Evaluation of Strategies to Increase Transportation System Resilience to Congestion Caused by Incidents

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16. Abstract

Congestion is a major transportation issue causing safety problems and huge economic losses. According to the Federal Highway Administration (FHWA, 2005), 25% of road congestion is attributed to traffic incidents, creating a need to develop strategies to handle these non-recurrent events. Many measures have been used to mitigate recurrent congestion for years, such as ramp metering and hard shoulder running. However, only a few previous studies systematically evaluated and compared the effectiveness of such strategies in combating non-recurrent congestion. This research evaluated four strategies to mitigate incident related congestion (opening a high occupancy vehicle (HOV) lane to all traffic, smoothing traffic flow by variable speed limits (VSL), diverting traffic by en route rerouting, and diverting traffic via variable message signs(VMS)) using microscopic simulation. A case study was conducted based on an actual medium sized road network located in Northern Virginia, including 3098 links/connectors and 315 nodes. The evaluation criteria included vehicle hours traveled for the overall network, average travel speed on freeways, average origin-destination travel time, maximum queue length, and resilience with respect to each of the previous measures. In this study, resilience is defined as the ratio of recovered performance due to a certain strategy with respect to total reduction of performance in the do-nothing case. These criteria were applied to simulations of four incident scenarios, i.e. one lane out of four lanes on I-66 blocked for 20 minutes during peak hours, one lane blocked for 40 minutes, two lanes blocked for 20 minutes and two lanes blocked for 40 minutes. The results showed that opening the HOV lane (20% of traffic is HOV) to general traffic and diverting traffic via VMS are the two most effective ways to increase transportation system resilience to congestion caused by incidents, these two strategies were found to be more consistently effective than smoothing traffic flow by VSL and diverting traffic by en route rerouting. It also was concluded that the VSL strategy causes slight negative effects on traffic performance with respect to vehicle hours and average travel speed for most incident scenarios, compared to do-nothing case; however, it does decrease maximum queue length caused by the incident slightly. This initial work can help transportation agencies make better decisions on when and where to implement different strategies to reduce congestion loss caused by incidents.

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Abstract

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Chapter 1 Introduction

Congestion is a major transportation issue causing safety problems and huge economic losses while affecting almost every individual every day. According to the Federal Highway Administration (FHWA), 25% of road congestion is attributed to traffic incidents, such as crashes, disabled vehicles and spilled loads (FHWA, 2005). Many measures have been used to mitigate congestion for years, including special lane use, ramp metering, variable speed limits, and hard shoulder running. However, few of them are dedicated to mitigating congestion caused by incidents, and few studies have systematically evaluated the effectiveness of such strategies in combating either recurrent or non-recurrent congestion. Therefore, study of incident congestion mitigation strategies and evaluation of their effectiveness will lead to better selection of strategies and reduced congestion.

The remainder of this chapter is divided into three sections. The first provides general background on congestion. The second describes the purpose of this study. Finally, the third section outlines the rest of the report.

1.1 Background

Congestion occurs for many reasons, such as incidents, work zones, weather, special events, signal timing and capacity. Due to the different reasons, congestion can be classified into recurring and non-recurring (as shown in Figure 1). Recurring congestion results from demand exceeding supply over a certain time or space. Non-recurrent congestion usually is caused by occasional events, e.g. incidents, work zones and special events.

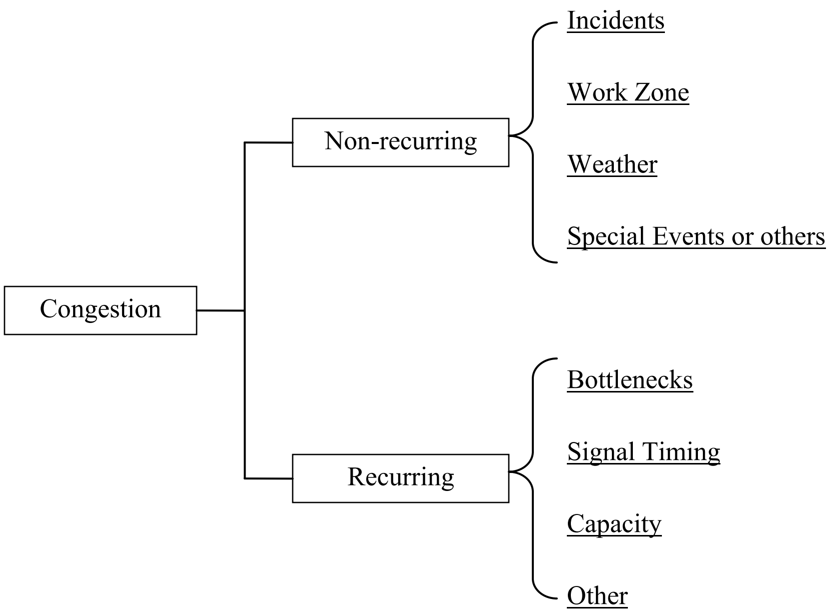

Figure 1 Classification of Traffic Congestion (GDOT, 2007)

According to the FHWA, non-recurrent events, such as incidents, work zones and weather, cause more than half of all traffic congestion (as shown in Figure 2), wherein half of this congestion (25% of all congestion) is solely attributed to traffic incidents (FHWA, 2005). Approximately 20% of all incidents are caused by previous incidents. These secondary incidents usually are minor, e.g. vehicle overheating or running out of fuel, but some of them may cause death or serious injuries (Helman, 2004).

