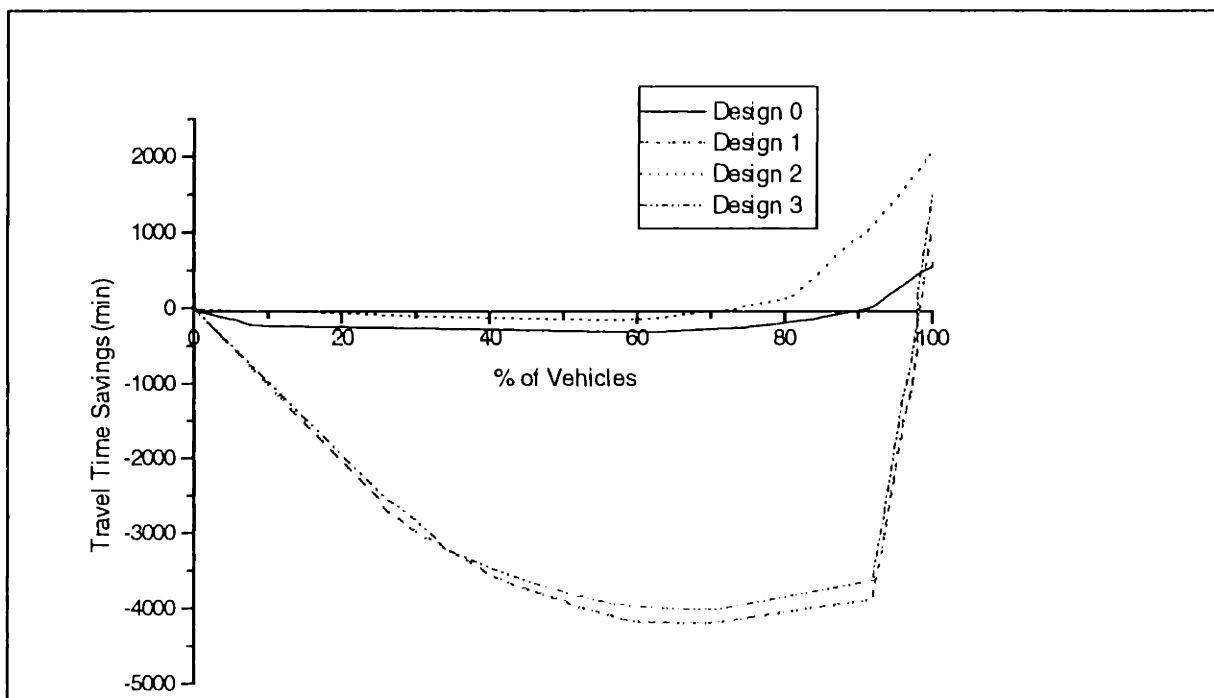


Figure III-13 Travel time savings distribution for 100% demand -Case Study 1

Speed Plots

All of the control designs resulted in higher speeds at the first two sensor stations than no control and similar speeds at the rest of the stations during the incident (Figures III-24 - III-26). Design 0 resulted in a higher speed at the first sensor station. Designs 0 and 2 had higher speeds than no control at the beginning of the recovery period (Figure III-27), and similar speeds at the end of the recovery period (Figure III-28). During the entire recovery period, Designs 1 and 3 had slower speeds, again indicating that route diversion is causing slower mainline speeds.

Scenario - 110% Demand

Travel Time

All control designs decreased the total network incident delay at the 110% demand level, as seen in Table III-2. The incident caused a total network delay of 43,474 minutes, and Design 0 reduced this delay by 3%. Both Designs 1 and 2 further reduced the delay by 9% and 5% respectively, indicating that the addition of route diversion and ramp metering independently to local control improve total network travel times. Design 3 resulted in a delay reduction of 8%. This was not as large of a decrease as Design 1, indicating that the combination of ramp metering with route diversion and local control was not optimally integrated. Further research can investigate a more successful integration of these controls for this demand.

Mixed mainline travel time results were again found at 110% demand, as seen in Table III-4. The incident caused a mainline delay of 28,619 minutes, and Design 0 decreased the delay by 2%. Design 2 further reduced the delay by 3%, indicating that the addition of ramp metering to local control was effective. But route diversion again increased mainline travel times. Designs 1 and 3 increased delay by 18% and 17% respectively. The additional mainline delay is due to the reasons stated previously.

Figure III-14 graphically presents the total network and mainline travel time savings. This figure shows that route diversion improved travel time for the entire network, but not for the mainline vehicles. This again indicates that although the total network travel time was reduced, the travel times of the mainline vehicles who pass through the incident were increased. Operators of the control center need to be aware of this tradeoff when determining if route diversion should be used. This figure also illustrates that ramp metering resulted in an increase in both total network and mainline travel time savings compared with Design 0.

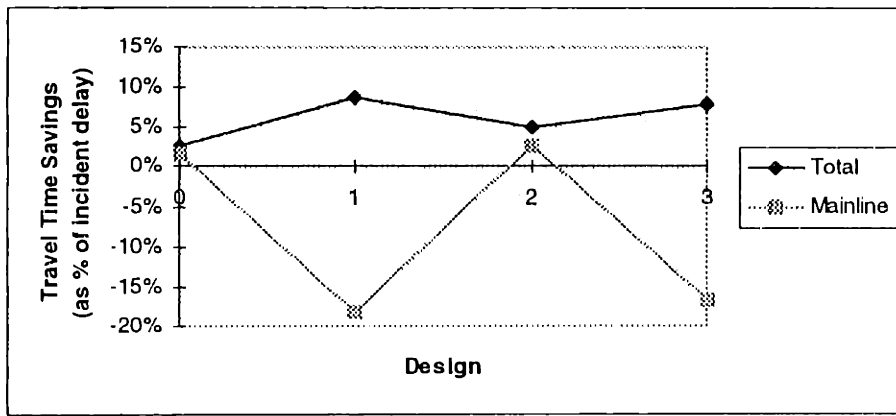


Figure III-14 Travel time savings for 110% demand -Case Study 1

Travel Time Savings Across OD Pairs

Figure III-15 shows the cumulative travel time savings for 110% demand. The curves of Designs 1 and 3 indicate that the majority of the vehicles experienced a travel time increase, while the rest experienced significant travel time savings. The travel time increases were due to the impact of the route diversion on the mainline travel times. The curves of Designs 0 and 2 are almost constantly sloping, indicating that there were uniform travel time savings experienced by vehicles. Design 2 has a higher slope, signifying a larger travel time savings per vehicle.

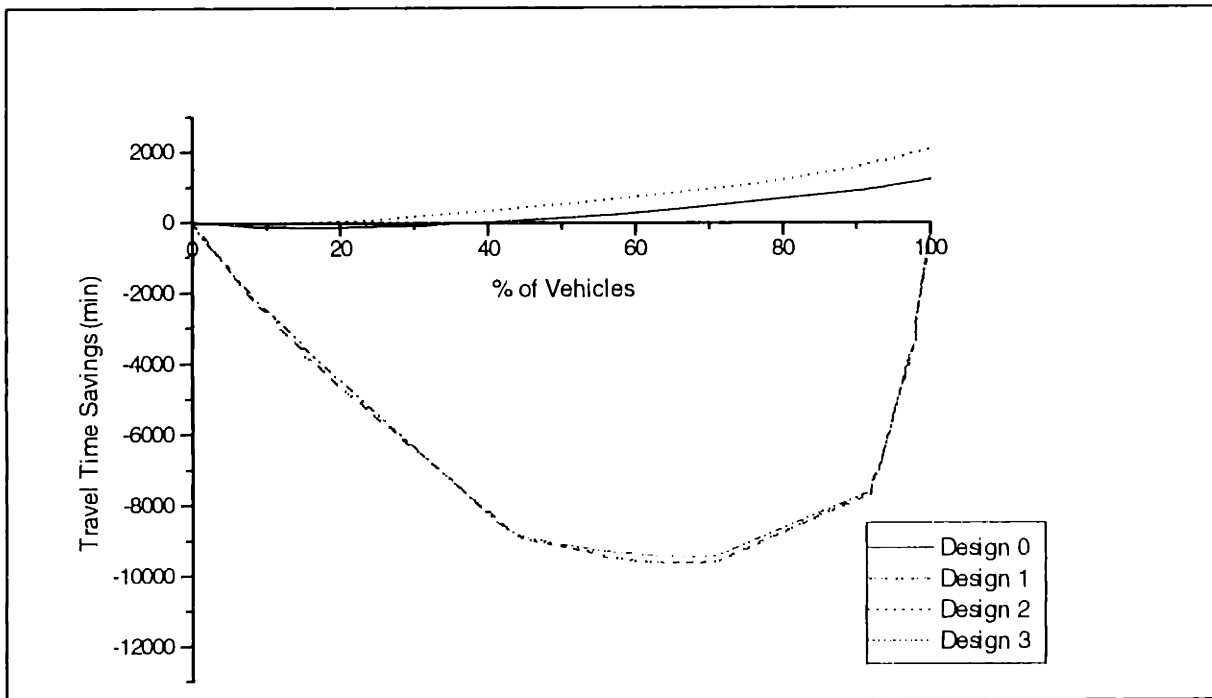


Figure III-15 Travel time savings distribution for 110% demand -Case Study 1

Speed Plots

The speed plots for 110% are shown in Figures B-26 to B-30. All control designs had higher speeds at Sensor Stations 1 and 2 than no control, and speeds similar to no control elsewhere during the duration of the incident (Figures B-26 - B-30). At the beginning of the recovery period, Designs 0 and 2 had higher speeds than no control (Figure B-29), and similar speeds at the end of the recovery period (Figure B-30). Once again, Designs 1 and 3 had slower speeds during the recovery period. This is due to the platoon sizes of the ramp vehicles resulting from the route diversion, and the corresponding mainline disturbance they cause.

3.4 Case Study 2 - Incident in the Ted Williams Tunnel

This case study investigates the integration of route diversion with other traffic control measures. It is a demonstration of route diversion feasibility and effectiveness. It attempts to identify when route diversion is beneficial, and other times when it is not. It also tries to show that the benefit may take on different forms. It investigates how route diversion may help the diverted vehicles and vehicles who pass through the effected area, but may worsen another portion of the network. This may actually be a benefit to the system if the improved area allows easier access for emergency vehicles or decreases the congestion of an extremely congested area, reducing the probability of a secondary incident.

This case study consists of two parts. First, scenarios are run using the travel patterns forecast for the CA/T network, followed by a second phase which modifies the OD demand to reflect unusual conditions.

3.4.1 Incident Location

The incident is placed in the westbound boor of the Ted Williams Tunnel (I-90 westbound). This tunnel connects downtown Boston with East Boston and Logan International Airport. Figure III-16 displays the location of this incident. The incident occurs between 4:50 and 5:10 PM in the simulations, which begin at 4:30 PM and represent the PM peak period. When control is used, it is activated at 4:55 PM. Thus, incident detection, confirmation and activation of the control system is assumed to require 5 minutes. The simulations are performed until all vehicles departing between 4:30 and 5:30 PM reach their destination (typically by 6:00 PM). This period is required since results are presented for vehicles departing between 4:40 and 5:30PM.

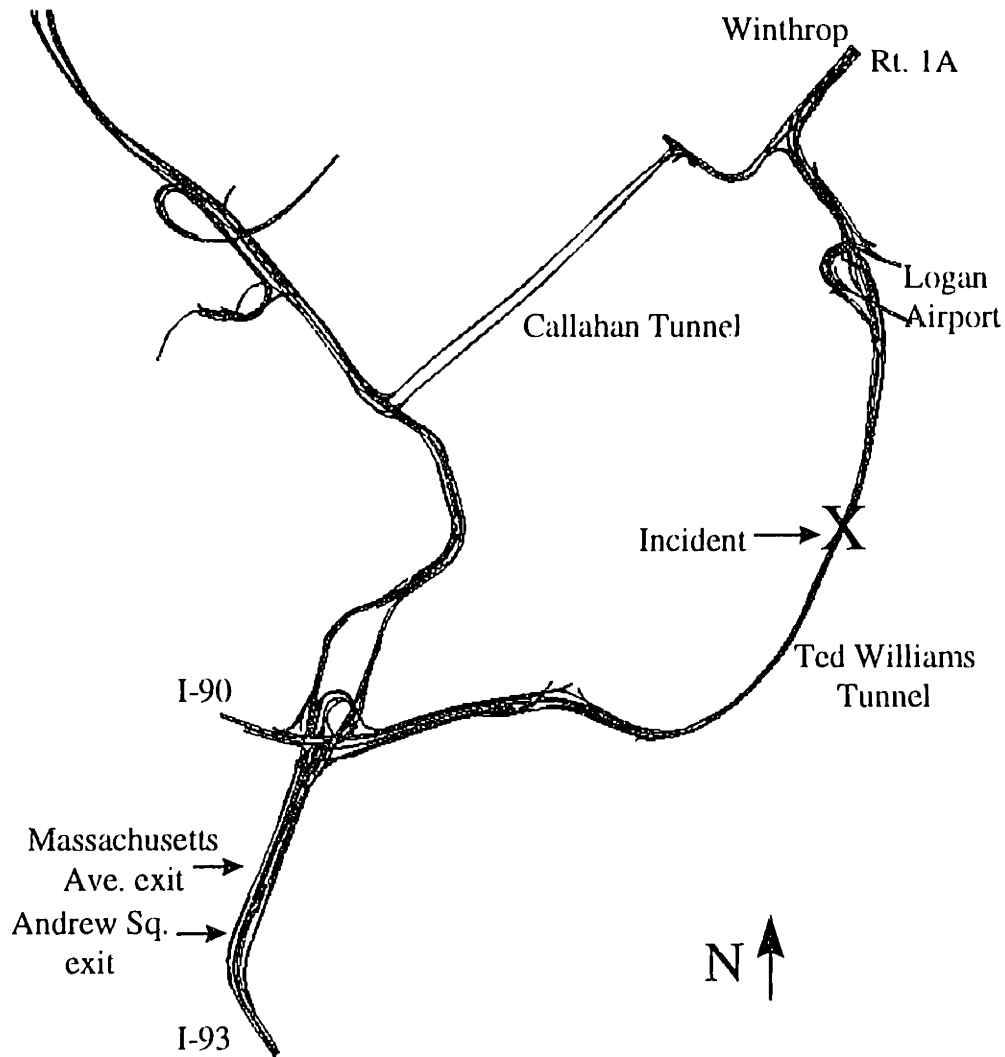


Figure III-16 Case Study 2 - Incident location

The Sumner Tunnel is an alternative route between downtown Boston and East Boston and Logan International Airport. Both of the Ted Williams Tunnel and the Sumner Tunnel are connected to I-93 southbound and I-90 westbound, although local streets are required to travel from the Sumner Tunnel to I-93 southbound and then I-90 westbound. Thus, route diversion is a possible control component.

3.4.2 Scenarios

The first phase of this case study uses three demand levels: 80%, 90%, and 100% of the 2004 pm peak period demand as specified for the CA/T project. Demand lower than 80% was not used since an incident at this demand does not cause enough congestion to require route diversion. It will be shown that higher demand levels are not warranted since congestion on alternative routes become worse than the congestion caused by the incident.

The second phase considers a high demand for airport OD pairs which reflects a high air travel period. This high airport OD demand is simulated at the 80% and 90% demand levels. Based upon the results found for 80% and 90% demand, it was determined that demands of 100% and higher were not required for simulation.

For this case study, only Designs 0 and 1 can be used. The upstream on-ramp nearest to the incident enters the Ted Williams tunnel downstream of a toll booth. Therefore it is not practical to use ramp metering. No control, Design 0 and Design 1 are simulated for each scenario along with a no incident case. It is necessary to simulate the no incident case in order to evaluate the impact of the incident, before distinguishing the effect of the control design. Two sets of simulations are also required for each scenario to develop link travel times for the no incident and incident situations. Thus, six sets of simulations are required for each of the five scenarios. Additionally, ten replications of simulation were performed for each set of simulations, requiring a total of 360 replications of simulation for this case study.

The origins and destinations which are affected by route diversion information are presented in Table III-5 and labeled in Figure III-16. These vehicles can use either the Ted Williams Tunnel or the Sumner Tunnel to complete their trips.

Table III-5 Route diversion origins and destinations.

Origins	Destinations
Logan International Airport	I-90 westbound
Rt. 1A southbound Northern Limit	Massachusetts Avenue
Winthrop	Andrew Sq. Exit
	I-93 southbound Southern Limit

3.4.3 Results

This section presents the results of Case Study 2. This section first shows travel time tables of results for all scenarios, and then presents results and analysis for each scenario.

Table III-6 shows the total network travel times for each design and scenario combination. As previously mentioned, these travel time values include vehicles which depart between 4:40 and 5:30 PM. Table III-7 presents the travel time savings as a percentage of incident delay for all vehicles. For this case study, OD specific travel times are considered for those OD pairs which use the Ted Williams Tunnel westbound. Table III-8 shows these values for all designs and scenarios. The of Design 1 include all vehicles of these OD pairs, including those which use an alternative route. Table III-9 shows the travel

time savings as a percentage of incident delay for these vehicles. The accuracy of these travel times was found to be within 2% of the mean at the 95% confidence level using 10 replications of simulation.

Table III-6 Total network travel time (in minutes) -Case Study 2

Demand	no inc	no control	Design 0	Design 1
80%	111420	113935	115187	114651
90%	139890	145203	146250	154881
100%	243514	256068	253886	256876
high air 80%	132354	147637	150945	146248
high air 90%	159475	182988	190110	200345

Table III-7 Travel time savings as % of incident delay for all vehicles -Case Study 2

Demand	Incident Delay	Design 0	Design 1
80%	2515	-50%	-28%
90%	5313	-20%	-182%
100%	12554	17%	-6%
high air 80%	15283	-22%	9%
high air 90%	23513	-30%	-74%

Table III-8 Travel time for all Ted Williams Tunnel vehicles (in minutes) -Case Study 2

Demand	no inc	no control	Design 0	Design 1
80%	8552	11079	12176	11686
90%	10270	15813	17259	11911
100%	13175	22617	23909	23843
high air 80%	23219	38999	41447	31045
high air 90%	26761	43678	49891	42249

Table III-9 Travel time savings as % of incident delay for Ted Williams Tunnel vehicles -Case Study 2

Demand	Incident Delay	Design 0	Design 1
80%	2527	-43%	-24%
90%	5543	-26%	70%
100%	9442	-14%	-13%
high air 80%	15780	-16%	50%
high air 90%	16917	-37%	8%

The speed profile plots for Case Study 2 are displayed in Appendix C in Figures C-1 through C-25. A set of five time dependent speed profile plots are presented for each scenario - one each for the incident periods of 4:55-5:00 PM, 5:00-5:05 PM, and 5:05-5:10 PM, and the recovery periods of 5:10-5:20 PM and 5:20- 5:30 PM. Each plot shows the speed along ten sensor (loop detectors) stations upstream of the incident. Figure C-26 shows the locations of these sensor stations, with Sensor Station 1 immediately upstream of the incident, and the sensor station numbers increasing opposite the direction of the flow.

80% Demand

Travel Time

At 80% demand, the incident caused 2,515 minutes of delay to the entire network, as can be seen in Table III-7. Both Designs 0 and 1 caused additional delay, increasing the delay by 50% and 28% respectively. Design 0's higher travel time indicates that local control increases delay at this demand. Despite this increase, it is essential to operate these control as an incident response due to safety considerations to reduce the probability of secondary incidents. The addition of route diversion in Design 1 decreases the delay compared to Design 0. So, at this demand level, route diversion is a useful control component when considering total network travel time.

Table III-9 shows that the incident caused 2,527 minutes of delay to the Ted Williams Tunnel vehicles, and both Designs 0 and 1 caused additional delay, increasing the delay by 43% and 24% respectively. This shows that Design 0 resulted in a higher travel time for the entire network and the vehicles which pass through the incident. Again it is important to remember that this local control must be used for safety concerns despite this increase of travel time. The addition of route diversion in Design 1 decreases the delay for the mainline compared with Design 0. Therefore, route diversion benefits mainline vehicles at 80% demand

Figure III-17 shows the travel time savings of the designs for the entire network and the Ted Williams Tunnel traffic. It shows that Design 1 resulted in a smaller delay increase than Design 0 when considering both the entire network and those vehicles traveling through the incident.