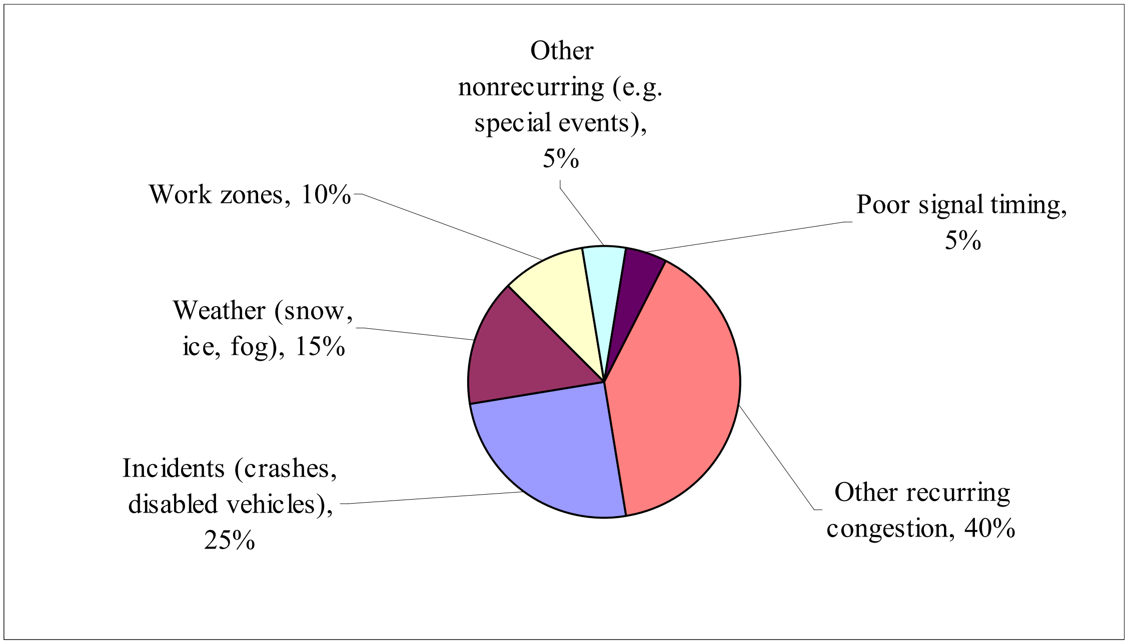

Figure 2 Causes of Highway Congestion (FHWA, 2005)

Incident congestion causes serious travel delay and therefore economic loss. Previous studies indicate that the presence of a stalled car causes 100-200 vehicle-hours of delay and a spill accident lasts 45-90 minutes and produces 1200-2500 vehicle-hours of delay (Dia et al., 2004). According to FHWA estimates, incidents account for approximately 60% of the vehicle hours lost to congestion (Robinson et al., 1993), which is onerous because incidents cannot be predicted, thus the drivers cannot plan for it. FHWA also estimates that 30% of these incidents are not reported; therefore they are assumed to be minor and have little impact on traffic. Among the remaining 70% of reported incidents, 80% are due to vehicle disablement such as running out gas, overheating and flat tires; accidents only account for 10% of these reported incidents (Robinson et al., 1993).

Impacts of incidents are accentuated during peak hours. One lane blocked for one minute usually needs four to five minutes to clear congestion during off-peak hours, while up to fifty minutes during peak hours (Dia et al., 2004). If a lane is blocked during peak hours, when traffic flow is near its capacity, the queue caused by the lane closure will not dissipate until the peak hour ends (Helman, 2004).

1.2 Purpose of the study

The impacts of an incident on the transportation system start from the incident occurrence and continue until traffic returns to its normal situation. The whole period is divided into incident detection, incident verification, incident response, incident clearance and traffic flow recovery, as illustrated in Figure 3. The incident detection phase can be shortened by applying new electronic detection devices or developing advanced incident verification algorithms; the incident response and clearance phases, referring to identifying and dispatching response vehicles and on scene operations, can be shortened by new emergency vehicle dispatching approaches or improving coordination among multi on-scene agencies (U.S. DOT, 2007). This study and the strategies it evaluates focus on the period from incident verification until normal flow returns, as illustrated in Figure 3; therefore, it does not take incident detection and verification into account. Furthermore, the study concentrates on general vehicles' behavior when facing an unexpected incident, while emergency vehicles and their dispatching and routing issues are outside the scope of this report.

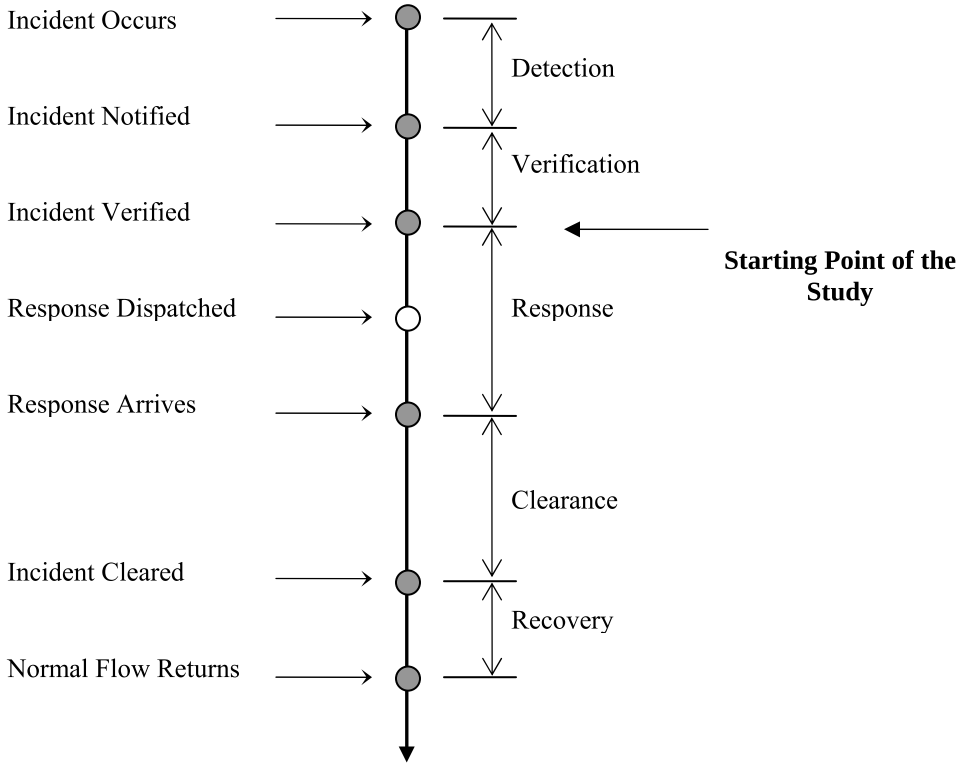

Figure 3 Timeline of an Incident (GDOT, 2007)

To mitigate traffic congestion, many strategies have been used, including special lane use, ramp metering, variable speed limits, and hard shoulder running. Even though most of these congestion mitigation measures have been used for years, few post implementation studies are conducted to evaluate their effects. However, knowing the performance of the strategies, what kind of strategies are suitable for a certain situation, on what level the strategies ought to be implemented, and how to find the optimal parameters of the strategies, are very important considerations for decision makers.

This study uses microscopic simulation technology as a tool to evaluate the performance of the proposed strategies that aim to mitigate traffic congestion caused by incidents. The proposed strategies include opening a High Occupancy Vehicle lane to all traffic, smoothing traffic flow through Variable Speed Limits, re-routing traffic by in-vehicle information, and diverting traffic via Variable Message Signs.

This study determines whether, how, and to what extent theses strategies can improve the network traffic performance in case of an incident and therefore provide a basis for strategy implementation. To achieve the objectives, this work uses VISSIM, a time step and driver behavior based micro-simulation model, to evaluate those strategies. VISSIM was developed to simulate traffic flow by modeling major elements of the transportation system such as lane configuration, traffic composition, driver behavior, and traffic signals, among others (PTV AG, 2005). As VISSIM simulates traffic flow over time and in great detail, it is capable of modeling time-dependent and congested traffic situations, which is the case in this study. Furthermore, it is capable of modeling incident occurrence by blocking lanes in a given location or section. Therefore, VISSIM is an appropriate tool for this work. Chapter 3 describes the advantages of applying micro simulation to this study in detail.

1.3 Report Organization

This report is organized as follows. Chapter 1 describes the background and purpose of this study. Chapter 2 reviews the widely-used congestion mitigation strategies and the past studies of the evaluation of these strategies. Chapter 3 provides a description of the methodologies used for the microscopic simulation, including VISSIM’s built-in dynamic traffic assignment method and route choice model. Chapter 4 depicts specific assumptions and scenarios for the case study in Fairfax County, Northern Virginia. Chapter 5 provides the simulation results and analysis. Chapter 6 concludes the study and gives recommendations.

Chapter 2 Literature Review

Currently many strategies are implemented and studied to mitigate traffic congestion, and many previous works involve using simulation techniques to evaluate strategies to mitigate recurrent or non-recurrent congestion. This chapter focuses on reviewing existing congestion mitigation strategies in the United States and Europe, and the previous works on evaluating non-recurrent congestion mitigation strategies using micro simulation techniques.

2.1 Congestion Mitigation Strategies

FHWA focuses on four general approaches to mitigate highway congestion, i.e., maintaining the existing infrastructures, constructing new facilities where appropriate to relieve bottleneck congestion, encouraging the transportation mode shift, and implementing system management and operation strategies to increase existing capacities (Paniati, 2004). This study does not take road construction and maintenance or other modes besides the highway system into consideration, thus it focuses on improving the capacity of current infrastructure and facilities by implementing operational strategies under congestion.

2.1.1 Strategies commonly used in the United States

Commonly used operational strategies in the United States include managed lanes, ramp metering and temporary hard shoulder use. These strategies are usually implemented to cope with recurrent congestion, especially peak-hour congestion. Managed lanes are restricted to a specific type of vehicle, e.g. bus exclusive lane. High Occupancy Vehicle (HOV) lanes are a form of managed lanes, used for vehicles carrying more than one passenger. HOV lanes are introduced to encourage carpool of commuters during peak hours, thereby mitigating peak-hour congestion.

2.1.1.1 Ramp Metering

Ramp metering controls traffic rates entering a freeway from on-ramps by using traffic signals located on those ramps. Ramp metering is introduced to reduce highway mainline congestion by reducing entering demands and facilitating smooth ramp merging operations by separating platooned vehicles (Pearson, 2001). The metering rates can be fixed based on historic data, or responsive to real time data to achieve local or system-wide optimization. Accordingly, the metering systems are divided into three categories: fixed time operation, local traffic responsive operation, and system-wide responsive operation. Fixed time operation adopts fixed metering rate based on historically averaged traffic conditions, local responsive ramp metering finds the optimal metering rate for each ramp meter individually, while system-wide responsive ramp metering seeks to optimize a multiple-ramp section of highway (Pearson, 2001). Ramp metering is widely used in the United States, e.g. New York City, Los Angeles, the San Francisco Bay Area, Seattle, Denver, Chicago, Phoenix and Minneapolis-St. Paul metropolitan areas.

2.1.1.2 Hard Shoulder Operation

Hard shoulder temporary operation opens the hard shoulder of a freeway to traffic during a certain time period of the day, usually during the peak-hour, to increase the capacity of the freeway and alleviate congestion. As a hard shoulder is designated as a location for vehicles to stop in case of an emergency, opening it to general traffic may cause a safety issue. This strategy is currently implemented on a section of I-66 outside the Capital Beltway.

2.1.1.3 Variable Speed Limits

Variable Speed Limits (VSL) is another strategy to mitigate congestion by adjusting highway speed limits according to real-time traffic conditions. VSL is adopted to smooth or even optimize road traffic flow by reducing speed limits under unusual conditions, e.g. incidents, congestion, or bad weather conditions, and thereby reducing congestion. VSL has been implemented in the United States for many years. For instance, on the New Jersey Turnpike, 120 VSL signs are installed in over 148 miles freeway (Steel et al., 2005). The posted speed limits are based on average travel speeds and can be reduced from the normal posted speed limit in 5 mph increments to a minimum posted speed of 30 mph. The current algorithms behind VSL were generally simple statistics and analysis of the current vehicle speed detected (Steel et al., 2005).

2.1.1.4 Strategies involving advanced technology

The previously mentioned strategies have been implemented for decades and do not involve advanced technologies. However, in the past ten years, electronic and computing technology has been developing at a dramatic speed, and applications of these advanced technologies to transportation have been widely studied by transportation engineers. The following paragraph is a general review of existing studies of new congestion mitigation strategies involving advanced technology.