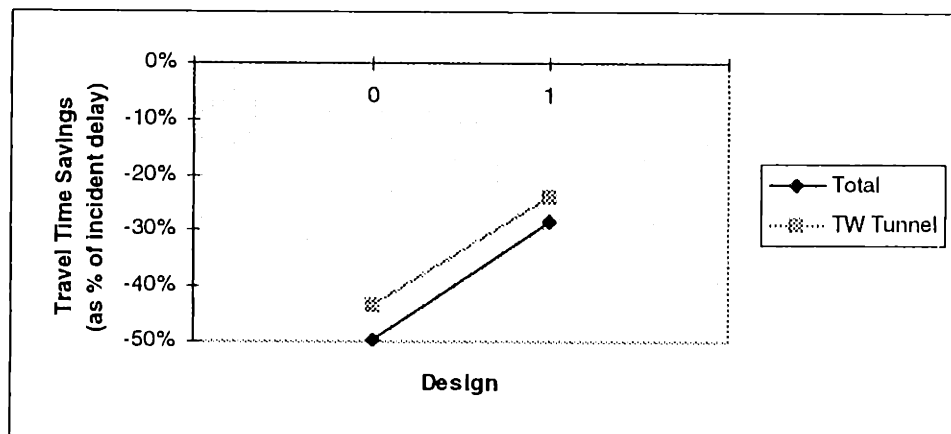


Figure III-17 Travel time savings for 80% demand -Case Study 2

Travel Time Savings Across OD Pairs

Figure III-18 displays the travel time savings distributions for 80% demand. It shows that both Designs 0 and 1 have similar curves, but that Design 0's curve has a larger negative slope at the beginning of the

plot. These similar curve shapes indicate that both designs impacted groups of vehicles in similar manners. A small number of vehicles experienced negative travel time savings, while the majority of vehicles received slight travel time increases to no travel time change. Since the shapes of the curves are similar, the control design implementation decision can be based upon the other measures such as total travel time.

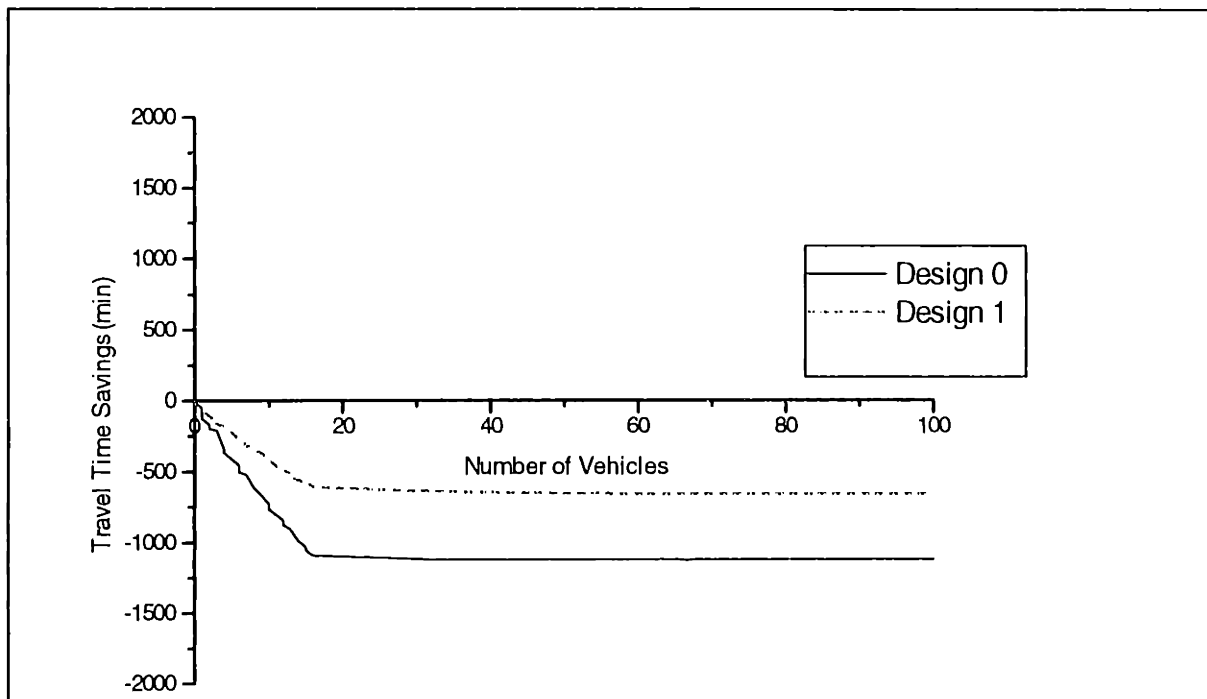


Figure III-18 Travel time savings distribution for 80% demand -Case Study 2

Speed Plots

The speed profiles for 80% demand are displayed in Figures C-1 through C-5. During the incident, the control designs resulted in slightly faster or similar speeds to no control in the congested area, and slower speeds upstream of the congestion. This occurred at Sensor Station 5 in Figure C-1, Sensor Station 6 in Figure C-2, and Sensor Station 7 in Figure C-3. Upstream of the congestion, the local controls were active in both control designs. The VSLs indicated a 30 mph speed limit to create a more uniform speed, attempting to reduce the chance of a secondary incident. It therefore is not surprising that the control designs lowered the speed of the area upstream of the congestion. During the beginning of the recovery period (5:10-5:20PM), both control designs resulted in slower speeds than no control. Of these, Design 1 consistently had higher speeds than Design 0, indicating that diverting some vehicles away from the incident quickens the recovery process. Speeds returned to normal by the end of the recovery period (5:20-5:30PM).

90% Demand

Travel Time

In the case of 90% demand, the control designs again result in more delay than the incident alone for the entire network. Table III-7 shows that the incident delay of the entire network was 5,313 minutes, and Designs 0 and 1 increased this delay by 20% and 182% respectively. Again it is important to note that a minimum of Design 0 is required due to safety impacts. At 80% demand, route diversion reduced the total network travel time compared to the base design. But at 90% demand, it substantially increased the network travel time.

Table III-9 shows that the incident delay for Ted Williams Tunnel Vehicles was 5,543 minutes, and Design 0 increased this delay by 26% while Design 1 reduced this delay by 70%. At 80% demand, Design 1 also resulted in a smaller delay than Design 0, but it increased the incident delay for the Ted Williams Tunnel vehicles. But at 90% demand, it actually decreased the travel time for these vehicles.

The travel time savings of the designs for the entire network and the Ted Williams Tunnel traffic are summarized graphically in Figure III-19. It shows that Design 0 resulted in a similar travel time increase as a percentage of incident delay for both the entire network and the Ted Williams Tunnel vehicles, while Design 1 resulted in different travel time changes for the two groups. This indicates that route diversion shifts the delay from one group of vehicles to another, and resulted in a higher total network travel time. The conditions of the Ted Williams Tunnel vehicles were greatly improved at the expense of other vehicles. Investigation of diverting vehicles, showed that sometimes they saved travel time and other times they diverted to a more congested path and did not save time. This diversion improved travel for other vehicles which passed the incident location, while negatively impacting vehicles who share portions of the diversion route. The alternate path uses the Sumner Tunnel and the Central Artery portion of I-93 southbound. Without the additional diverted vehicles, the Central Artery experienced congestion at 90% demand. The addition of these diverted vehicles caused this congestion to worsen, significantly increasing the travel times of all vehicles which pass through this congestion. This in turn resulted in the large network travel time experienced at 90% demand.

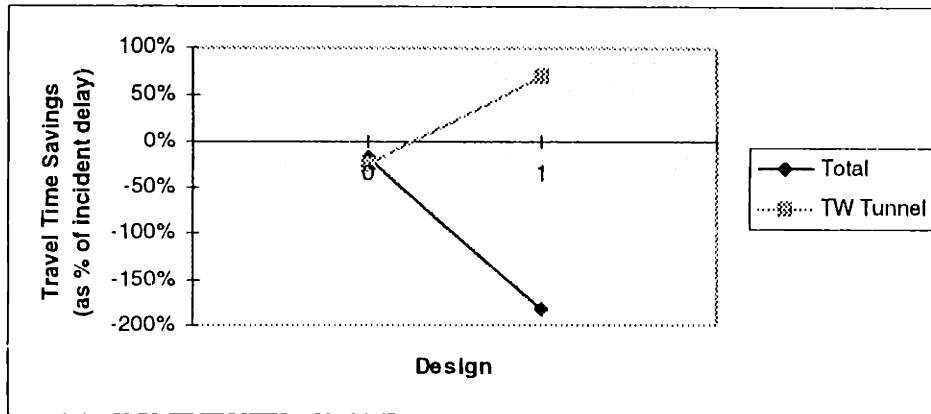


Figure III-19 Travel time savings for 90% demand -Case Study 2

The operators of the TMC need to be aware of this delay tradeoff, and determine how the control should be used. Sometimes it could be beneficial to redistribute delay amongst different portions of the network to ensure that one section does not become too congested, potentially leading to further complications. Improving the conditions near the incident may facilitate the speed with which emergency vehicles can access and clear the incident.

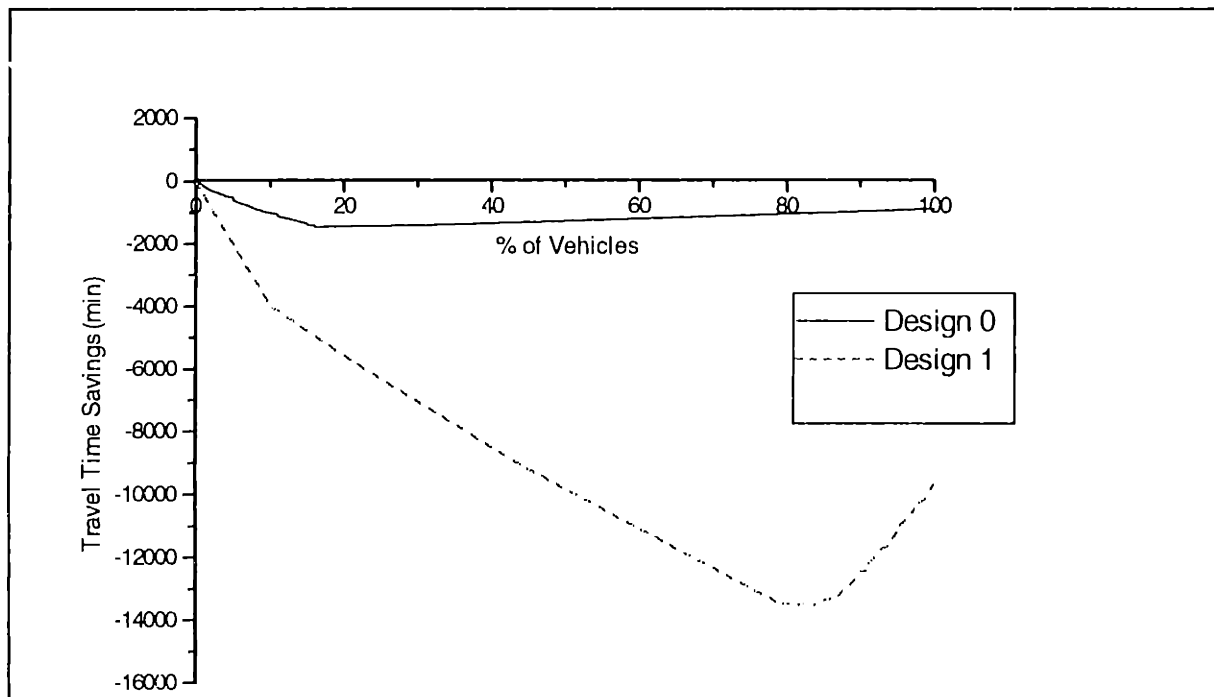


Figure III-20 Travel time savings distribution for 90% demand -Case Study 2

Travel Time Savings Across OD Pairs

The cumulative travel time savings curve plot for 90% demand is seen in Figure III-20. Design 0's curve indicates that about 25% of the vehicles' travel times are increased slightly, and the rest of the vehicle's

travel times are improved, with little net savings. Design 1's curve indicates larger travel time changes for all vehicles. About 80% of the vehicles experienced large travel time increases and the rest of the vehicles received travel time savings. This large travel time savings variance of Design 1 highlights the findings of the travel time investigation, which was that Ted Williams Tunnel vehicles experienced travel time savings at the expense of vehicles who shared the diversion route. This plot helps identify the dual impact of Design 1 so that policy-makers can properly base their decisions.

Speed Plots

Figures C-6 through C-10 show the speed profiles for 90% demand. Throughout the incident and recovery period, Design 1 resulted in higher speeds than no control and Design 0. This is a result of route diversion, since there were significantly less vehicles using this section. These higher speeds may lead to swifter incident clearance, reducing the incident impact. During the incident, Design 0 resulted in similar speeds to no control except upstream of the congestion, the section where VSLs govern speed. This happens at Sensor Stations 6, 7, and 9 in Figures C-6, C-7, and C-8 respectively. Design 0 recovered slower than no control. Notice that control designs experienced a more gradual spatial speed delay. This is an important safety impact which should reduce the occurrence of secondary incidents.

100% Demand

Travel Time

Table III-7 shows that the control designs performed better at 100% demand than at the other demand levels when considering the total network travel time. A total network incident delay of 12,554 minutes resulted, and Design 0 decreased this delay by 17% while Design 1 increased it by 6%. But the addition of route diversion again increased the total network travel time, but not by as much as at 90% demand.

Table III-9 shows that both control designs increase the delay experienced by the Ted Williams Tunnel vehicles. The incident delay for these vehicles was 9,442 minutes, and Designs 0 and 1 increased the delay by 14% and 13% respectively. Design 0 continued the trend of a lower increase in mainline travel time as the demand level increases. Design 1 caused slightly less delay than Design 0, due to the few vehicles which diverted. Due to the success of local control and the growing congestion of the alternative route (via the Sumner Tunnel and Central Artery), the alternative route was not as attractive, and fewer vehicles diverted than at 90% demand. Since less vehicles diverted, the congestion of the Central Artery was not increased as much as at 90% demand, and therefore the impact on total travel time is not as large (Table III-7).

Figure III-21 graphically summarizes the travel time savings of the designs for the entire network and the Ted Williams Tunnel traffic. It shows the large difference in travel time change between the designs for

the total network, and the similar delay increases for the Ted Williams Tunnel vehicles. Although Design 0 increased the delay to the Ted Williams Tunnel vehicles, the secondary effects of this control decreased the delay for the entire network. The route diversion in Design 1 caused slightly less delay to the Ted Williams Tunnel vehicles than Design 0, but significantly more delay for the entire network.

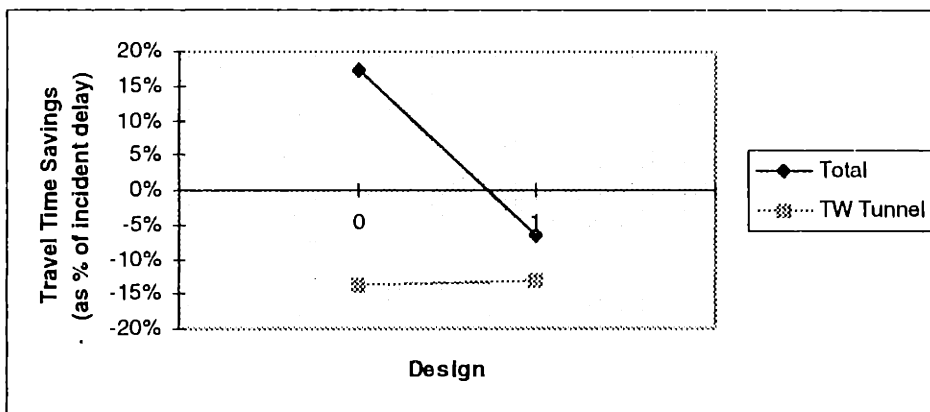


Figure III-21 Travel time savings for 100% demand -Case Study 2

The travel times at 100% demand again indicate that route diversion results in a transferring of delay away from the incident location. The network conditions at this demand level did not make route diversion as attractive as at lower demand levels, but those vehicles which did delay greatly impacted vehicles of the alternative route. Again, it is important for operators of the control center to be aware of this delay exchange when determining whether or not to use route diversion. A more advanced route diversion strategy could predict this impact and not implement this control.

Travel Time Savings Across OD Pairs

Figure III-22 displays the cumulative travel time savings curves for 100% demand. The comparison of the curves show that not as many vehicles were negatively affected in Design 0 as in Design 1. It also shows that some vehicles experienced a larger travel time improvement due to Design 0.

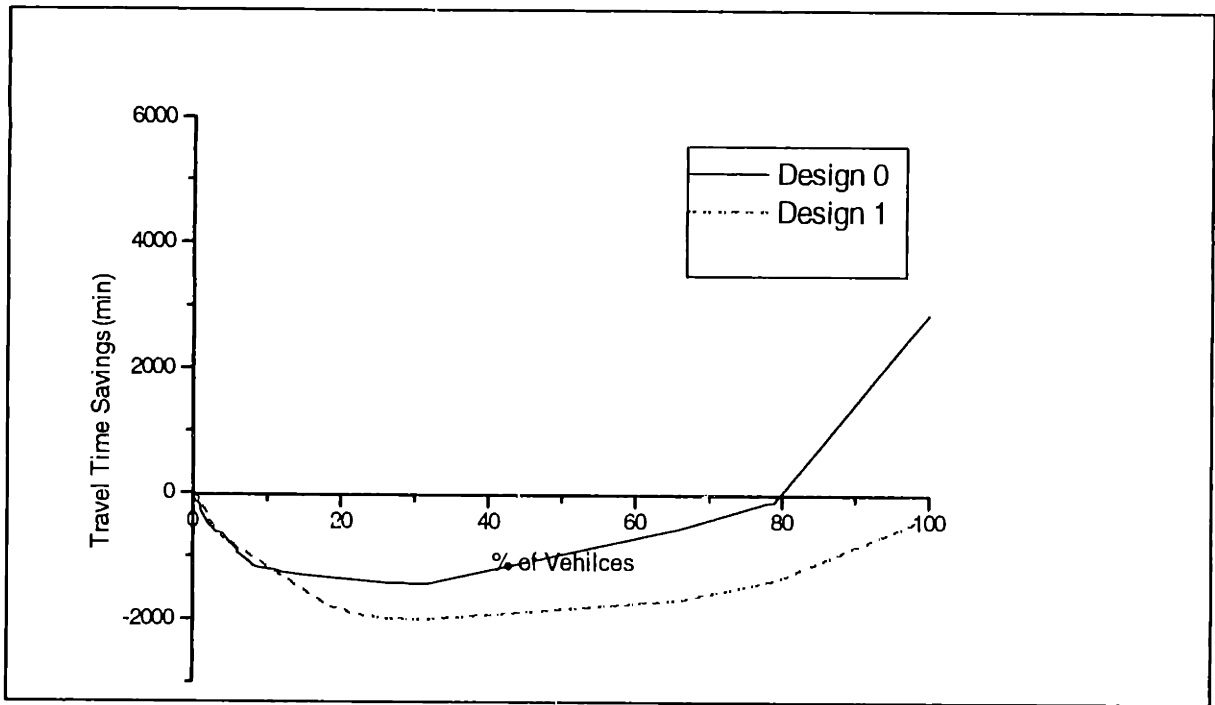


Figure III-22 Travel time savings distribution for 100% demand -Case Study 2

Speed Plots

The 100% demand speed profile plots are displayed in Figures C-11 through C-15. At this demand, both designs resulted in similar speeds, since few vehicles divert. During the beginning of the incident (4:55-5:00 PM) the control designs resulted in a more gradual spatial speed decrease. During the rest of the incident and the beginning of the recovery period, both of these designs result in speeds similar to no control. Figure C-15 shows that the speeds of both designs required more time to recover than no control, with Design 1 recovering faster than Design 0 due to the slightly lower number of mainline vehicles caused by route diversion.

High Air 80% Demand

Travel Time

The 80% demand level with high airport travel resulted in 15,283 minutes of incident delay for the entire network, as seen in Table III-7. This is a much larger delay than found with normal travel patterns at 80% demand. Design 0 increased the delay 22%, which is a smaller increase than without the extra airport demand (50%). With this altered travel pattern, the addition of route diversion in Design 1 resulted in a 9% reduction of delay. This indicates that on an unusual day with high airport demand, the incident delay has become large enough to warrant route diversion. With the regular travel, Design 1

outperformed Design 0, but still increased the incident delay. With this travel pattern, route diversion improves the network travel time.

Table III-9 shows that the incident experienced by the Ted Williams Tunnel vehicles was 15,780 minutes, which is a large increase over the normal 80% demand's incident delay. The local controls used in Design 0 increased delay by 16%, which is a smaller increase than found for 80% demand. This indicates that the local controls did not cause as large of an increase in delay when the incident congestion was more severe. This is due to less of an impact from the VSLs since the incident congestion caused lower speeds. Design 1 benefited the Ted Williams Tunnel vehicles, reducing their delay by 50%. This is caused by a large diversion of vehicles away from the incident.

Figure III-23 graphically summarizes the travel time savings of the designs for the entire network and the Ted Williams Tunnel traffic at the high airport 80% demand. It shows the travel time advantage of Design 1 when considering both the entire network and the Ted Williams Tunnel vehicles. Thus, for this unusual travel activity, route diversion benefits the entire network and the Ted Williams Tunnel vehicles.