Daganzo et al. (2002) presented ten strategies for freeway congestion mitigation with advanced technologies. These strategies involve either an emerging technology or the advanced application of an old technology. The strategies are grouped as dynamic lane assignments, dynamic HOV designations, ramp metering actions and miscellaneous control actions. Dynamic lane assignment uses Variable Message Signs (VMS) and associated technologies to separate drivers by destination and allow them to change lanes only in designated sections in order to reduce the friction of lane-changing maneuvers and corresponding undesirable jam. Dynamic HOV Designations is an innovative approach to mitigate congestion and aims to increase the use of HOV lanes without hindering HOVs significantly by dynamically switching the HOV designation between *on* and *off* according to the detection of a queue in the HOV lanes. The HOV lane is open to all traffic until a queue is detected upstream; once the queue is detected, the HOV designation is switched on and that lane is open to only HOVs until the queue is dissipated, and then the HOV designation is turned off again. This approach faces application problems because of compliance, enforcement and driver attitude. Ramp metering strategies include destination-specific metering at on-ramps, dynamic off-ramp management, dynamic merge control and gridlock management. Other control strategies include dynamic speed limits, rationing free access, diversion strategies and dynamic use of shoulder lanes. Most of these strategies involve detecting real-time traffic condition using advanced technology. Impacts of recently developed technology such as automatic vehicle identification (AVI) on implementation of these potential strategies were discussed, but no field test has been conducted for any strategy in this study.

2.1.2 Review of European strategies

European countries adopt some strategies that are not commonplace in the United States to reduce congestion, e.g., tidal flow, dynamic lanes and congestion pricing. Tidal flow reverses the direction of traffic in one or more lanes on a highway or freeway to cope with peak hour traffic. Dynamic lanes change the number and width of lanes on a highway with the use of lights similar to cats' eyes set in the surface of the road to increase the road capacity (NAO, 2004). Dynamic lanes are currently under trial in the Netherlands and Germany.

Congestion pricing is applied as an incentive to efficiently use the road system under congestion situations, since the vehicles not only cause delays for themselves but also for other vehicles, and charging them for delay costs could encourage allocating resources more efficiently. Congestion pricing is intended to shift the unnecessary demand to other modes, times, or routes to achieve the objectives of reducing congestion and generating revenues. A relatively small shift of demand can lead to a substantial mitigation of overall congestion (FHWA, 2007). The price may vary with the level of congestion, i.e.

higher prices are charged under congested situations and lower prices are charged under less congested situations. Road congestion pricing has been implemented in Central London since 2003 and proved to be successful, due to its significant traffic congestion reduction, public transit services improvement, substantial revenues, and growing public acceptance.

This study includes three feasible and commonly used strategies involving HOV lanes, VSL and VMS and one en-route rerouting strategy involving advanced technology, and evaluates the benefits of these strategies quantitatively.

2.2 Strategy Evaluation

Many previous works in the past decade were related to evaluating strategies to mitigate recurrent or non-recurrent congestion using simulation techniques. Those involving non-recurrent congestion were reviewed; the relevant strategies are mainly related to route diversion, route guidance, or ITS strategies, such as ramp metering.

2.2.1 Route diversion

Cragg and Demetsky developed a methodology to investigate the diversion strategy under incident-induced congestion using CORSIM, a micro simulation model developed by the FHWA (Cragg et al., 1995). The authors concluded that the physical capacity of the ramps and weaving sections that conduct diverted traffic is crucial for successful diversion. The research also showed that for one-lane blocked incidents, the optimum percentage of diverted traffic usually exists so that freeway delay will increase once the diverted traffic percentage exceeds the optimum due to friction caused by vehicles on weaving sections attempting to exit.

Wunderlich established a quantitative relationship between network congestion and the benefits of a real time route guidance system measured by travel-time reduction and employed the INTERGRATION traffic simulation model to a case study in Detroit

(Wunderlich, 1998). The results indicate the existence of a 20mph threshold of overall network travel speed. Benefits of route guidance increase as the extent of network congestion increases until the overall network travel speed drops to 20mph; below that, benefits decline although they still remain positive.

Other works discussed the disadvantages of the simple route diversion strategy. Cuneo et al. (2004) evaluated integrated freeway traffic control and route diversion using microscopic simulation. They concluded that a simple route diversion strategy often led to increased travel time because of overreaction and a simple route guidance system which is based on current traffic information implies the need for a prediction-based information system.

Rathi also demonstrated that the benefits of route diversion/ guidance are only significant when the *predictive* information about the network traffic state is provided to drivers (Rathi, 2007). The existing route diversion system via Variable Message Signs (VMS) usually informs drivers of present travel time on the affected and alternative routes; this may lead to positive impacts if VMSs are located closely to the affected route and updated frequently, otherwise, when drivers reach the route, the conditions could be significantly changed. In order to tackle this disadvantage, Rathi developed a methodology to display predictive route guidance information to the drivers through VMS using DynaMIT, a simulation-based dynamic traffic assignment tool designed to predict future traffic conditions and provide unbiased and consistent information to drivers. The methodology was tested by a case study in the Lower Westchester County, NY. The results show that significant travel time savings on the overall network were achieved with the presence of predictive VMS in the case of non-recurrent congestion. However, no comparison of benefits between an unpredictive and predictive route guidance system was conducted in Rathi’s thesis.

2.2.2 VMS location determination

The above studies indicated benefits of route diversion strategy under non-recurrent congestion; however, while route diversion information is disseminated via VMS, whether or how the strategy works partly relies on how many drivers can see the messages and from where they can see them. This discussion leads to an important problem of this strategy, which is to find the optimal location of VMS so the right travelers receive the right information in the right locations.

Chiu et al. (2001) introduced a framework to find an optimal set of locations to install a given number of VMS; its objective was to seek the minimum of long term expected system costs under a variety of unknown situations, e.g. incident locations. The expectation of total travel time was averaged over the space of stochastic incidents. A case study was conducted in the Fort Worth network with a minimum of one and up to four VMS, and the results emphasized complex dynamics of traffic flow and driver behavior in the presence of VMS diversion information and indicated the effects of some factors such as incident characteristics, network configuration and VMS compliance rate.

Differing from focusing on the fixed VMS locations of Chiu's work, Huynh et al. (2003) proposed a solution to find optimal locations for portable VMS to divert traffic to alternative paths in the case of incidents. Another contribution of Huynh's study compared with previous studies is the solution of a mathematic program in a relatively short time. A near-optimal solution is found instead of the optimal one; this is crucial to traffic incident management (TIM) since reducing the reaction time of each phase is one of the main objectives of TIM. The solutions of the proposed procedure are found to outperform the *a priori* solutions to a stochastic programming formulation, and are consistently within 15% of the optimal solutions.

The VMS locations in this study are predefined, depending on predefined alternative routes; the latter are done according to understanding of incident location, network configuration and travel demand patterns.

2.2.3 Drivers' response to route diversion

Not taking drivers' response to route diversion information into account is another disadvantage of route diversion strategies. Nonetheless, few works relating to this were conducted. Allen et al. (1991) investigated the human factors of decision making related to diverting to alternative routes according to the information given by in-vehicle navigation systems to avoid non-recurrent congestion. The results of this study indicated that the majority of drivers were willing to follow the guidance to the alternative route provided by advanced navigation systems. Characteristics of the navigation system had a significant effect of diversion behavior, but other elements like gender, route familiarity and commercial driver experience did not affect the results significantly.

Peeta et al. (2000) studied drivers' response to route guidance via VMS and investigated the impacts of different message content on driver diversion response. An on-site stated preference user survey was conducted in the study and logit models were developed to simulate the drivers' diversion decisions. The results showed that message content in terms of level of detail of relevant information significantly affected drivers' willingness to divert and indicated a difference of response attitude between semitrailer truck drivers and automobile drivers.

Peeta et al. (2001) developed a VMS control heuristic framework consistent with driver diversion behavior to determine the information displayed on VMS, including VMS location, message content and update frequency. The developed message display algorithm (MDA) considers both current network traffic condition and drivers' attitudes toward diversion information to determine the message displayed on VMS.

According to the above studies, it is concluded that the strategy of route diversion or guidance needs to be carefully operated, otherwise negative impacts may occur. In this study, VMS locations, message content (detour strategy), message update frequency, and route diversion rates are pre-specified based on the network configuration, travel demand pattern, the incident location, and the objective of the study. Previous literature conclusions are taken into consideration to make these assumptions as well. These assumptions will be described in detail in Chapter 4.

2.2.4 Other ITS strategies

Chu et al. (2004) presented a micro-simulation method to evaluate the effectiveness of potential intelligent transportation system (ITS) strategies under incident scenarios. The ITS strategies include incident management, local adaptive ramp metering, coordinated ramp metering, traveler information systems, and combinations of the above. Their results show that all ITS strategies have positive effects on the network performance.

The previous works provide many useful conclusions on evaluation of congestion mitigation strategies, however, most of them focus on route diversion or ITS related strategies, and few incident characteristics, such as severity and duration, are taken into consideration. The combinations of incident characteristics and mitigation strategies, including additional measures not discussed above, need further and thorough investigation. This gap is addressed in this study.

Chapter 3 Methodology

As previously mentioned, the simulation tool VISSIM is used to evaluate the proposed congestion mitigation strategies. This chapter mainly focuses on describing VISSIM's built-in dynamic traffic assignment method, including the route choice model. This chapter also describes the advantages of applying microscopic simulation to this study.

3.1 Microscopic simulation

In this study, microscopic simulation technology is used to evaluate the proposed strategies to mitigate congestion caused by incidents. Micro simulation has been developed recently in the field of transportation with the aid of rapidly developing computing technology. Micro simulation can model the road network and traffic management and control measures, such as traffic lights, in great detail and over time, dispatch vehicles into the predefined network, track their driving behaviors such as lane changing and car following behavior, and finally achieve the objective of simulating road traffic situations.

The advantages of applying micro simulation technology to this study are indicated as follows.

1. One of the most beneficial characteristics of micro simulation technology is that it simulates traffic over time, rather than loading all traffic into a network simultaneously as the conventional four-step travel demand forecasting model does. Micro simulation dispatches vehicles into a network, models their driving behaviors and tracks their routes every simulation step time until they leave the network; in other words, micro simulation models each individual car over time and space. Based on this characteristic of micro simulation, it is ideal for modeling **time-dependent**

traffic situations (Sundaram, 2002), which is the case in this study. The key purposes of this work are to analyze how an occasional incident influences the whole network over time and how implementing a certain strategy affects congestion over time. The studied process includes congestion build up, queues, spillovers and dissipation, which significantly varies with time; therefore, micro simulation is selected for this study.

2. Micro simulation has great capability to model **congested** road networks (Wikipedia, 2007). Unlike traditional empirical models that provide little meaningful results once saturated traffic conditions are reached, micro simulation can still continue to provide results under high degrees of saturation, as it models traffic situations in great detail and also includes a time axis.

3. To simulate the occurrence of incidents and implementation of strategies, this study requires making changes to the network during the simulation period. Micro simulation can model the **physical changes** of the network (Wikipedia, 2007), such as lane closure and implementation of VMS signs, and meanwhile reflect changes in driver behaviors from physical changes of the network.

4. Compared to macro simulation, micro simulation models road network and driver behavior in great detail; in that way, impacts of traffic control such as signal timing, and lane changing and car following behavior can be modeled, which makes the micro simulation model closer to the real world than macro simulation.

As micro simulation has many advantages that are needed in this study, it is selected to be the analysis tool to accomplish the purpose of this work.

Currently the widely-used microscopic traffic flow simulation software packages include VISSIM, CORSIM, PARAMICS and TRANSIMS. Since the transportation system is extremely complex in nature, none of these packages can model the actual traffic situation with absolute accuracy; therefore they have to be used with extensive considerations. VISSIM is a component of the PTV Vision suite, which offers a high level of integration within the overall transportation planning process including strategic planning, transport operations and traffic engineering (PTV, 2007). VISSIM is a time step and driver behavior based multi-purpose microscopic traffic simulation program. It was developed to model major elements of the transportation system such as lane configuration, traffic composition, driver behavior, and traffic signals, among others (PTV AG, 2005). VISSIM is selected to be used as the evaluation tool in this study because of its ability to model physical changes in the network and represent network in great detail.

VISSIM uses the psycho-physical driver behavior model developed by Wiedemann in 1974 to reflect the process that a faster vehicle decelerates to obtain a desired following distance and corresponding speed to the lead slower moving vehicle, while he reaches his individual perceived threshold (PTV AG, 2005). As the following vehicle cannot determine the exact speed of the leading vehicle, it decelerates and accelerates iteratively to achieve the stable car following status. This oscillatory driver behavior can be captured by the VISSIM built-in car following model. In addition, the model requires several parameters, and the default values of these parameters were calibrated by previous studies and thus adopted in this study.