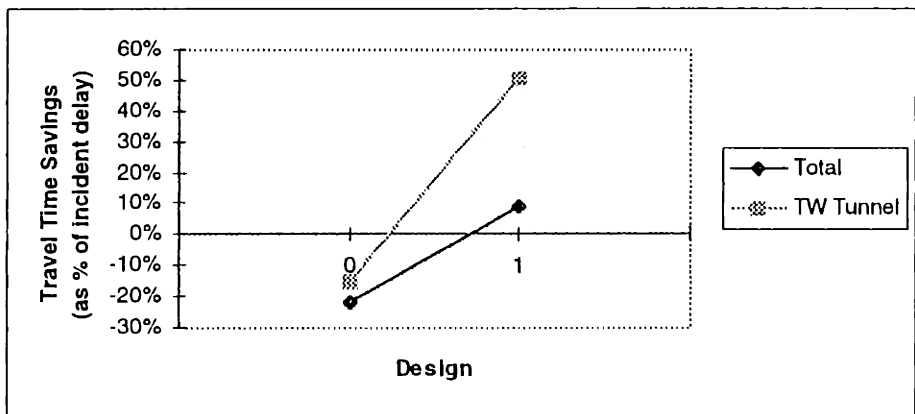


Figure III-23 Travel time savings for high airport 80% demand -Case Study 2

Travel Time Savings Across OD Pairs

The cumulative travel time savings plot for 80% demand with higher air travel is shown in Figure III-24. Design 0's curve indicates that about 20% of the vehicles experienced travel time increases and the rest had little travel time change due to Design 0. Design 1's curve shows that about 20% of the vehicles experienced significant travel time increases, but another 20% of the vehicles realized large travel time savings. The rest of the vehicles' travel times were slightly increased. Design 1's curve show the shifting of delay caused by Design 1. The travel time increases were much larger in Design 1 compared with Design 0, due to the diversion impact on Central Artery southbound vehicles. The large travel time savings in Design 1 were experienced by the Ted Williams Tunnel vehicles whose travel was greatly

improved due to the lower number of vehicles which traveled through the incident. A control operator should be aware of this tradeoff when making a decision about using route diversion.

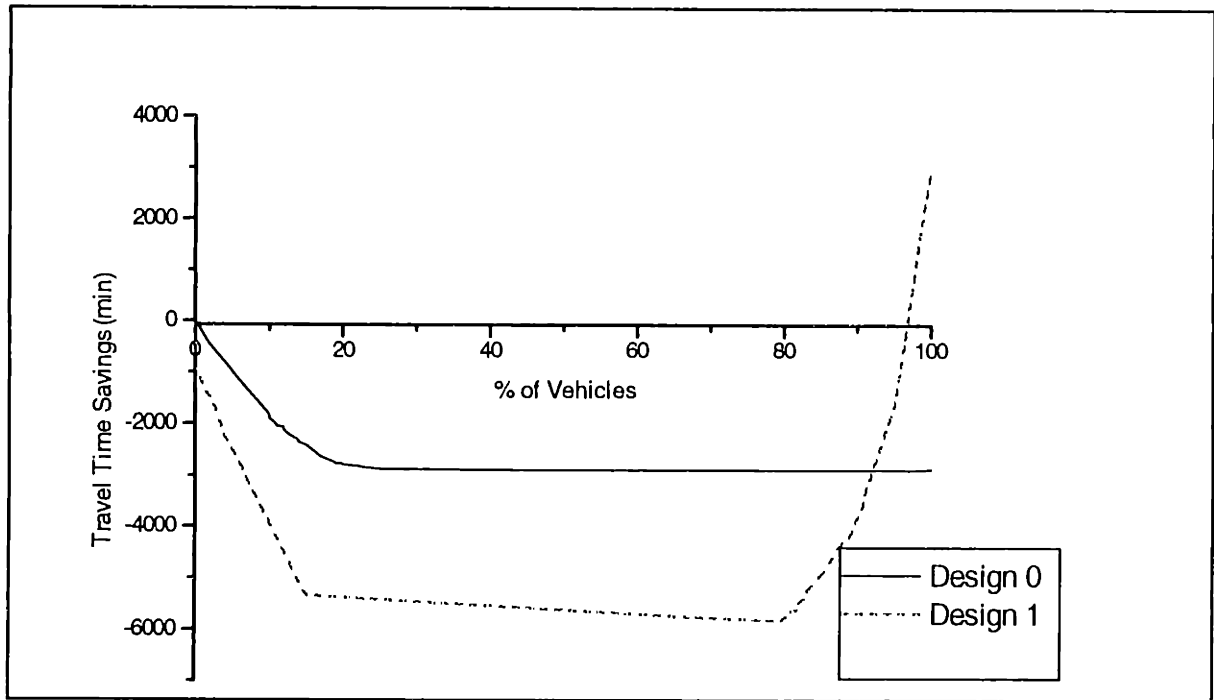


Figure III-24 Travel time savings distribution for high airport 80% demand -Case Study 2

Speed Plots

Figures C-16 through C-20 show the speed profile plots for the high airport 80% demand. Both Designs 0 and 1 had similar speeds to no control during the incident, except upstream of incident congestion. At these locations, Sensor Stations 7 and 9 in Figures C-16 and C-17 respectively, the VSLs caused speeds to reduce sooner than the incident alone. Design 1 outperformed no control and Design 0 during the recovery period due to the lower number of vehicles in this section as a result of the diversion. At the beginning of the recovery period (Figure C-19), Design 1 had higher speeds upstream of Sensor Station 4. The speeds had almost fully recovered at the end of the recovery period (Figure C-20) for Design 1, while no control and Design 0 were still experiencing much slower speeds. Although the speed advantage of Design 1 was not found until after the incident had been cleared, the speed improvement is important. It greatly reduces the potential of secondary incidents.

High Air 90% Demand

Travel Time

Table III-7 shows that the total network's incident delay was 23,513 minutes with 90% demand and the increased airport travel. This was again a much larger delay than with 90% demand and the usual airport travel. When the usual 90% demand was considered, both Designs 0 and 1 increased the incident, with Design 1 causing a much larger increase in total network travel time. With the additional airport travel, Designs 0 and 1 again increase the incident delay, by 30% and 74% respectively. By Design 1 having a larger delay than Design 0, it indicates that route diversion caused more delay to the alternative route than the delay it reduces on the incident route. It should be noted that less vehicles divert at the 90% demand with increased air travel, than at 80% demand with increased air travel, due to congestion that existed on the Central Artery southbound at 90% demand. This additional congestion made the alternative route less attractive at 90% demand despite the increased incident congestion.

The Ted Williams Tunnel vehicles experienced 16,917 minutes of incident delay at 90% demand with altered airport travel patterns, as seen in Table III-9. Design 0 increased the delay by 37%. Table III-9 shows that the Ted Williams Tunnel vehicles' incident delay, representing congestion, increased as the demand grew from 80% to 100% demand, and Design 0 resulted in smaller delay increases as the incident delay grew. But this is not the case when considering Design 0's impact on the Ted Williams Tunnel vehicles at 80% and 90% demand with unusual travel. Design 0 increased the delay more at the high airport 90% demand than at high airport 80%. This pattern indicates that Design 0 caused less delay, as a percentage of incident delay, as congestion grew to a certain point, then it increased delay for larger congestion levels. Design 1 reduced the incident delay 8% for the Ted Williams Tunnel vehicles, due to less vehicles passing through the incident because of the route diversion.

The travel time savings of the designs for the entire network and the Ted Williams Tunnel vehicles at the high airport 80% demand are graphically summarized in Figure III-25. It shows that Design 1 resulted in an improvement for the Ted Williams Tunnel vehicles, but a much larger travel time increase for the entire network than Design 0. This demonstrates the tradeoff which route diversion can impose on a network: greatly benefiting some vehicles at the expense of others. In this case there is a net negative network impact.

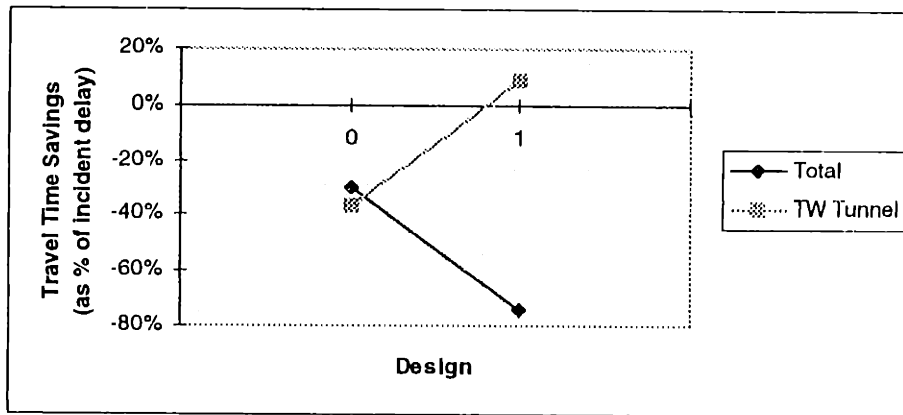


Figure III-25 Travel time savings for high airport 90% demand -Case Study 2

Travel Time Savings Across OD Pairs

Figure III-26 displays the cumulative travel time savings plot for high air travel 90% demand. Design 0's curve indicates that about 20% of the vehicles experienced a travel time increase and the rest had little travel time change. Design 1's curve on the other hand, shows that about 80% of the vehicles experienced significant travel time increases, while most of the other 20% realized large travel time savings. This curve illustrates the transfer of delay from one group of vehicles to another due to the route diversion in Design 1. As shown before, Design 1 increased the total network delay. But when considering only the Ted Williams Tunnel vehicles, Design 1 seemed very favorable. The policy makers need to be aware of all of these measures when determining whether to use route diversion. Its possible that improving the incident location is more important than preventing congestion in another portion of the network.

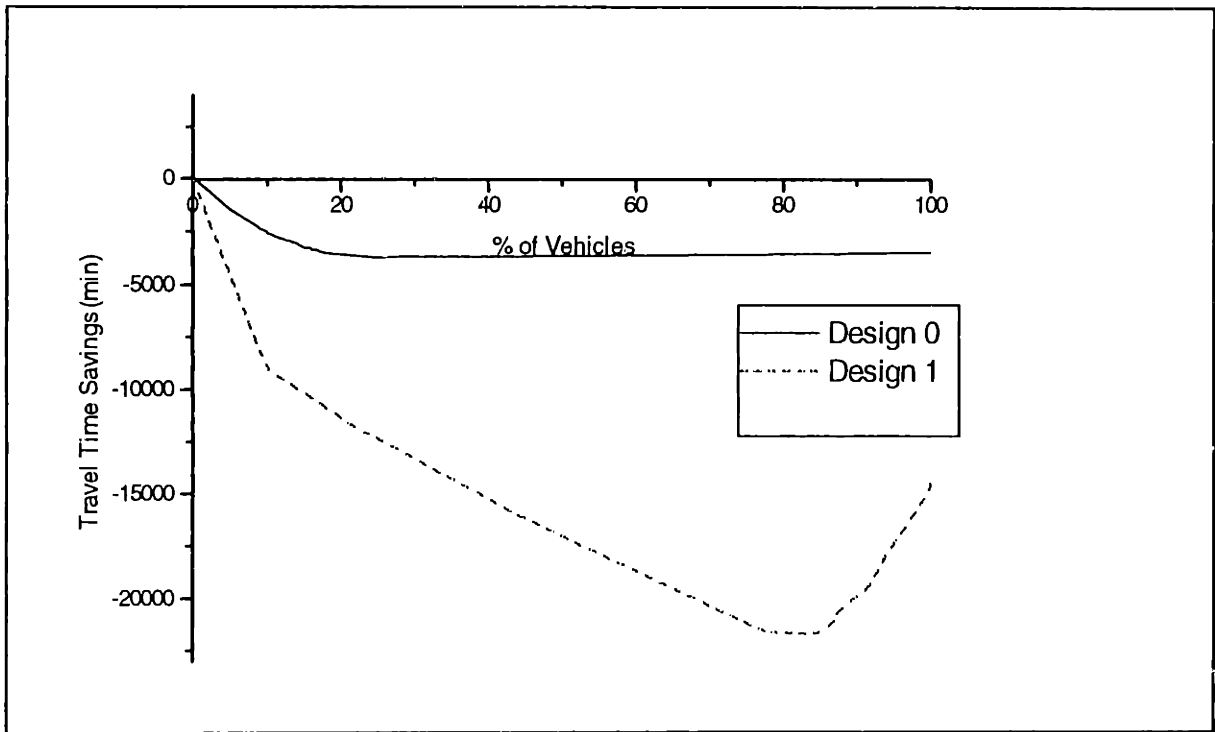


Figure III-26 Travel time savings distribution for high airport 90% demand -Case Study 2

Speed Plots

Figures C-21 through C-25 show the speed profile plots for the high airport travel 90% demand. With this demand, both Designs 0 and 1 result in speeds similar with each other and no control throughout the incident and the recovery period. This indicates that the incident congestion is so severe that control does not have an impact on speed from 4:50 to 5:30 PM. The control designs' speed impact might appear after 5:30 PM.

Chapter 4 Findings

Two case study evaluations of a traffic control design were presented in Chapter 3. Based upon the simulation results, analysis was performed and several findings were identified. This chapter presents these findings, first focussing on universal findings which can be applied to other projects, and then presenting case-specific findings.

4.1 Insights Derived from Case Studies

4.1.1 System-Wide Evaluation

The system-wide investigation provided insights which a local level investigation could not. The control design impact was sometimes substantially different for the entire network than for the incident location. For example, the ramp metering used in Case Study 1, often improved mainline conditions while deteriorating them for the entire network. This also indicated that this ramp metering, which was designed for local optimization, may not result in a global optimization. A system-wide evaluation is essential for identifying such situations.

The use of multiple MOEs provided additional insights of traffic control impacts. It may not be possible to describe the total impact by one MOE. Furthermore, for comparison between designs which have similar performance with respect to one MOE, additional MOEs can identify differences in performance. The travel time savings across OD pairs is an important MOE for understanding the full impact of control, by identifying the uniformity of improvement. In situations where it identified that some vehicles benefited at others expense, further investigation is needed to identify which travel patterns are improved and which are worsened. An understanding of the delay tradeoffs can also lead to a better control design implementation.

4.1.2 DTMS Implementation

These case studies implemented DTMS in a simplified manner. Little thought was given to the interactions of the various control components when planning their performance specifications. The results showed that this simplified DTMS implementation sometimes lead to marginal improvements, and sometimes a deterioration. This insinuates that careful consideration should be given to integration and coordination of the DTMS before implementation so that a detrimental situation can be avoided, and a more sophisticated DTMS design can be developed.

4.1.3 Route Diversion

The route diversion strategy implemented often did not improve the transportation network. In fact, it often deteriorated traffic conditions in some portion of the network. A more advanced route diversion strategy could improve this situation. Travel time information in this study was based on existing traffic conditions, a strategy which has adverse impacts [Ben-Akiva, 1991]. Thus, the findings of this research indicate the importance of a prediction based routing strategy.

When route diversion was effective, it was a function of the network configuration and demand pattern. The evaluation identified limited situations when route diversion benefited the entire network. Usually it resulted in a redistribution of delay. However, for a different network or demand pattern, route diversion could be a very beneficial component of incident management.

Route diversion often resulted in a redistribution of delay. It is important to notice that even though route diversion did not substantially decrease total travel time, it helped reduce delay for vehicles directly affected by the incident. These improvements to the incident location may be at the expense of other portions of the network, leading to small total network travel time savings, or even additional delay. But there may be additional benefit, beyond travel time savings, due to the improvement of the incident location. For example, an improvement in the conditions of the Ted Williams Tunnel could prevent secondary incidents and reduce the vehicle emissions.

Diverting vehicles away from the incident helped improve speeds in the vicinity of the incident. When the speed increases occurred during the incident, they facilitate access of emergency vehicles, resulting in a faster incident clearance. Speed improvement in the recovery period signifies faster clearance of the incident congestion which should reduce the probability of secondary incidents.

Next, case-specific findings are presented for the two case studies

4.2 Case Study 1

Case Study 1 tested and evaluated integrated control designs for a range of demand scenarios. On the whole, DTMS implementation in Case Study 1 was found to cause marginal network improvements, again indicating that a more advanced control design integration should be investigated for additional benefit. From this evaluation, insights were drawn about the control design use at low demand, ramp metering, route diversion, and the fully-integrated design.

4.2.1 Low Demand

This case study tested traffic control design over a range of demands. The lowest demand scenario, 60% demand, resulted in minimal congestion, and the use of all control designs increased travel times. It is important to note that the use of these controls were necessary due to safety concerns.

4.2.2 Ramp Metering

Case Study 1 provided several insights into the use of ramp metering for management of this incident:

- The integration of ramp metering with local control often resulted in an increase in total travel time. Design 2, which added ramp metering to LCS and VSLs, increased the total network delay compared to the base design for the 60%, 70%, 80%, and 90% demand scenarios. This shows that the control strategy, which was optimized for the local level, did not perform well at a network-level.

However, the integration of ramp metering with local control and route diversion resulted in an improvement of network traffic conditions for some scenarios. For the 80% and 90% demand, Design 3, (ramp metering + local control + route diversion), decreased total network delay compared to Design 1 (local control + route diversion).

These findings suggest the need for better calibration of the parameter values or a refinement of the control algorithm for ramp metering usage in these scenarios for incident management.

- Although ramp metering increased the total network travel time compared with the other control designs, it improved the mainline speed during and after the incident. These higher speeds during the incident allow emergency vehicles to access the incident sooner, leading to a smaller incident clearance time. The higher speeds after the incident indicate that the incident congestion was dissipating sooner, lowering the chance of a secondary incident.
- The ramp metering parameters used for this study have been shown to improve network conditions when only ramp metering was used [Jha, 1998(b)]. In order to achieve similar network improvement in case of an integration design, the control design must consider the interactions of the controls.

4.2.3 Route Diversion

The use of route diversion in Case Study 1 led to the following findings:

- At demands of 90% and greater, route diversion caused increases to the mainline travel time. This was an unexpected result due to a combination of network geometry and travel demand patterns. Appendix A describes an explanation for this counter-intuitive result.

- Although the mainline travel time increased for demands of 90% and greater, the total network delay decreased. This indicates that route diversion was distributing the incident delay over a range of OD pairs. It is important to identify these delay distributions in order to correctly predict the impact of route diversion across OD pairs.

4.2.4 Fully Integrated Design

The integration of all control components in Design 3 resulted in the following findings:

- At 80% demand, the fully integrated design outperformed the other control designs with respect to all MOEs (total network travel time, mainline travel time, travel time savings across OD pairs, and speed profile). This indicates that the integration of these controls was adequate to generate additional savings. More sophisticated approaches can be expected to create further improvement.
- At the other demand levels, the fully integrated design did not outperform the other designs with respect to all MOEs. These results indicate that for these demands, one or both of the following existed:
 1. Travel conditions (network geometry and travel demand) were such that improvement was not possible for a certain control device as currently designed. A sophisticated DTMS design can identify these conditions.
 2. An inefficient integration of control devices existed when the control designs independently improved conditions, but not when integrated. Consideration of the interactions between these controls can identify integration methods to avoid this inefficiency.

4.3 Case Study 2

The integration of route diversion with local control was investigated in Case Study 2 for an incident in the Ted Williams Tunnel. It was found that the naïve design of DTMS in Case Study 2 did not improve traffic conditions, highlighting the need for investigation of more sophisticated DTMS design. Additionally from this evaluation, a number of insights were drawn about the use of the local control and route diversion.

4.3.1 Local control

The evaluation of local control (Design 0) in Case Study 2 showed that this design increased the delay at 80% and 90% demand with both the normal and unusual travel patterns. Despite this finding, the local controls should be used to improve safety in this area. Further investigation may help design a more efficient implementation of these controls to reduce delay without sacrificing safety.

4.3.2 Route Diversion

The focus of Case Study 2 was the integration of route diversion into an incident management control design. The use of this route diversion had mixed results, sometimes improving all conditions compared to local control only, other times greatly deteriorating sections of the network. A more advanced route guidance logic could predict the impact of the routing instructions and prevent implementation of detrimental diversion. This investigation led to universal findings described previously in section 4.1.2. The following findings were specific to Case Study 2:

- At 80% demand, route diversion improved both the travel times for the total network and Ted Williams Tunnel vehicles compared to local control. This indicates that there was enough incident congestion to warrant route diversion of vehicles. Route diversion also caused a marginal speed increase in the Ted Williams Tunnel during the incident and recovery periods, which is beneficial for incident clearance and safety.
- At 90% demand, the delay was reduced for Ted Williams Tunnel vehicles, but increased for the entire network. This delay tradeoff needs to be identified to understand the full impact of route diversion. Large speed increases in the Ted Williams Tunnel were also caused during the incident and recovery periods, again indicating incident clearance and safety benefits.
- At 100% demand, the Ted Williams Tunnel vehicles experienced slightly less travel time, but the entire network's travel time greatly increased due to route diversion. Few vehicles diverted since the alternative was not significantly more attractive. As a result, diverted vehicles significantly increased travel time on the alternative route. This identifies the delay tradeoff which needs to be identified and accounted for in a routing strategy.
- At high airport 80% demand, route diversion comparatively improved travel time for both the Ted Williams Tunnel vehicles and the entire network. The travel time savings across OD pairs identifies that although rerouting decreased total travel time, it increased travel times for some vehicles. The rerouting also led to speed improvements in the Ted Williams Tunnel during the recovery period, indicating that incident congestion dissipated sooner, returning conditions to the normal safety level.
- At high airport 90% demand, the travel time for the Ted Williams Tunnel vehicles improved, while that for the entire network worsened, implying a delay tradeoff .

This chapter enumerated findings and insights from the simulation studies. The next chapter will present the summary of the research, the conclusions drawn, and suggest directions for future research.

Chapter 5 Summary, Conclusions and Future Research

5.1 Summary

The development of well-designed DTMS is essential for future management of congestion. DTMS are responsible for traffic monitoring, implementation of traffic control, and providing traveler information. Evaluation of DTMS design is needed to ensure a successful implementation. Simulation plays an important role in the testing and evaluation of DTMS design, by providing a better understanding of a traffic system and assisting in selection of an appropriate DTMS design for that system. Simulation can also identify situations which require design enhancement.

This research presented two case studies demonstrating the use of microscopic simulation for DTMS evaluation, and the usefulness of simulation as an evaluation tool. These case studies were performed for the Central Artery/Tunnel (CA/T) network, scheduled for completion in year 2004. Much of the CA/T network is designed as a tunnel, requiring an efficiently designed DTMS to ensure smooth traffic. The traffic control system of the CA/T includes the following control components: lane control signals, variable message signs, variable speed limit signs, ramp metering, and route diversion. These control components were integrated to develop the control designs tested in the case studies.

Case Study 1 demonstrated an evaluation of the integrated control designs. Over a range of demand scenarios, this experiment simulated use of a basic control design, combinations of control components, and a full-component design for management of an incident placed in a weaving section. The components used include LCS, VSLS, ramp metering, and route diversion. This experiment presented results for multiple MOEs which were used for both local and system-wide evaluation. The analysis identified situations when certain controls should or should not be used, or suggested improvements of their design.

Case Study 2 also investigated the use of route diversion as part of an incident management strategy. In this case study, an incident was placed in one of two tunnels connecting Logan Airport and downtown Boston. Since there existed another tunnel, many vehicles had an alternative route. In the previous case study, only a limited number of vehicles could divert. This case study also differed from Case Study 1 by not including ramp metering in full-component design, since the incident location was not near an adequate on-ramp for metering. This experiment attempted to identify situations which facilitated the integration of route diversion with local controls. Two travel patterns were simulated at different demand levels to create a range of situations for this analysis. The MOEs collected allow the analysis to consider not only the overall control impact, but also the impact on the incident location, and the redistribution of delay among different OD pairs. Improving travel conditions in a certain location,

such as the incident location, may sometimes be more important than the overall impact, and this case study was able to identify the magnitude of these impacts.

5.2 Conclusions

A number of conclusions can be drawn based upon this research. This research was a successful demonstration of the testing and evaluation of DTMS design by a microscopic simulation laboratory. It was able to identify situations of poor and beneficial DTMS implementation, and identify this performance at the local and network levels. This allows for a detailed understanding of the situation resulting from the control. This detail of evaluation can only be produced from a simulation laboratory, like MITSIM laboratory, or from actual field implementation. The advantages of evaluation by simulation are its much lower costs, and its ability to test a wide-range of designs without concern for disrupting traffic.

The case studies showed that the DTMS designs either resulted in a marginal improvement or a deterioration of the system. Case Study 1 identified that there were situations which led to the best performance from the fully-integrated control design, but this was not the case for the most part. The experiments also showed that there were network conditions when it was not beneficial from a travel time savings perspective to use one or more controls. A more advanced DTMS design is required to correct these situations. The naïve integration approach used in this research does not adequately address the interactions of the control components. These components need to be jointly optimized for improvement to the entire system. Chen and Ben-Akiva [1998] considered a joint optimization of urban traffic control and routing. Development of other integration strategies of this sort need to be pursued. The control implementation also needs to exhibit more intelligent behavior. On-line optimization needs not only to determine the optimal control to implement, but verify that its implementation does improve conditions.

The evaluation of route diversion demonstrated that there were few conditions which made route diversion feasible under the diversion logic used. This highlights the need for a more advanced route guidance strategy which not only predicts future traffic conditions, but also drivers' responses to information about those conditions. Ben-Akiva et al. [1998] present a system which used this strategy, DynaMIT. DynaMIT predicts the future conditions based upon travelers' responses to that information, and determine if it is beneficial to implement the guidance control. Diversion determined in this manner has been demonstrated to be beneficial using the same transportation network [Bierlaire, 1998].

The use of multiple MOEs was found to be a successful way to evaluate the DTMS performance at both the local and network levels. Situations were often found which resulted in some improved conditions at the expense of other locations. Estimates of travel times, variances, and speed measures provided much insight into this delay tradeoff. It is important to be aware of this impact at both the local and network level.

Case Study 1 demonstrated that microscopic simulation can identify complex phenomena which may not be possible with macroscopic simulation or analytical modeling. For example, we found an increase in mainline congestion due to route diversion which may not have been predicted before implementation. While this specific finding may raise some questions, it suggested a need for further investigation before the control is implemented. Microscopic simulation can provide insight into unexpected findings of this sort. Other examples include analysis of traffic flow near capacity, which can lead to unexpected results.

In summary, this research used microscopic simulation to identify the deficiencies of a simplified DTMS approach. Advances are required to ensure beneficial DTMS implementation, and a microscopic simulation laboratory like MITSIM can be used to assist in the development and testing of these designs.

5.3 Future Research

DTMS is an emerging technique for alleviating traffic congestion. A simulation framework and experimental results were presented to demonstrate the evaluation of DTMS design for a real project. It showed that a naïve DTMS design may not be beneficial, and more effort must be invested in advanced DTMS development. The following areas should be investigated in future research to assist the further development of DTMS:

- Development of a sophisticated DTMS strategy which accounts for the interactions of the components being integrated should lead to more significant improvements. In other words, integration and coordination among various components of DTMS should be achieved in an optimal framework.
- The CAVT network has limited alternative routes since the urban road network is not included. A more effective evaluation of route diversion needs a network with additional alternative routes. Such a study which includes urban roads, also allows for integration of traffic signal control with the other control devices tested.
- This work discussed scenarios in terms of demand levels. It would be more useful to specify the inputs in universal terms that can be quantified to a TCC. For example, traffic flows of the mainline and on-ramps.
- Case Study 1 identified an unusual phenomenon: that route diversion from the mainline deteriorates traffic conditions on the mainline. This was found to happen due to the headway size distribution of merging vehicles resulting from ramp congestion. We performed simulation experiments to investigate this situation. However further study is needed to substantiate the nature and extent of its impact.

- When the incident did not result in substantial congestion, local controls were found to increase travel times. It is important to continue use of these controls for safety reasons, but improvements may be found by modifications to the local control implementation. A more "intelligent" design may be able to achieve this.
- The findings of these case studies needs to be validated through further empirical studies.
- A field study is essential to validate the findings.

Appendix A Empirical Investigations of the Impact of Merging Vehicles Headway Size on Mainline Disturbance

A.1 Introduction

It was found in Case Study 1 (Chapter 3) that for certain demand levels, when vehicles were diverted away from the mainline it caused slower speeds and higher travel times for mainline traffic. Mainline throughput (not presented in Chapter 3) was also found to be lower when route diversion was used. An incident occurred from 4:50 to 5:10 PM, and the lower speeds and throughputs were found from 5:10 to 5:30 PM. We believe that this phenomenon is caused by the headway size of vehicles as they merge with the mainline. When route diversion was used, the formation of a bottleneck upstream of the on-ramp was delayed due to a lower demand for the ramp. The ramp bottleneck acts like a natural meter, reducing the number of vehicles which enter the mainline with small headways, thus lowering the mainline disturbance.

This appendix attempts to substantiate our a-priori belief through the following investigation steps:

1. Use the same network for a modified OD table, which reduces OD demand of vehicles which uses Ramp-C, the ramp in question. This attempts to verify that a lower ramp demand results in a lower mainline throughput, due to headway distribution of merging vehicles.
2. A stop sign is added on this ramp, and simulations are performed for both the high and low ramp demand levels. This attempts to show that headway distribution is the cause of the above counter-intuitive results. The stop sign causes a uniform headway for merging vehicles. It will be seen that the throughput is the same for the two demand levels with identical headways.
3. Sensitivity of MITSIM's merging model with respect to its key parameters is performed to substantiate that the above phenomenon is not due to the model's parameters used in this study.

A.2 Replication in CA/T Network

To confirm the occurrence of this phenomenon, simulations were run using the CA/T network and modified demand for Ramp-C. Two sets of simulation runs were performed using the following demand: 1.) 100% of 2004 PM peak period demand, and 2.) 100% of 2004 PM peak period demand, with reduced demand for Ramp-C. It is important to note that this low ramp demand still creates a bottleneck on the ramp, but later in the simulation. Our a-priori belief is that headways of merging vehicles are causing the difference in throughputs. In order to better understand this, one must be aware of the network geometry and its resulting impact.

A.2.1 Network Geometry

Ramp-C connects I-90 eastbound and westbound to I-93 northbound. Figure A-1 shows that one lane joins from westbound (Ted Williams Tunnel) and the other one from eastbound (Massachusetts Turnpike) before merging into one lane, about 600 ft upstream of the merge with mainline traffic. When there is sufficient demand, congestion starts to form upstream of the junction (point "+" in Figure A-1).

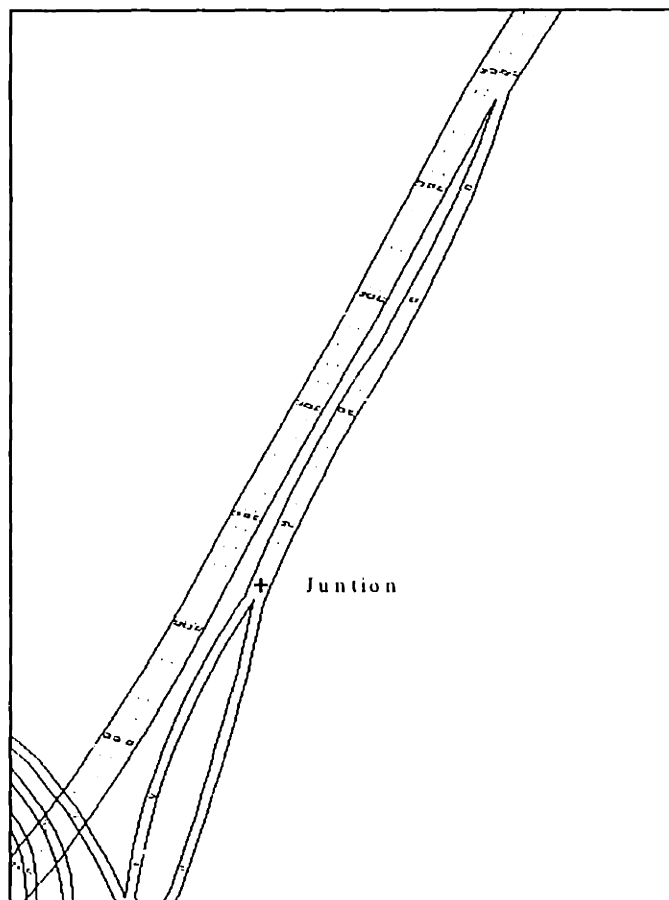


Figure A-1 Ramp junction

The upstream mainline section is three lanes wide and the on-ramp merges as an add lane, creating a fourth mainline lane. The incident is in the right lane (add lane), about 2,000 ft downstream of the beginning of the add lane. Additionally, this lane becomes an exit lane about 2,500 ft downstream of the incident. Thus, all the vehicles entering from Ramp-C need to merge to the left.

A.2.2 Resulting Impact

A high ramp demand gives rise to a bottleneck formation at the junction where two lanes join to form a one-lane merge with the mainline. This bottleneck acts like a natural meter, allowing vehicles to enter the mainline at a more uniform headway. This, in turn, prevents platoons of vehicles from entering the

mainline with small headways, which is believed to reduce mainline throughput. When a lower ramp demand is used, this bottleneck should form later in the simulation. Thus a longer period of small headways should be expected, causing higher disturbances.

In Case Study 1, the lower throughput for route diversion was not found until after the incident had been cleared. While the incident occurred, the mainline capacity was reduced, limiting the mainline throughput regardless of the merging disturbance. This disturbance did impact the conditions upstream of the incident, creating more congestion. So when the incident was cleared, the mainline was more congested due to the higher disturbance of the route diversion situation. This resulted in the lower mainline throughput found in the recovery period.

A.2.3 Supporting Experiment

Simulations were performed using two ramp demand levels to investigate the impact of ramp congestion on mainline throughputs. The incident occurred from 4:50 to 5:10 PM, same as in Case Study 1. The throughputs from these simulations are presented in Tables A-1 and A-2. The accuracy of the throughputs was found to be within 1% of the mean at the 95% confidence level. Figure A-2 displays the three sensor locations referred to in the throughput tables, with location 1 representing downstream mainline, location 2 representing the on-ramp, and location 3 representing upstream mainline. Table A-1 shows that the throughputs are almost identical for the two scenarios during the incident. But once the incident ends, the high ramp demand scenario resulted in higher throughputs for the mainline (locations 1 and 3), as seen in Table A-2.

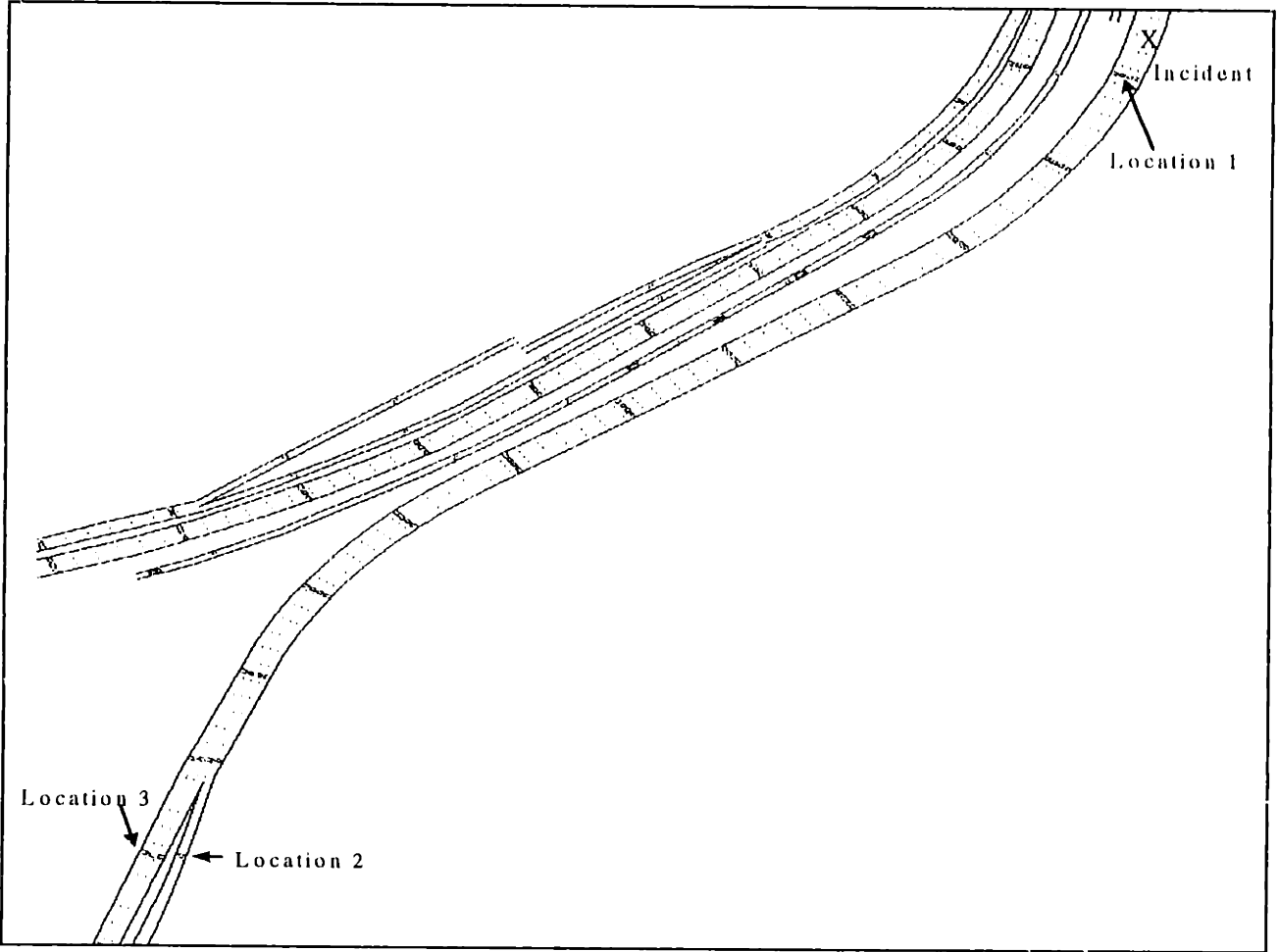


Figure A-2 Throughput sensor station locations

Table A-1 Throughput during incident (4:50 to 5:10 PM)

Location	High Ramp Demand	Low Ramp Demand
1	1713	1708
2	341	342
3	1499	1496

Table A-2 Throughput after incident (5:10 to 5:30 PM)

Location	High Ramp Demand	Low Ramp Demand
1	2323	2284
2	593	593
3	1602	1568

Time headways were collected to investigate the difference in platoon size between two ramp demand levels. Figure A-3 displays the time headway distribution of the two demand cases for 4:50 to 4:55 PM. This time period was selected because the ramp bottleneck begins to form around 4:50 PM for the high ramp demand, and around 4:55 PM for the low ramp demand. Figure A-3 verifies that more vehicles have small headways, 1 second, when the low demand is used.

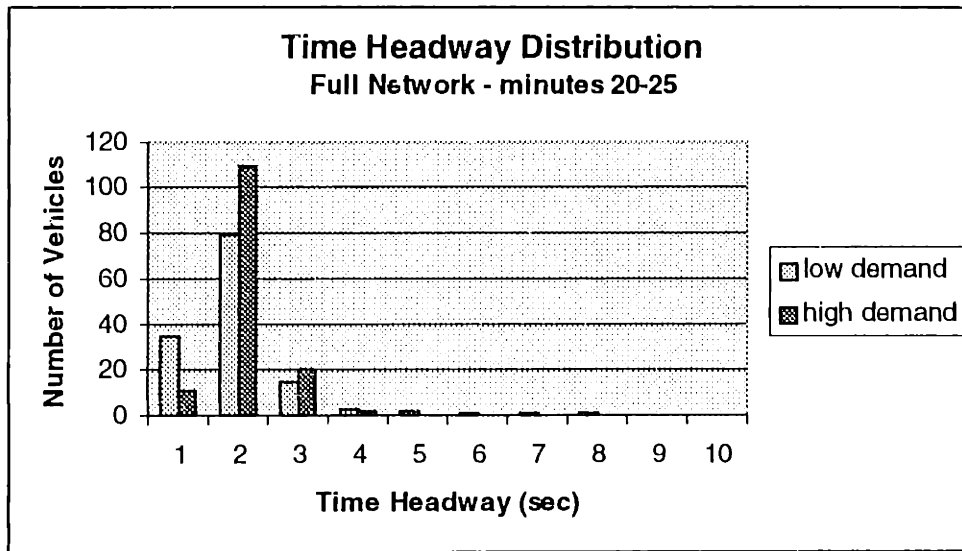


Figure A-3 Time headway distribution of full CA/T network

In order to verify that small headways of merging vehicles were responsible for the lower throughput after the incident, a stop sign was added to the ramp at the junction of the two-lane reduction to one lane. The stop sign was added to break platoons which merge with the mainline. Again simulations were run for both high and low ramp demand. Tables A-3 and A-4 show that the throughputs were similar for both levels of ramp demand when the stop sign was used. This supports the a-priori belief that small merging vehicle headways reduce mainline throughput.

Table A-3 Stop sign network throughput during incident (4:50-5:10 PM)

Location	High Ramp Demand	Low Ramp Demand
1	1702	1700
2	341	342
3	1499	1496

Table A-4 Stop sign network throughput after incident (5:10-5:30 P.M)

Location	High Ramp Demand	Low Ramp Demand
1	2174	2170
2	339	340
3	1697	1698

A.3 Hypothesis for Phenomenon

From the experiments described above, it appears that headway size of merging vehicles has a large impact on the throughput of the mainline. When vehicles merge in a single-vehicle platoon, they seem to cause less mainline disturbance than when they merge in larger-sized platoons with smaller headways. Previous research by Elefteriadou [1997] has investigated this situation. Her research has shown that the disturbance due to a merge increases with the cluster size of merging vehicles.