3.2 Dynamic traffic assignment (DTA)

One of the key issues of microscopic traffic simulation is route choice, so the methodology of this study focuses on route assignment. Traffic assignment determines which routes are chosen to complete the trips for each OD pair, according to travel time, cost, or trade offs between time and cost. One of the classic traffic assignment theories was developed by Wardrop in 1952, therefore called Wardrop's first and second principles. Wardrop's first principle states: "*The journey times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route*" (Wardrop, 1952). This principle finds an equilibrium point, which has similar meaning with Nash Equilibrium in game theory, that no driver in the system can achieve better service, i.e. accomplish his/her trip in less travel time, by unilaterally changing to a new route. As the principle is introduced from the drivers' point of view, and implies that each driver seeks to find his best route without any cooperation, the traffic flow associated with this implication is usually considered as user equilibrium (UE) flow. Wardrop's second principle states that "*at equilibrium the average journey time is minimum*" (Wardrop, 1952). This principle takes the best performance for the whole system as the objective instead of for an individual car, by defining the optimal state as the one that leads to the least cost for the system. Wardrop's second principle is equivalent to system optimal (SO) assignment.

However, either equilibrium state satisfied by these two Wardrop's principle can hardly be achieved in reality. For Wardrop's first principle, the hypothesis that all users have perfect knowledge of the network and system is over optimistic. Stochastic user equilibrium (SUE) assignment is developed to improve UE assignment by introducing a concept of "perceived travel time" to replace actual travel time used in UE assignment. Perceived travel time leads SUE assignment model closer to reality, as in the real world, different travelers perceive travel time differently, which causes different results of route choice. For Wardrop's second principle to be realistic requires that the system be under a completely automated control, so all drivers will follow the control and no one will unilaterally change his route.

Generally, two disadvantages of Wardrop's principles are that they represent the ideal static balance status which can hardly be achieved in reality and meanwhile overlook the difference of individuals perceiving travel time. To accomplish Wardrop's principles, some assignment approaches are developed, including stochastic dynamic assignment built in to VISSIM.

3.2.1 Dynamic Assignment in VISSIM

Traffic assignment is basically a procedure of route choice. Traditional traffic assignment uniformly distributes demand in a fixed time interval, i.e., it deals with static or deterministic demand. Dynamic assignment refers to an approach dealing with dynamic demand or a changeable network in general, to reflect the fact that both demand and the network will not be constant during a day. In this study, the traffic is assumed to keep a constant rate during the whole peak hour period, thus dynamic demand is not taken into consideration. Nonetheless, a changeable network is included to represent the impacts of the given strategies on route choice. As a result, dynamic traffic assignment is selected to model driver behaviors of route choice in this study.

VISSIM has a built-in dynamic assignment option designed to simulate the drivers' behavior of route choice. VISSIM accomplishes dynamic assignment procedures on the basis of iterated simulation. A modeled network is simulated multiple times; each time, drivers make decisions on route choice based on their experience of traffic situations in the preceding iterations of the simulation. The iterated simulation runs end when a stable traffic situation is reached, i.e., convergence is achieved. VISSIM defines convergence as when travel times and volumes do not change significantly between two consecutive iterations (PTV AG, 2005). The convergence criterion for this study is a path travel time difference of less than 10%.

Figure 4 illustrates the procedure of dynamic assignment in VISSIM. First, VISSIM finds a set of possible routes for each origin and destination pair, so that demand of the OD pair is assigned to multiple routes instead of only the best route, as VISSIM assumes not only the best routes but also the less attractive routes are chosen by travelers even though by the minority. Then VISSIM assesses these alternatives in terms of travel cost and finally determines drivers' route choice based on that assessment using a logit model, a type of discrete choice model (PTV AG, 2005). The set of the *k* best routes needs to be determined; however, currently no efficient mathematic approach exists to find this set of routes, at least not for dynamic traffic assignment. VISSIM solves this problem by computing best routes in each iterated simulation and therefore building a growing archive of possible routes for drivers to choose from (PTV AG, 2005).

The dynamic assignment option in VISSIM provides the ability to model vehicle rerouting phenomena in case of special situations, such as congestion due to incidents. Additionally, a network built in VISSIM associated with dynamic assignment can be considered as a simulation-based DTA system, which has the advantage of capturing the time-dependent interactions between traffic demand and supply (Sundaram, 2002). Therefore, VISSIM’s dynamic assignment is appropriate to be used in this study to model incident congestion and the proposed diverting strategies.