A.4 Sensitivity Analysis

In order to substantiate the above hypothesis, it is essential to demonstrate that the results are not due to parametric values in the merging model. Thus, the impact of headway size was evaluated for a range of parameters in the merging model.

A.4.1 Base Case

Simulations were performed using a simple test network to reproduce the traffic conditions on the mainline. Figure A-4 displays this test network and the sensor locations used to measure throughput. A mainline demand of 1500 vehicles/hour/lane and ramp demand of 1100 vehicles/hour were used for this experiment.

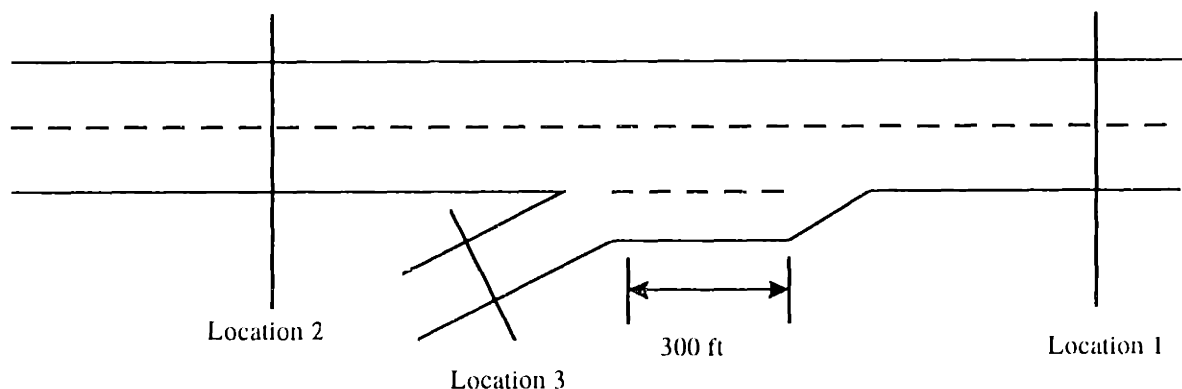


Figure A-4 Test network and sensor locations

Two scenarios were run: one with “uniform” headways and one with “random” headways. Since it is believed that small headways cause larger mainline disturbance, we wanted to create a scenario which had more small headways. The majority of vehicles enter the mainline in single-vehicle platoons in the “uniform” headway scenario, whereas they enter in random sized platoons in the “random” headway case. Although MITSIM loads vehicles with randomly distributed sized headways, at this ramp demand level (900 vehicles/hour), their headways are almost uniform, based upon the arrival distribution in MITSIM. The longer vehicles travel in the network, the more likely they are to form clusters of small headways due to stochasticity in vehicles’ desired speeds. A ramp of 800 ft is used in the “uniform” scenario so that most vehicles enter the mainline with the headways they are loaded. On the other-hand, the on-ramp is about 1 mile long in the “random” headway scenario, allowing vehicles to form platoons (due to desired speed differences) when they reach the mainline.

Tables A-5 through A-7 display three periods’ throughputs for these scenarios using the default merging model parameters. The accuracy of these throughputs was found to be within 2% of the mean at the 95% confidence interval using 15 replications of simulations. The first period begins at minute 5 and lasts until minute 15. It starts at minute 5 to allow the network to load. Table A-5 shows that there is a higher mainline throughput (locations 1 and 2) in the “uniform” headway scenario during minutes 5 through 15. Table A-6 shows that the “random” headway scenario has similar mainline throughput (within the error range) during minutes 15 through 30, since there are more vehicles waiting to pass due to the lower throughput in the previous period. Table A-7 shows that the throughputs are similar during minutes 30 through 45. The higher mainline throughput of the “uniform” headway scenario during the first period supports the hypothesis that clusters of vehicles cause more mainline disturbance.

Table A-5 Throughput for minutes 5-15 for test network

Location	Uniform Headway	Random Headway
1	592	572
2	410	391
3	199	193

Table A-6 Throughput for minutes 15-30 for test network

Location	Uniform Headway	Random Headway
1	742	748
2	482	485
3	259	263

Table A-7 Throughput for minutes 30-45 for test network

Location	Uniform Headway	Random Headway
1	740	739
2	480	477
3	260	262

In order to verify that the “uniform” and “random” headway scenarios actually resulted in uniform and random headways, the headway distributions of these scenarios were plotted. Figure A-5 displays the time headway distributions for minutes 5 through 15. It shows that the “random” headway scenario has more vehicles with small headways indicating more clusters. This is similar to the headway distribution comparison between the low and high ramp demands for the full CA/T network, where the low ramp demand had more small headways. The sensitivity of the merging model parameters was studied next.

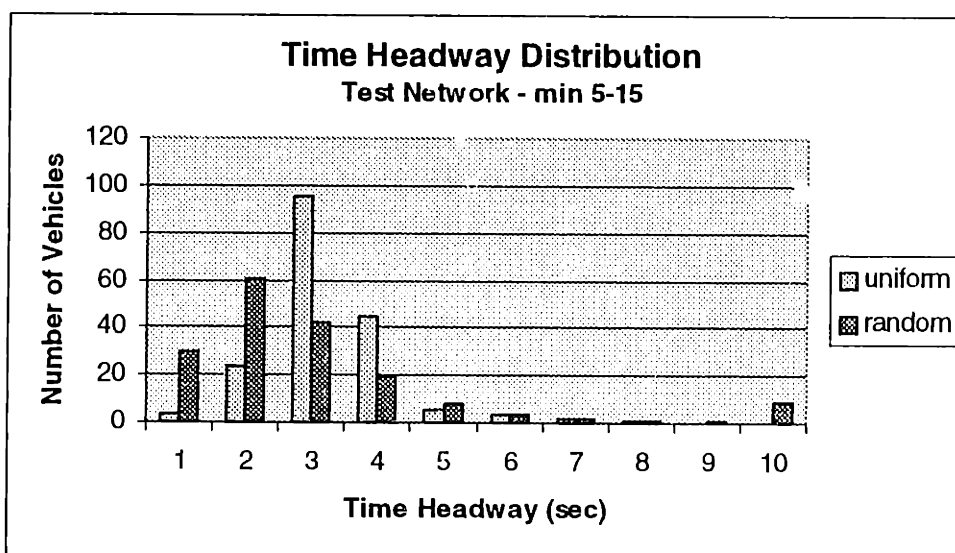


Figure A-5 Time headway distribution of test network for minutes 5-15

A.4.2 Merging Model Parameter Sensitivity Analysis

Two merging model parameters were varied for sensitivity analysis: lag gap scaling factor, and the ramp lane drop coefficient. The lag gap scaling factor is used in the mandatory lane changing model. It scales the calculated minimum lag gap value of a driver before comparison with the actual gap. When this scaling factor is increased, it is more likely that this minimum lag gap calculation will be above the actual gap, thus decreasing the likelihood of a lane change. The ramp lane drop coefficient is also used

in the mandatory lane changing model. Increasing this coefficient results in a smaller mandatory lane changing distance.

Five parameter values were tested for both parameters. These parameter values are presented in Table A-8. Parameter values used in the case studies were 1.0 and 0.5 for the lag gap scaling factor and ramp lane drop coefficient respectively. Throughputs were considered at the same locations and are presented in Figures A-6 through A-11. The accuracy of these throughputs was found to be within 4% of the mean at the 95% confidence interval using 15 replications of simulations. This large error was due to a higher variability that accompanied a couple of the parameter values. The accuracy of most scenarios was still within 2%.

Table A-8 Merging model parameter values

Parameter	Values Tested				
Lag Gap Scaling Factor	0.25	0.5	1.0	2.0	4.0
Ramp Lane Drop Coefficient	0.1	0.25	0.5	1.0	2.5

Figures A-6 through A-8 show the throughput plots for sensitivity analysis with respect to lag gap scaling factor. Each of these plots shows the throughputs of the “uniform” and “random” scenario for minutes 5 through 10 and 15 through 30. The throughputs between minutes 30 and 45 were found to be similar to minutes 15 through 30, and are not presented for sake of brevity and clarity. Figures A-6 and A-7 show that the mainline throughput was higher in case of “uniform” headway scenario during minutes 5 through 15 for all of the lag gap parameters tested. This suggests that the platoon size impact on throughput is independent of the lag gap parameter of the merging model. The ramp throughputs were similar for all parameter values. All throughputs were found to be similar during minutes 15 through 30, as had been found with the lag gap parameter used in the case studies. These figures also show that the value of the lag gap scaling factor does have a large impact on the throughputs.

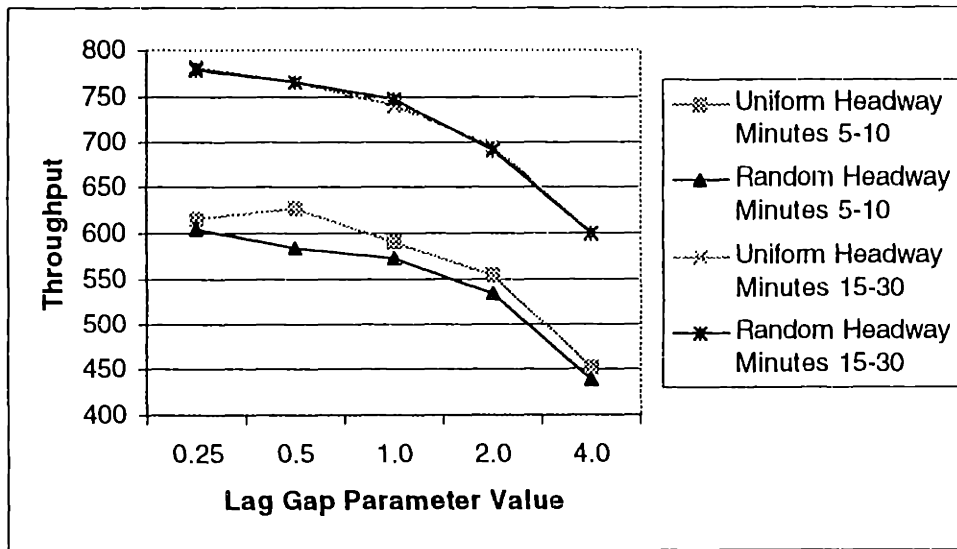


Figure A-6 Location 1 sensitivity with respect to lag gap scaling factor

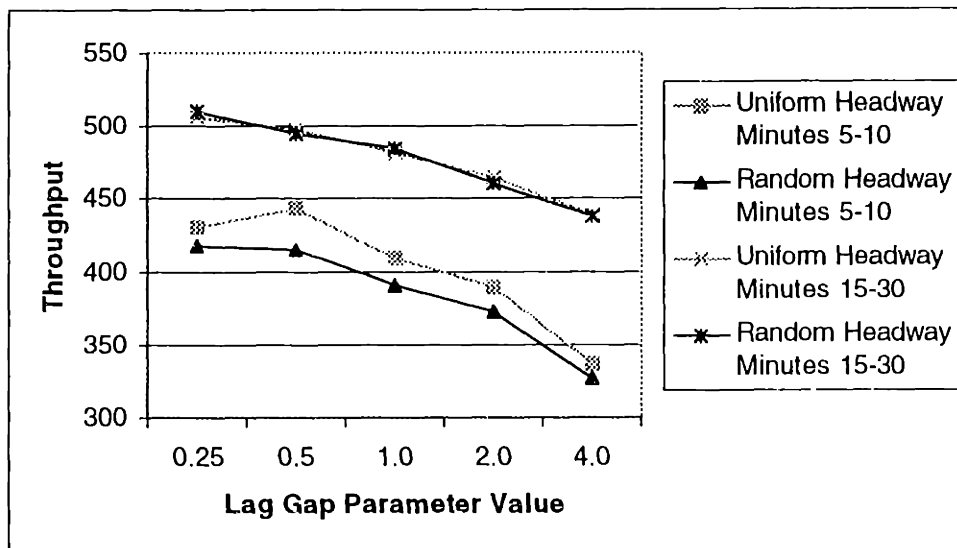


Figure A-7 Location 2 sensitivity with respect to lag gap scaling factor

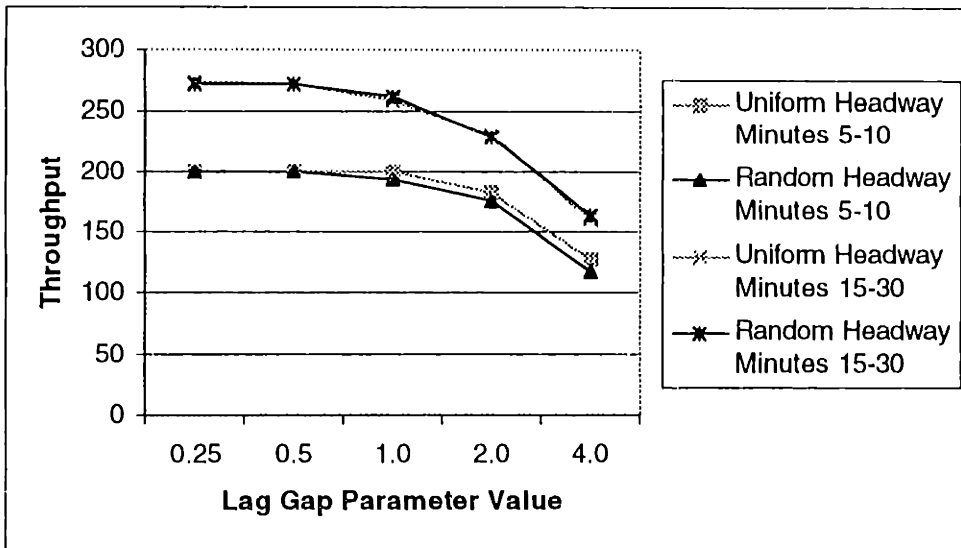


Figure A-8 Location 3 sensitivity with respect to lag gap scaling factor

Figures A-9 through A-11 show the throughput plots for the ramp lane drop coefficient testing for minutes 5 through 15 and 15 through 30. During minutes 5 through 15, the mainline throughputs are higher for the “uniform” headway scenario, as seen in Figures A-9 and A-10. This again supports our a-priori belief that this phenomenon is independent of the ramp lane drop coefficient. The “uniform” headway scenario also has slightly higher mainline throughputs during minutes 15 through 30. Although these throughput increases are less than the error term, they are consistently higher. Figure A-11 shows that the “uniform” headway scenario has greater throughputs at the two smallest lag gap parameter values, and similar throughputs at the others.

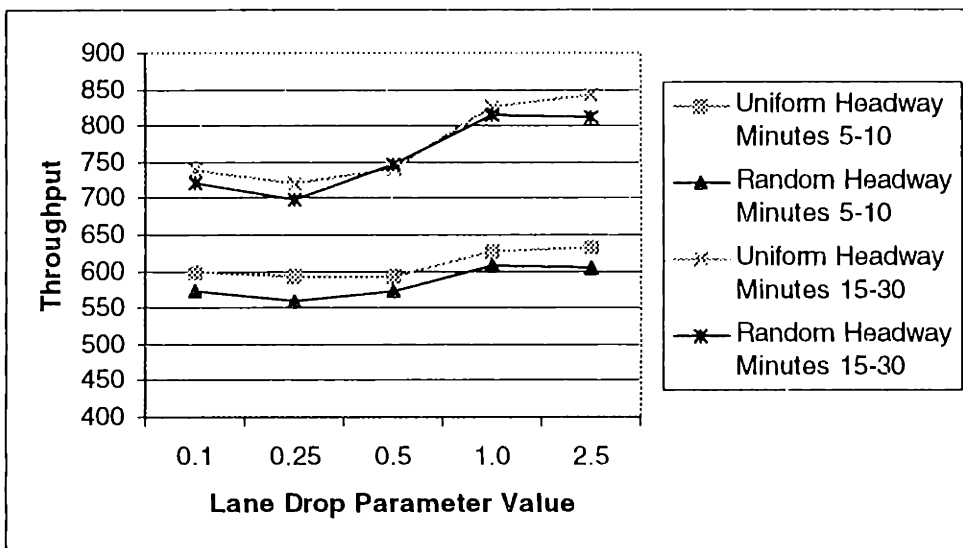


Figure A-9 Location 1 sensitivity with respect to ramp lane drop coefficient

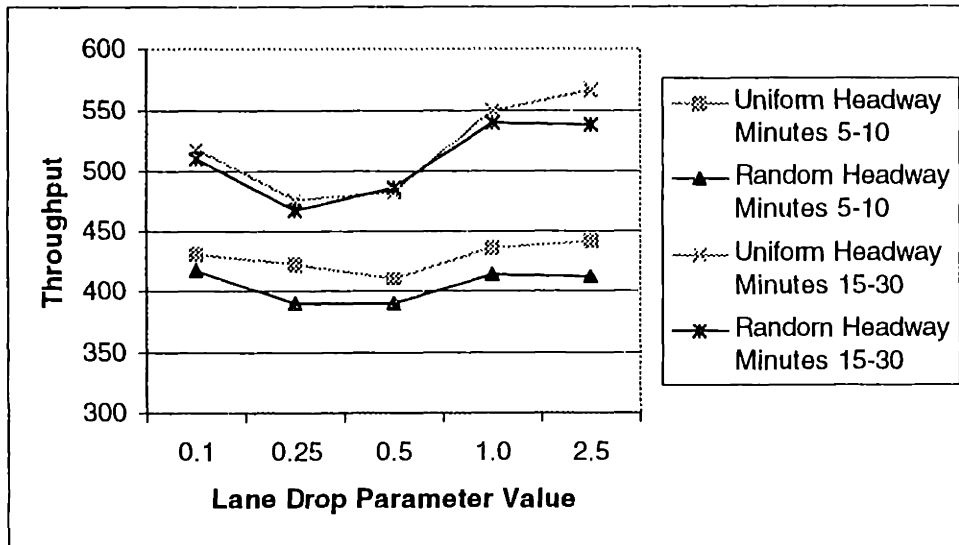


Figure A-10 Location 2 sensitivity with respect to ramp lane drop coefficient

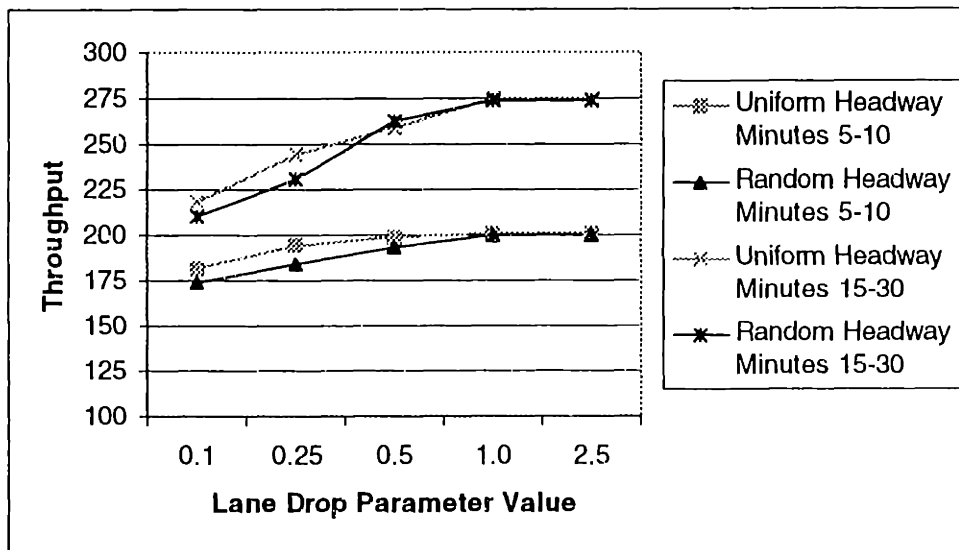


Figure A-11 Location 3 sensitivity with respect to ramp lane drop coefficient

This sensitivity analysis supports the findings that the ramp vehicle platoon size impacts mainline throughput.

A.5 Conclusion

This appendix empirically examined the impact of platoon size on the mainline traffic. When vehicles merge with constant headways, less disturbance is caused. The network geometry of Case Study 1 is such that high ramp demand caused a bottleneck on the ramp. As vehicles passed through this bottleneck, they were spaced with almost constant headways. Thus, there was less mainline disturbance when the bottleneck formed on the ramp. A higher ramp demand level was found to cause this ramp bottleneck to occur sooner, causing less mainline disturbance. This is consistent with the findings of Case Study 1, where at high demand levels (over 90% demand), route diversion from this ramp caused increased mainline travel times. Sensitivity analysis of MITSIM's merging model parameters support this claim. Further investigation is recommended to substantiate the nature and extent of the impact of merging vehicle platoon size on the mainline.