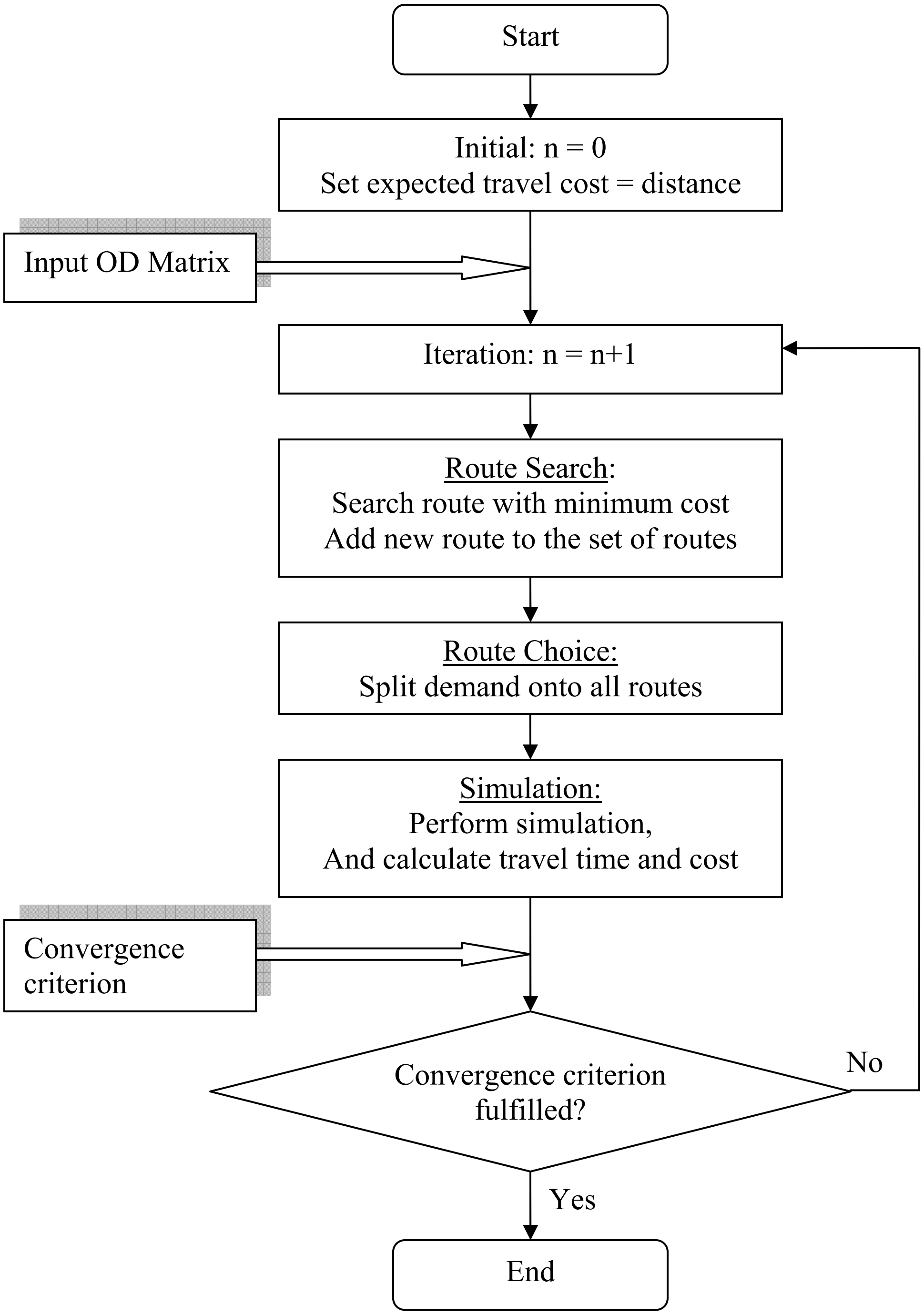

Figure 4 Procedure of Dynamic Assignment in VISSIM (PTV AG, 2005)

3.2.2 Route Choice Model in VISSIM - Logit model

The route choice procedure chooses one route out of several routes based on a certain type of route assessment. VISSIM assesses the alternate routes by the general cost, the weighted sum of travel time, travel distance and cost, e.g. tolls, defined as Equation (1) (PTV AG, 2005).

$$\text{general cost} = \alpha * \text{smoothed travel time} + \beta * \text{travel distance} + \gamma * \text{financial cost} \qquad (1)$$

Equation (1) indicates that travel time, travel distance and financial cost, influence route choice. Travel time of a route is the average travel time vehicles spend on traveling from the beginning to the end of the route in the current simulation. Smoothed travel time is computed by exponential smoothing of travel time resulting from all previous iterations, and is the one actually used in the general cost function, Equation (1) (PTV AG, 2005). The exponential smoothing factor is assumed to be 0.25 in this study, which means the measured travel time from the last iteration n comprises 25% of the expected travel time in the current iteration, and travel time measured from the iteration $n-1$ and before comprises the other 75%. The coefficients α, β and γ are defined in this study as 1, 0, 1, respectively. So, only travel time and tolls are considered as factors of route choice in this work.

VISSIM's route choice model is a typical case of discrete choice models, based on the assumption that not only the best route with least general cost will be chosen for each OD pair, but other routes will be chosen too, even though by a minority of drivers. The Kirchhoff distribution formula, as illustrated in Equation (2), is one transformation of the logit model and used for route choice in VISSIM (PTV AG, 2005).

$$P(R_j) = \frac{U_j^k}{\sum_i U_i^k} \qquad (2)$$

where U_j = utility of route j

$P(R_j)$ = probability of route j to be chosen

k = sensitivity of the model

Different sensitivity factors have been tested in this study, and k equal to 2.75 is found to provide fairly realistic results in terms of the balance of traffic volume on freeways and arterial roads. So the sensitivity factor *k* is assumed to be 2.75 in this study. The utility value *U* is used to assess the alternatives in the Kirchhoff distribution formula. As the general cost *C* is the inverse of *U*, so the reciprocal of *C* is used as the utility function, as illustrated in Equation (3) (PTV AG, 2005).

$$U_j = \frac{1}{C_j} \tag{3}$$

Where U_j = utility of route j

C_j = general cost of route j

To summarize this chapter, VISSIM's built-in dynamic traffic assignment model and logit route choice model are the main approaches involved in this study.

Chapter 4 Case Study Modeling

A case study is conducted to simulate the congestion mitigation strategies on a 3098 link, 315 node road network located in Northern Virginia, covering 16-18 miles of freeway and approximately 100 intersections. This chapter includes brief descriptions of the studied network and of nine incident scenarios. This chapter also demonstrates the proposed strategies and the basic assumptions of implementing these strategies. The procedure of OD matrix estimation for the study area is also included in this chapter. The results of the simulations are discussed in Chapter 5.

4.1 Network Description

The study site is based on a location in Northern Virginia, including a portion of the city of Falls Church, part of Arlington County, and part of Fairfax County. As shown in Figure 5, the network includes segments of I-66, I-495, Route 7, Route 29, Route 50, Route 123, Route 243 and some local roads. Figure 6 displays the modeled network in VISSIM.