Appendix B - Case Study 1 Results

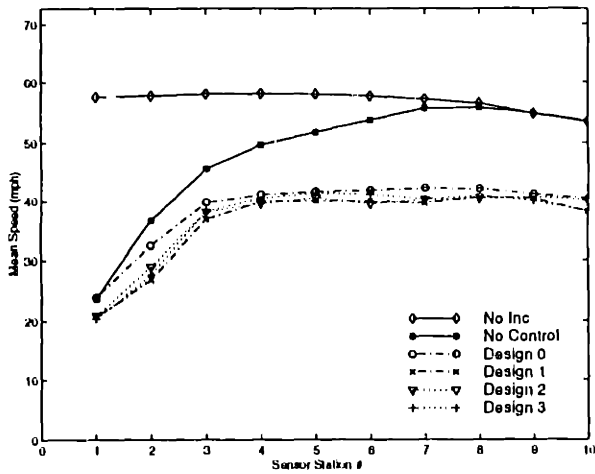


Figure B-1 Speed profile for 60% Demand
4:55-5:00 PM

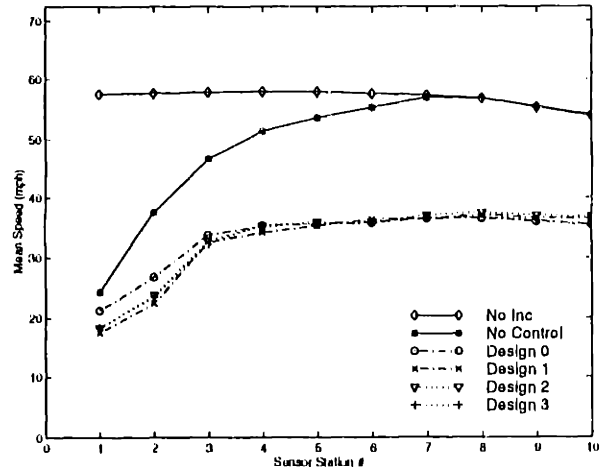


Figure B-2 Speed profile for 60% Demand
5:00-5:05 PM

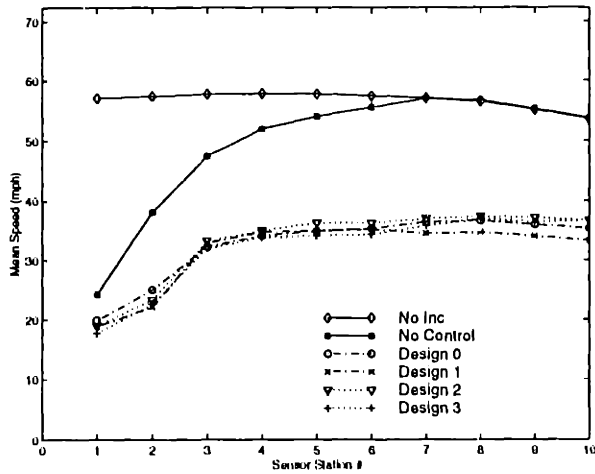


Figure B-3 Speed profile for 60% Demand
5:05-5:10 PM

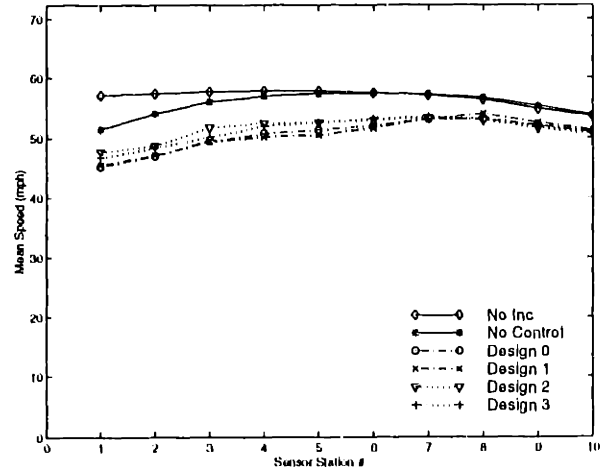


Figure B-4 Speed profile for 60% Demand
5:10-5:20 PM

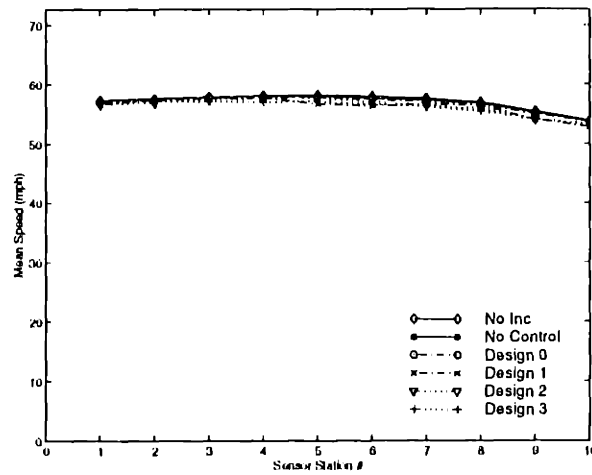


Figure B-5 Speed profile for 60% demand 5:20-5:30 PM

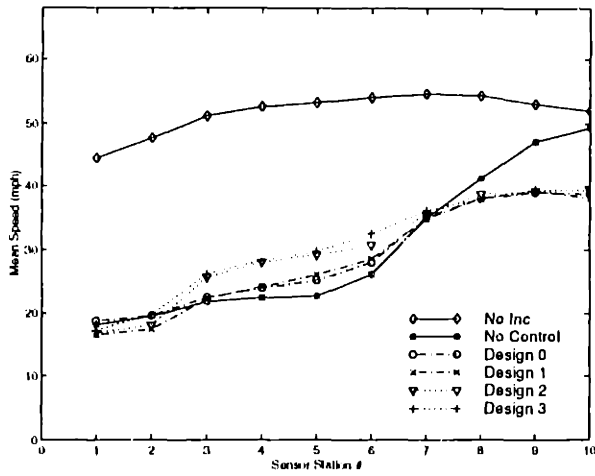


Figure B-6 Speed profile for 70% Demand
4:55-5:00 PM

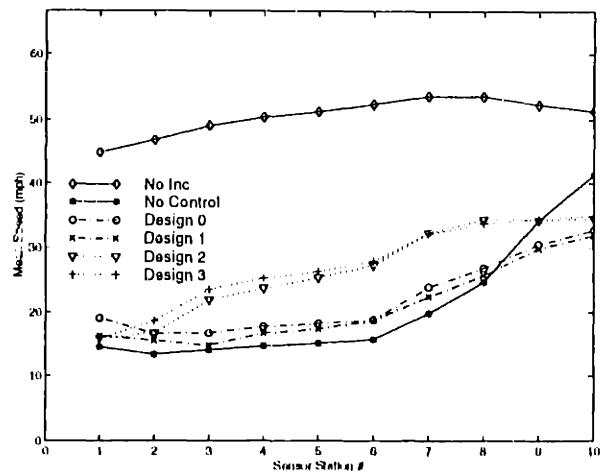


Figure B-7 Speed profile for 70% Demand
5:00-5:05 PM

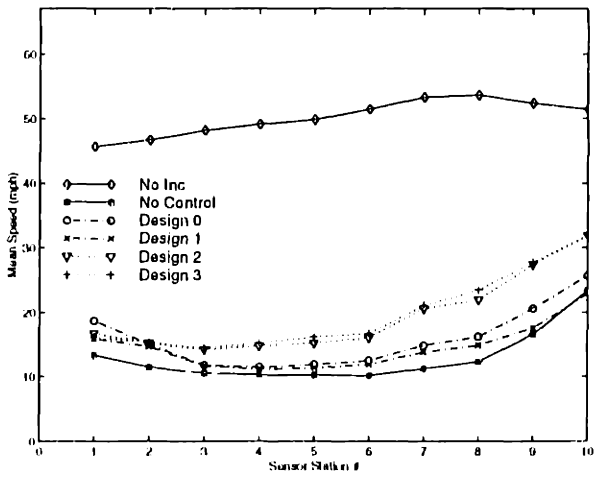


Figure B-8 Speed profile for 70% Demand
5:05-5:10 PM

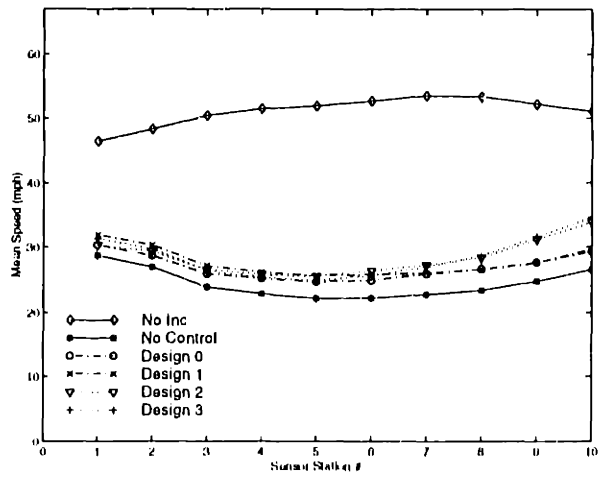


Figure B-9 Speed profile for 70% Demand
5:10-5:20 PM

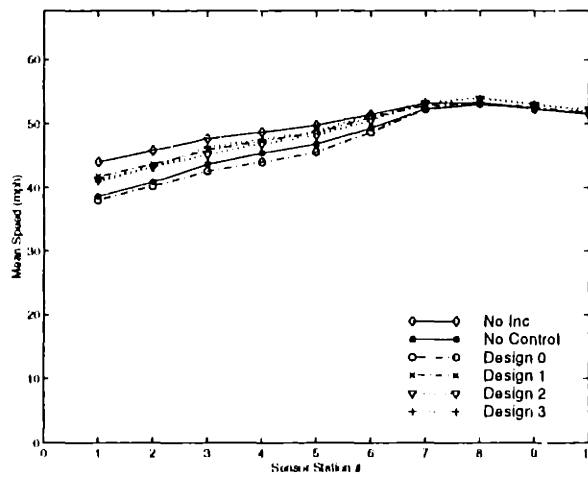


Figure B-10 Speed profile for 70% demand 5:20-5:30 PM

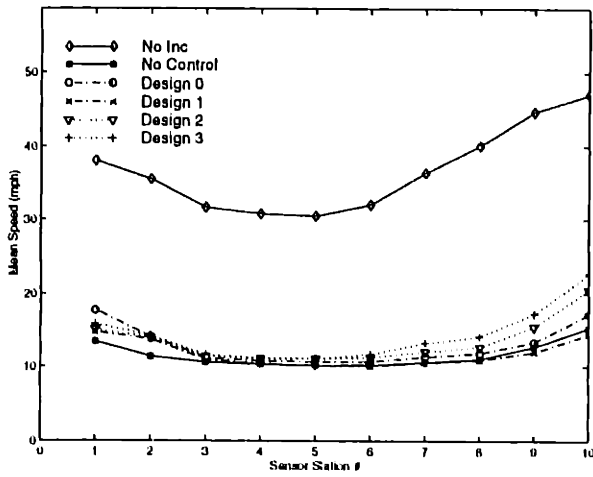


Figure B-11 Speed profile for 80% Demand
4:55-5:00 PM

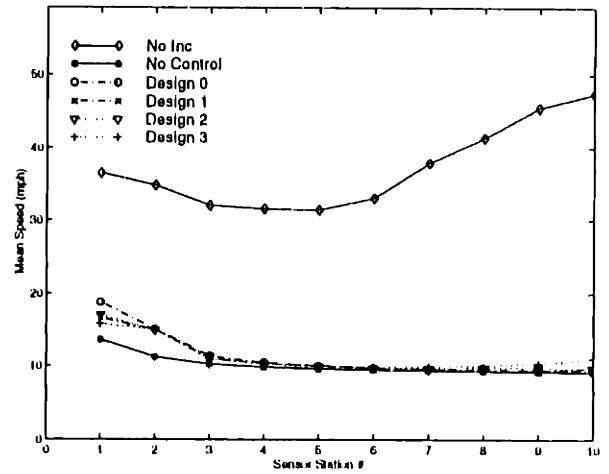


Figure B-12 Speed profile for 80% Demand
5:00-5:05 PM

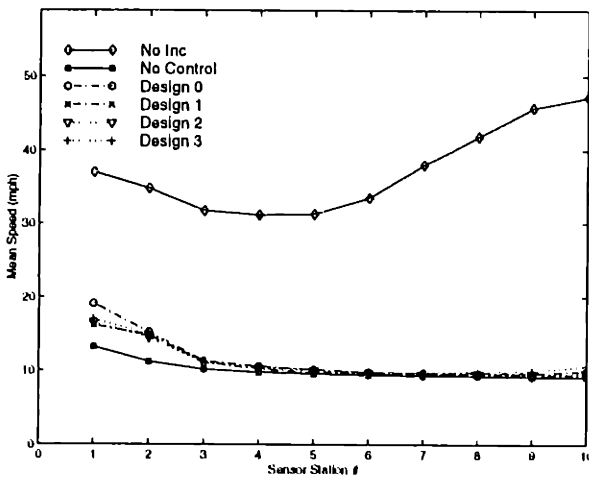


Figure B-13 Speed profile for 80% Demand
5:05-5:10 PM

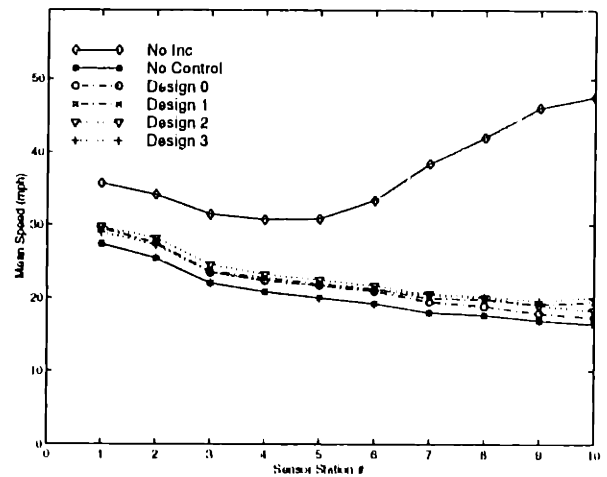


Figure B-14 Speed profile for 80% Demand
5:10-5:20 PM

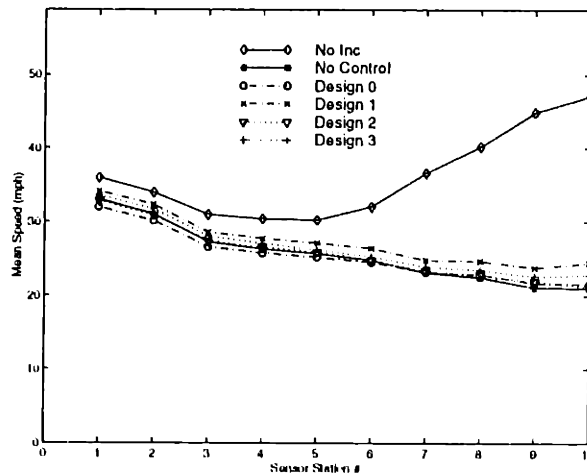


Figure B-15 Speed profile for 80% demand 5:20-5:30 PM

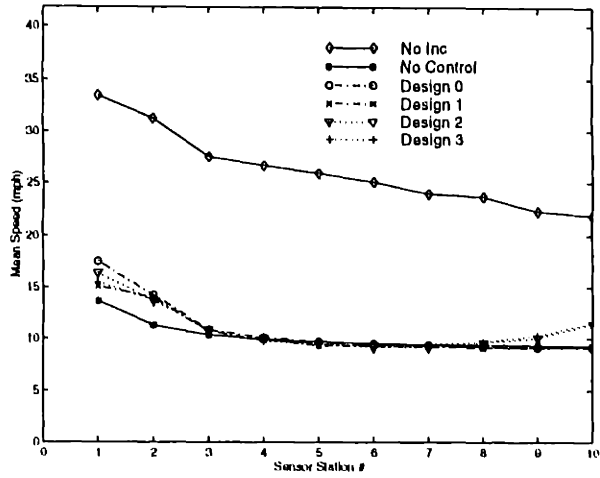


Figure B-16 Speed profile for 90% Demand
4:55-5:00 PM

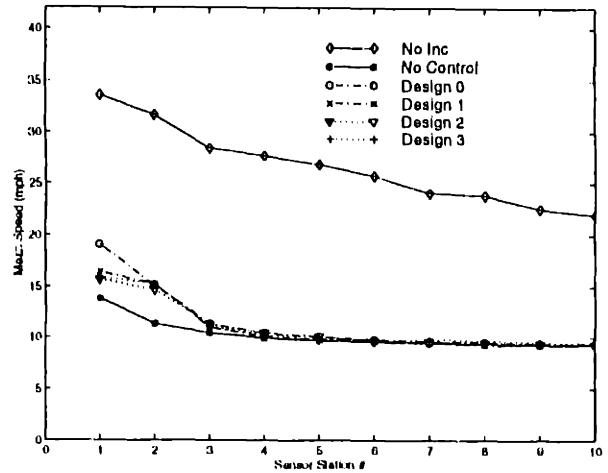


Figure B-17 Speed profile for 90% Demand
5:00-5:05 PM

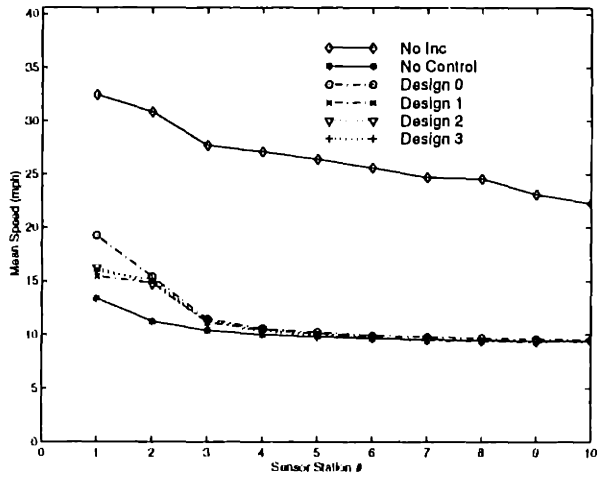


Figure B-18 Speed profile for 90% Demand
5:05-5:10 PM

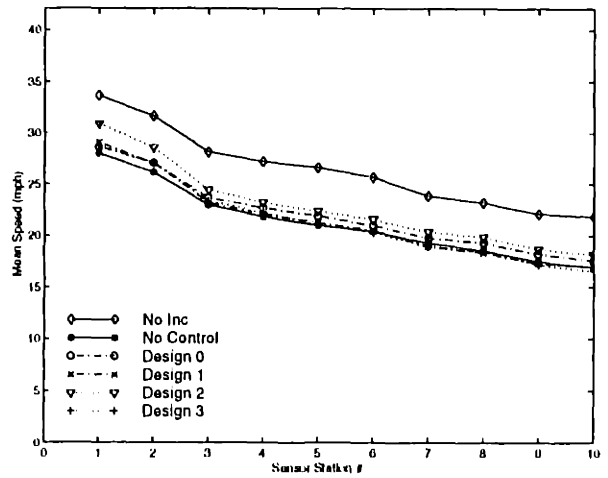


Figure B-19 Speed profile for 90% Demand
5:10-5:20 PM

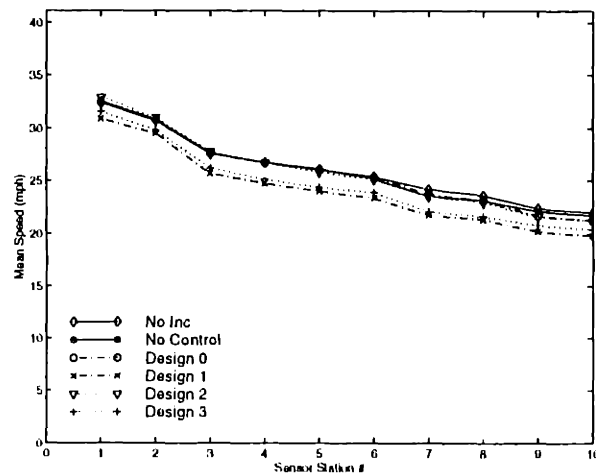


Figure B-20 Speed profile for 90% demand 5:20-5:30 PM

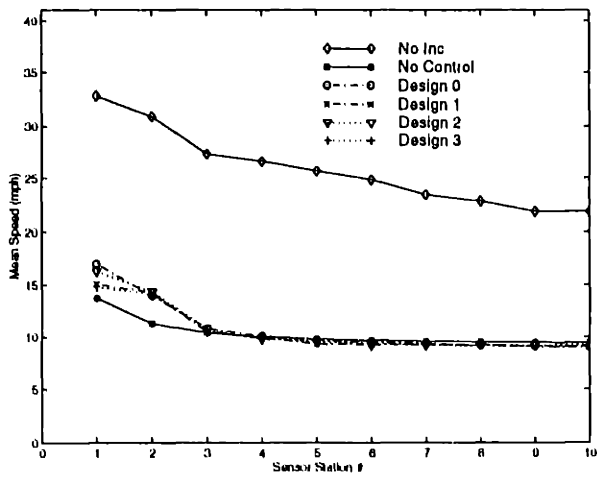


Figure B-21 Speed profile for 100% Demand
4:55-5:00 PM

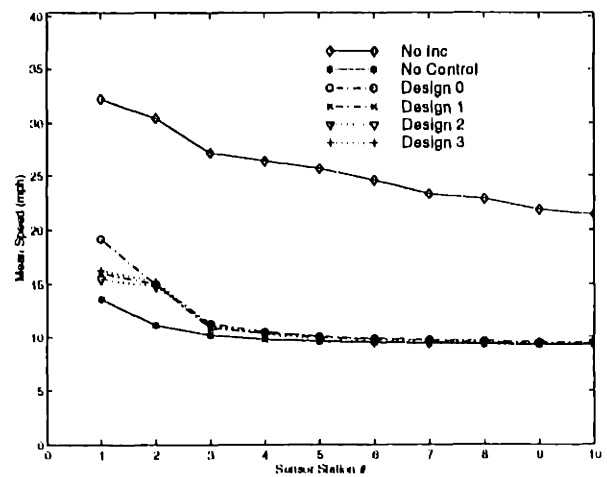


Figure B-22 Speed profile for 100% Demand
5:00-5:05 PM

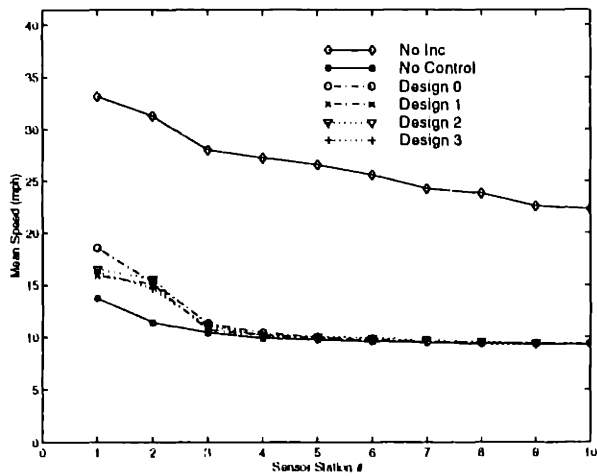


Figure B-23 Speed profile for 100% Demand
5:05-5:10 PM

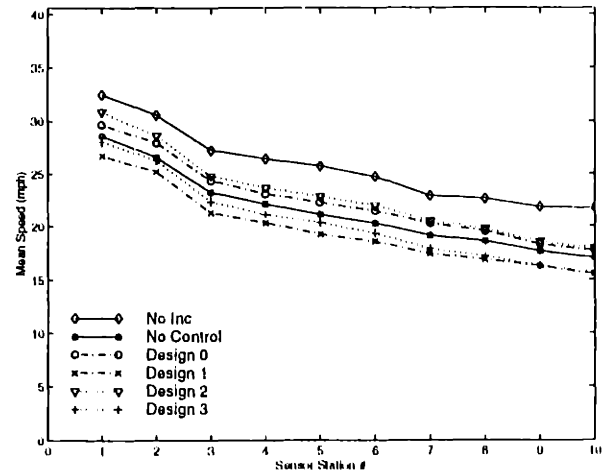


Figure B-24 Speed profile for 100% Demand
5:10-5:20 PM

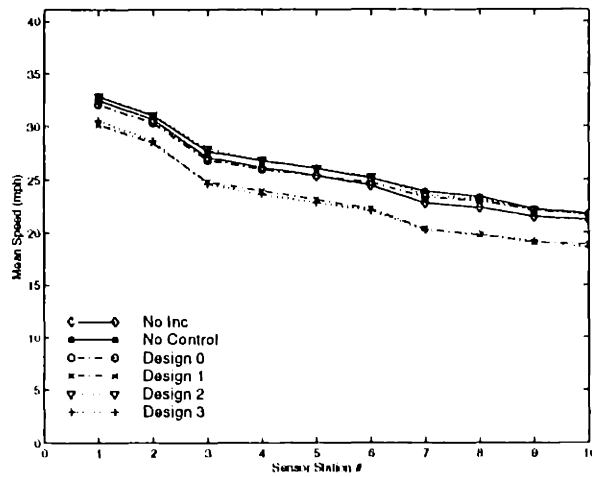


Figure B-25 Speed profile for 100% demand 5:20-5:30 PM

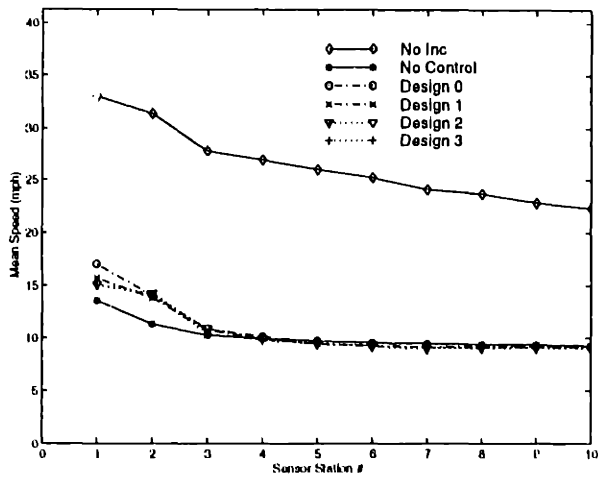


Figure B-26 Speed profile for 110% Demand
4:55-5:00 PM

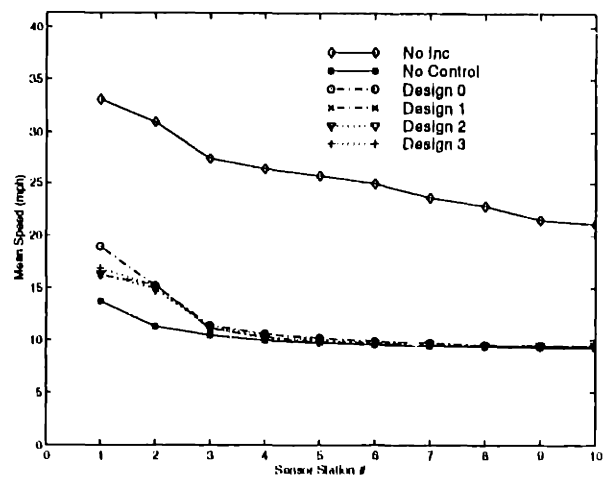


Figure B-27 Speed profile for 110% Demand
5:00-5:05 PM

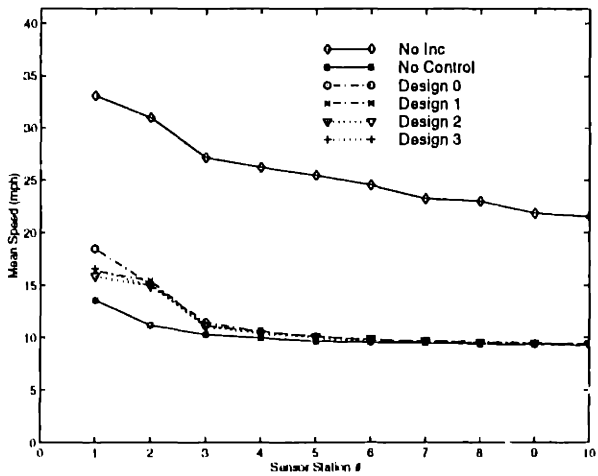


Figure B-28 Speed profile for 110% Demand
5:05-5:10 PM

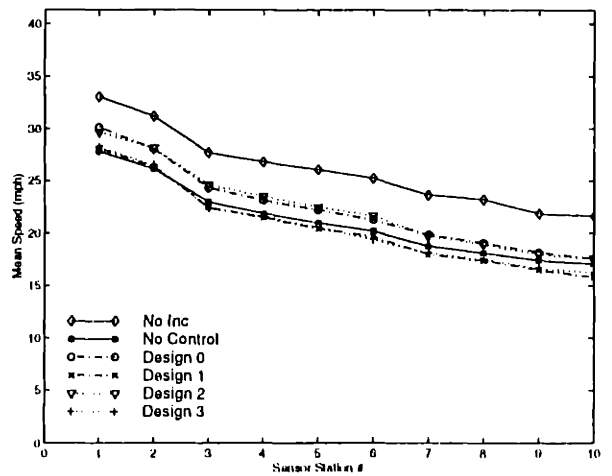


Figure B-29 Speed profile for 110% Demand
5:10-5:20 PM

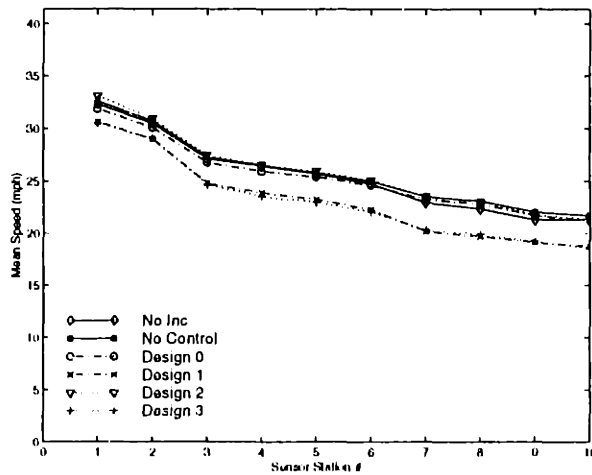


Figure B-30 Speed profile for 110% demand 5:20-5:30 PM

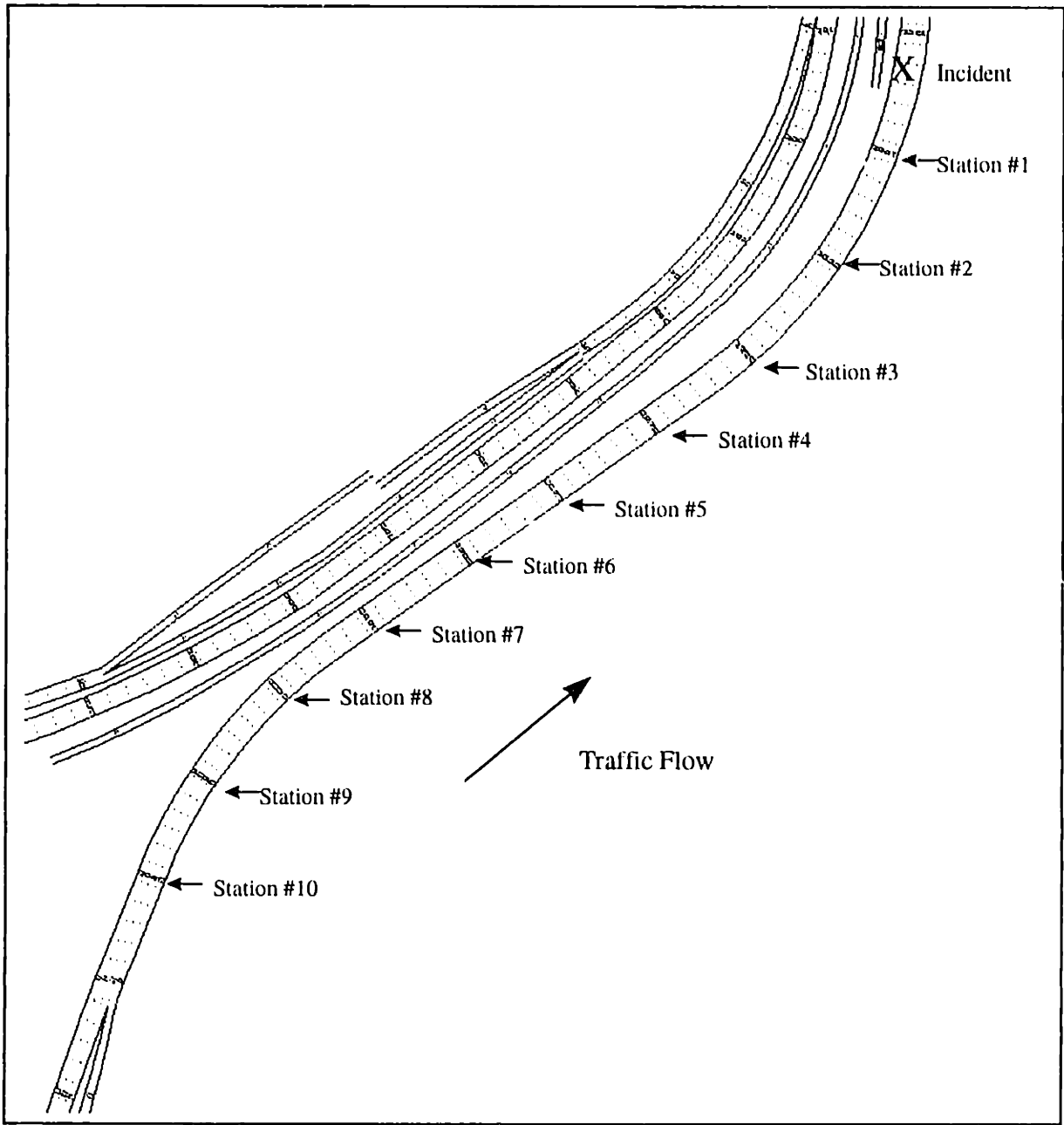


Figure B-31 Speed sensor station locations for Case Study 1

Appendix C - Case Study 2 Results

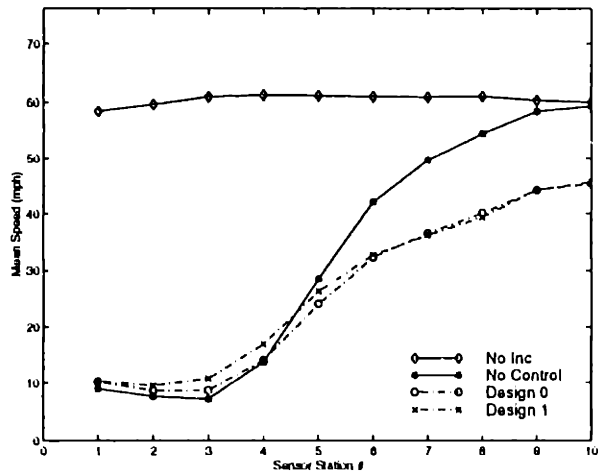


Figure C-1 Speed profile for 80% demand
4:55-5:00 PM

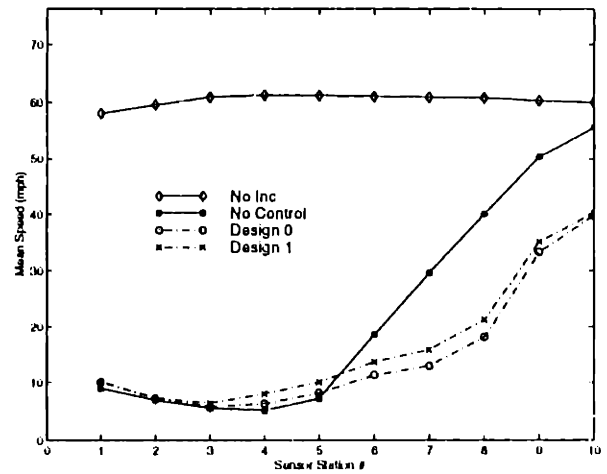


Figure C-2 Speed profile for 80% demand
5:00-5:05 PM

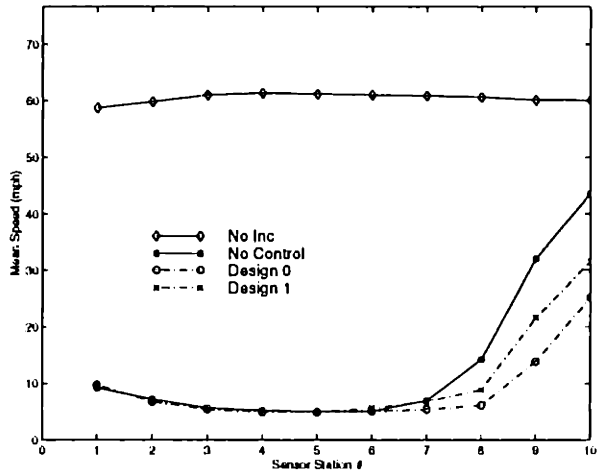


Figure C-3 Speed profile for 80% demand
5:05-5:10 PM

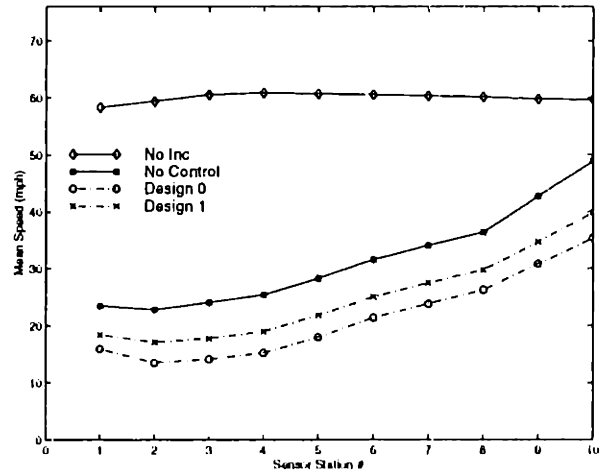


Figure C-4 Speed profile for 80% demand
5:10-5:20 PM

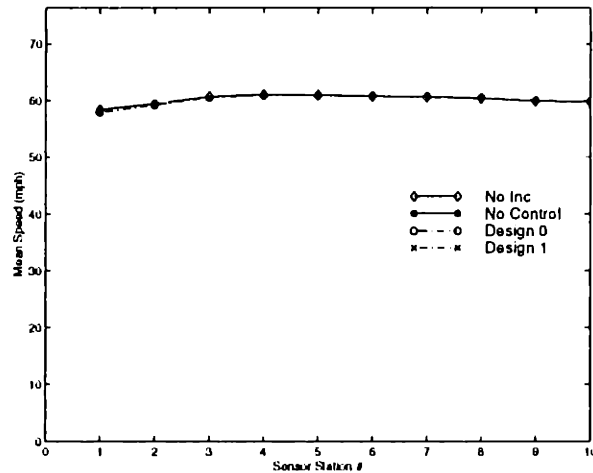


Figure C-5 Speed profile for 80% demand 5:20-5:30 PM

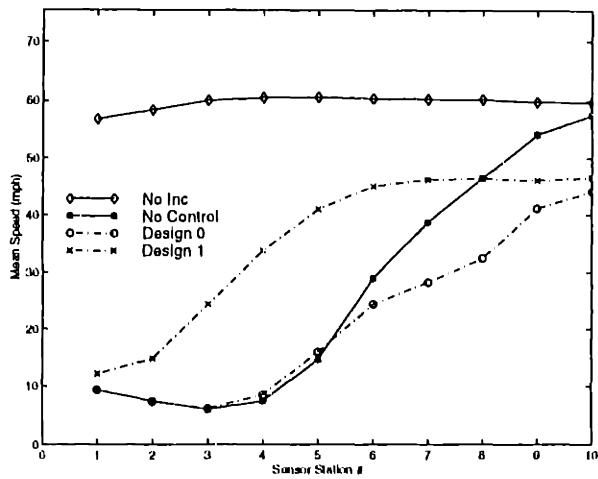


Figure C-6 Speed profile for 90% demand
4:55-5:00 PM

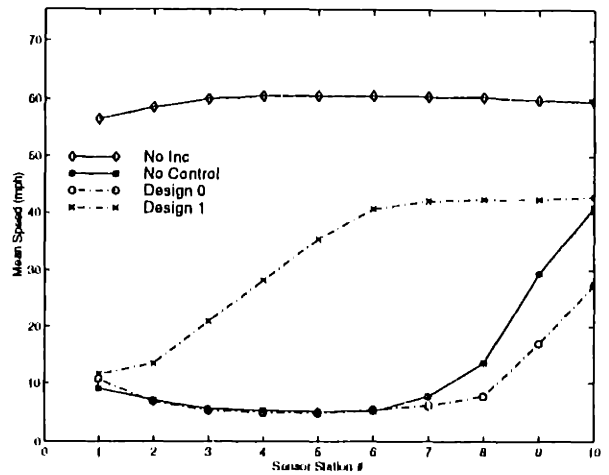


Figure C-7 Speed profile for 90% demand
5:00-5:05 PM

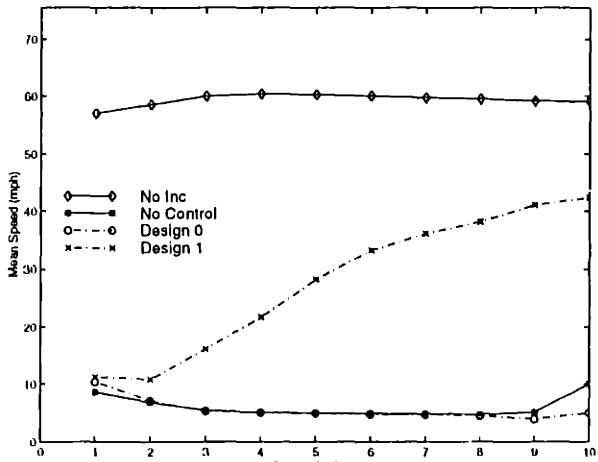


Figure C-8 Speed profile for 90% demand
5:05-5:10 PM

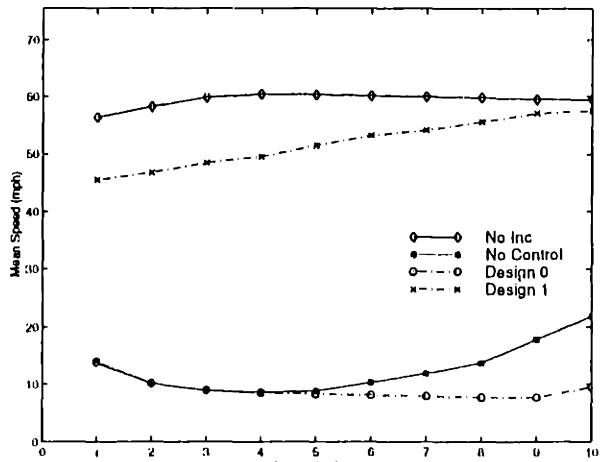


Figure C-9 Speed profile for 90% demand
5:10-5:20 PM

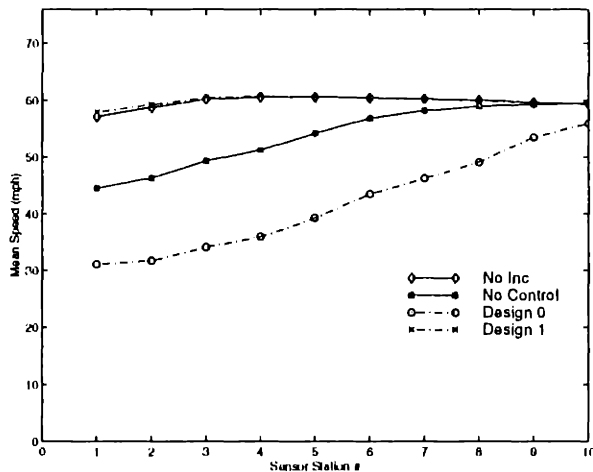


Figure C-10 Speed profile for 90% demand 5:20-5:30 PM

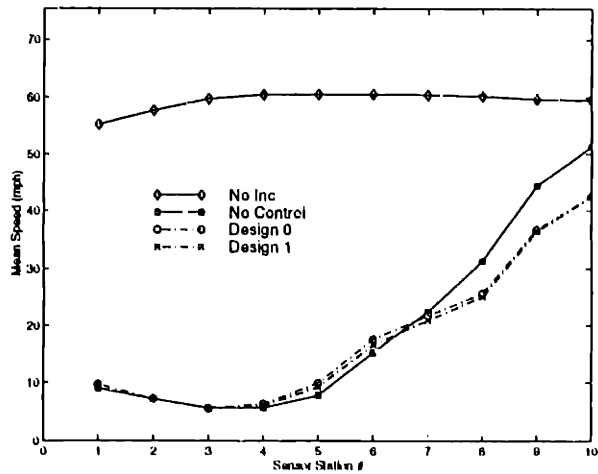


Figure C-11 Speed profile for 100% demand
4:55-5:00 PM

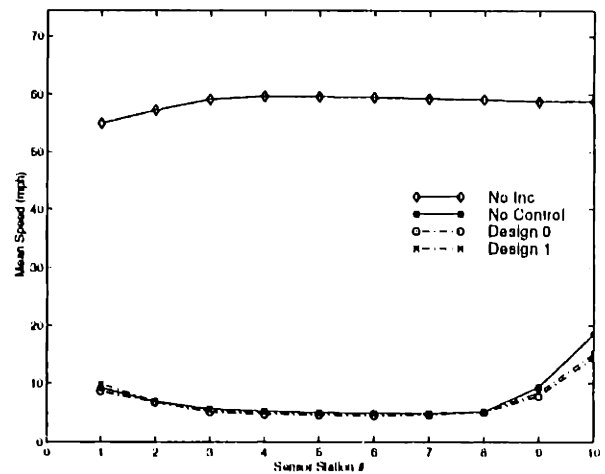


Figure C-12 Speed profile for 100% demand
5:00-5:05 PM

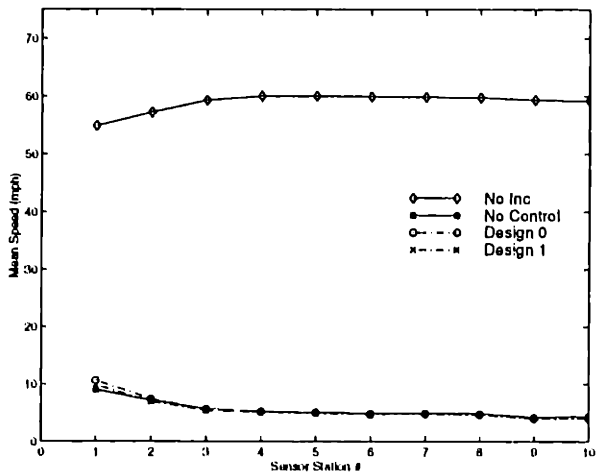


Figure C-13 Speed profile for 100% demand
5:05-5:10 PM

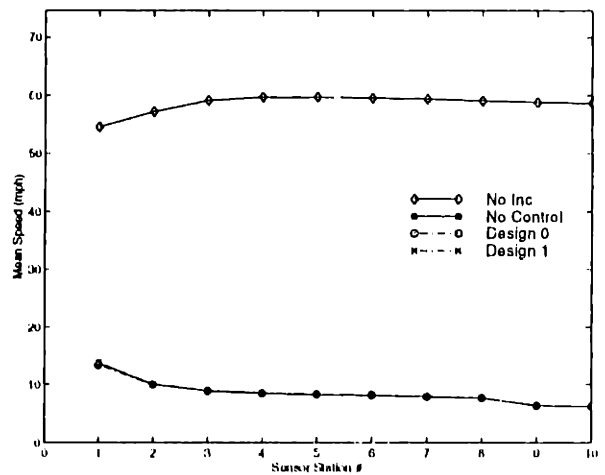


Figure C-14 Speed profile for 100% demand
5:10-5:20 PM

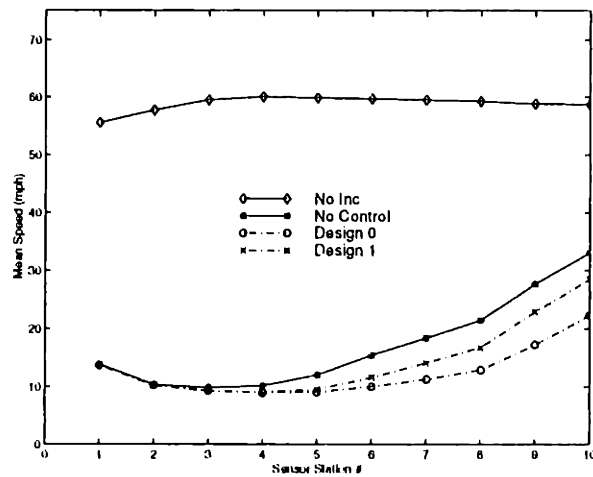


Figure C-15 Speed profile for 100% demand 5:20-5:30 PM

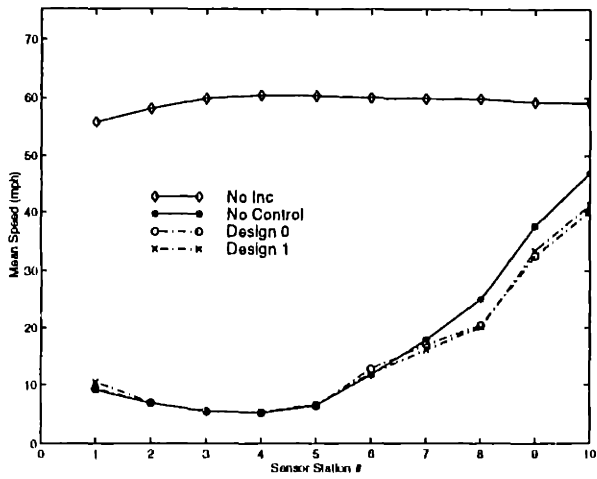


Figure C-16 Speed profile for high airport
80% demand 4:55-5:00 PM

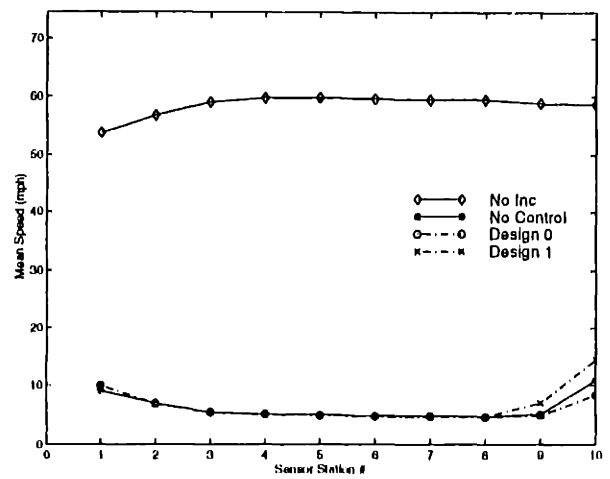


Figure C-17 Speed profile for high airport
80% demand 5:00-5:05 PM

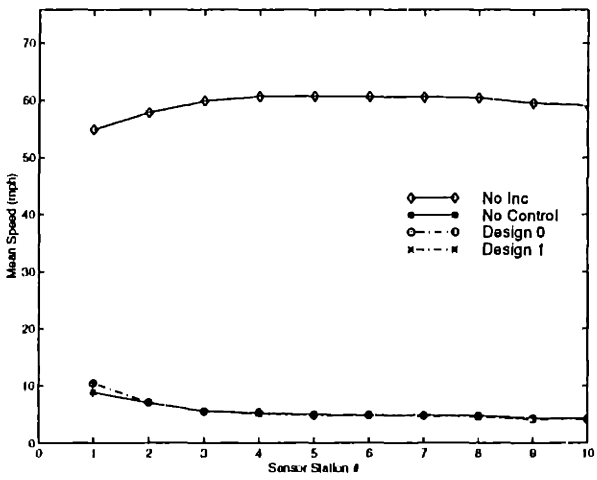


Figure C-18 Speed profile for high airport
80% demand 5:05-5:10 PM

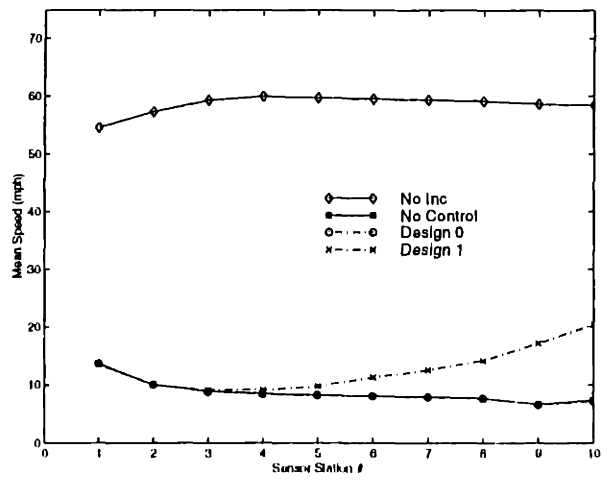


Figure C-19 Speed profile for high airport
80% demand 5:10-5:20 PM

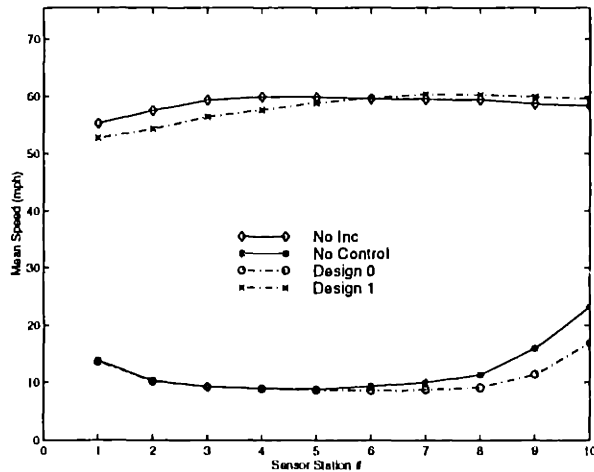


Figure C-20 Speed profile for high airport 80% demand 5:20-5:30 PM

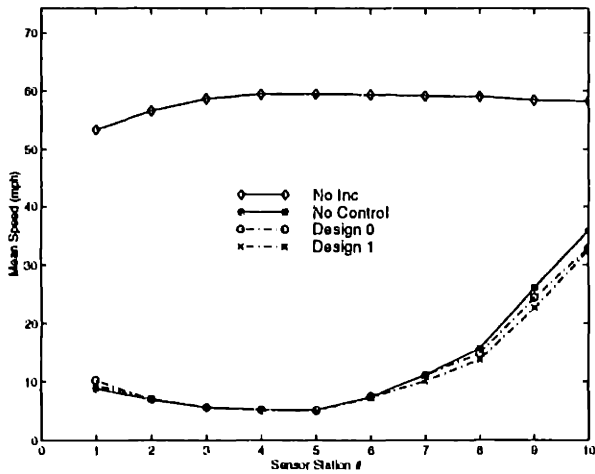


Figure C-21 Speed profile for high airport
80% demand 4:55-5:00 PM

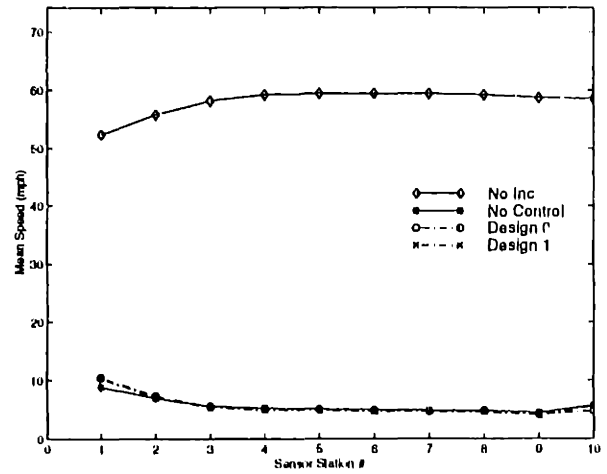


Figure C-22 Speed profile for high airport
80% demand 5:00-5:05 PM

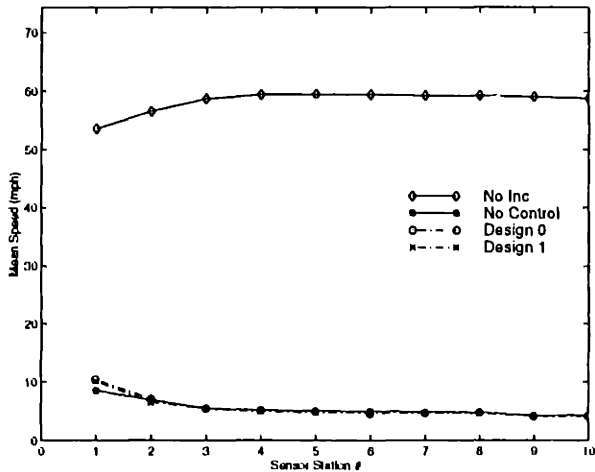


Figure C-23 Speed profile for high airport
80% demand 5:05-5:10 PM

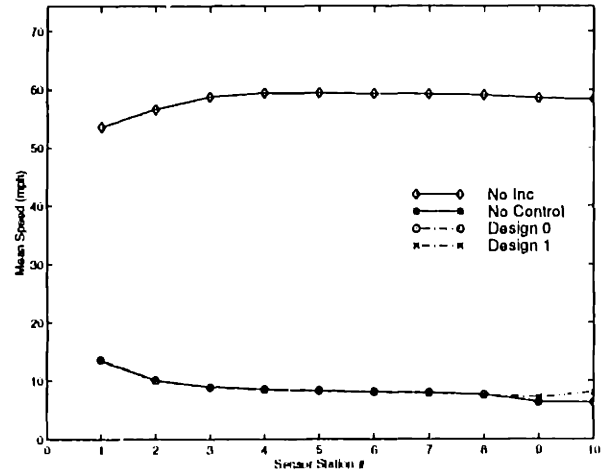


Figure C-24 Speed profile for high airport
80% demand 5:10-5:20 PM

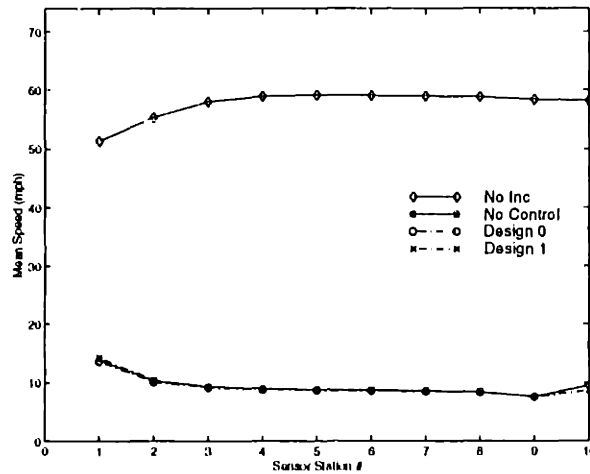


Figure C-25 Speed profile for high airport 80% demand 5:20-5:30 PM

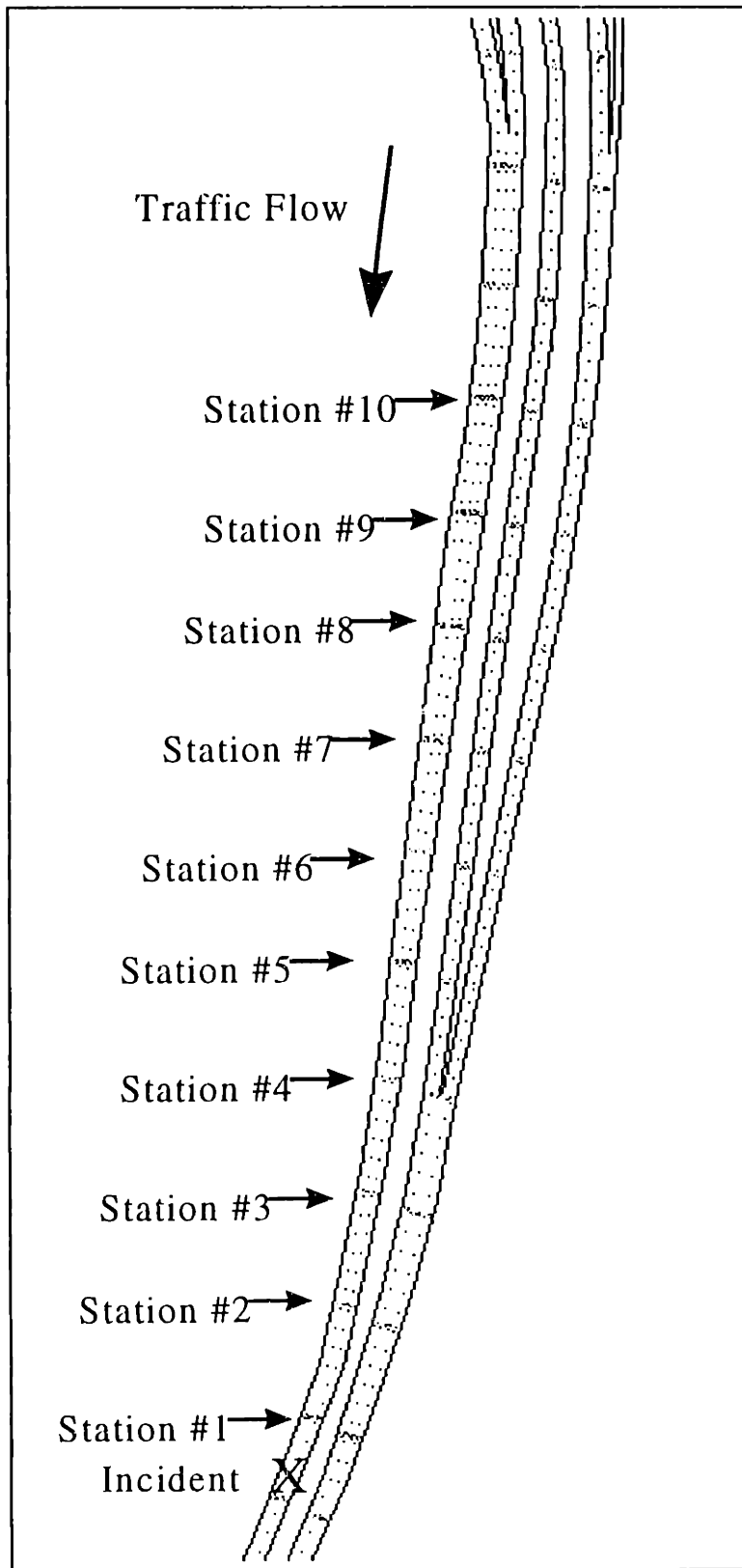


Figure C-26 Speed profile for high airport 80% demand 5:20-5:30 PM

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