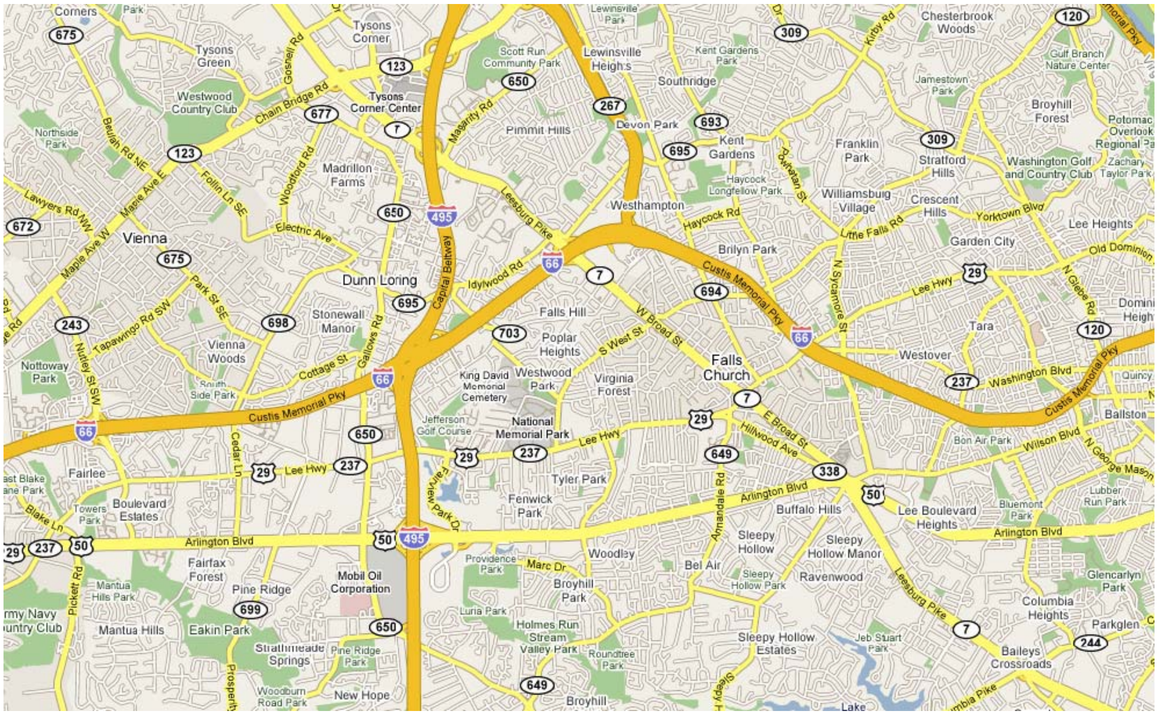

Figure 5 Overview of the Actual Network (*http://www.maps.google.com*)

Figure 6 Overview of the Modeled Network in VISSIM

I-66 is the main road connecting Northern Virginia with Washington, D.C. I-66 is functionally divided into two parts by the Capital Beltway (I-495), and each side conducts different travel patterns and has different configurations. The western segment of I-66, outside the Capital Beltway, conducts the traffic to Washington, D.C. It is modeled as a dual six to eight-lane freeway. In the peak travel direction, the left lane adjacent to the median would be restricted to high occupancy vehicles (HOV) and the hard shoulder is open to traffic and counts as an additional general-purpose lane. The eastern segment of I-66, inside the Capital Beltway, carries traffic to Washington, D.C. and is modeled as a dual four to six-lane freeway restricted to HOV only in the peak travel direction.

I-495, the Capital Beltway encircling Washington, D.C., is the main road connecting Northern Virginia and Maryland. The modeled segment of I-495 is a dual eight to ten-lane freeway, running in north-south directions and connecting with I-66 at exit number 64. The speed limit along I-495 and I-66 is assumed as 55 to 65 mph. VISSIM adopts a desired speed distribution approach to model speed limits. A driver travels at his desired speed with slight oscillations when not hindered by other vehicles (PTV AG, 2005). In this study, desired speeds are assumed to be evenly distributed between the predefined minimum and maximum speed for each vehicle type, so average speed is the median value.

Route 29 and Route 50 are two major arterial roads running in the east-west directions parallel to I-66 within the study area. Route 243 and Route 123 connect I-66 and I-495. The speed limit along the arterial roads is assumed as 42-50 mph. Some local roads are also included in the model to connect arterial roads, and the speed limit along these local roads is set to be 32-40 mph.

The network includes around 100 intersections, of which more than 80 are signalized. Signal timings for these intersections are assumed based on general knowledge of signal controls within the study area and calibrated during the simulation.

4.2 Simulation period

The total simulation period consists of the *warm-up period* and the *simulation analysis period*. Both periods are clarified in the following paragraphs. Figure 7 illustrates the components of the whole simulation period.

The warm-up period is introduced at the beginning of the simulation to fill in the empty network to obtain realistic results. The duration of the warm-up period is determined by the network size. The bigger the network is, the more time it takes to fill in the network. Theoretically, it needs to be more than the longest origin-destination travel time so that after the warm-up period the whole network represents a realistic traffic situation. In this model, 95% of vehicles spend less than fifteen minutes traveling in the network with free-flow speed. Hence, it is reasonable to set the warm-up period to be half an hour in this study.

The main focus of this study is the *simulation analysis period*. It starts from the moment of incident verification 5:30PM, and lasts for one and a half hours. Meanwhile, on-scene incident clearance time is included and assumed to last twenty or forty minutes depending on the different scenario. Therefore, the simulation analysis period is one and a half hours, including the twenty and forty-minute incident durations.

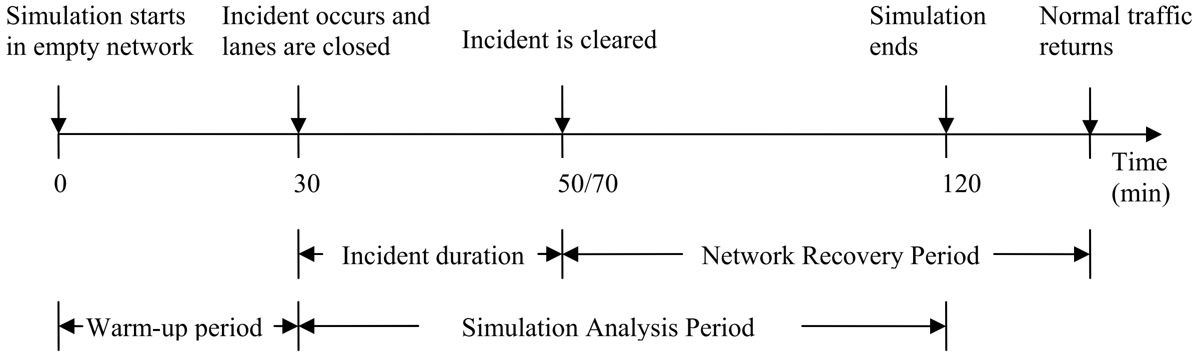

Figure 7 Timeline of the Simulation

4.3 Scenario Description

Incidents significantly affect road traffic and cause congestion; the extent of these impacts mainly relies on the characteristic of incidents such as occurrence time, location and severity. Incident occurrence time and location directly determine the number of affected vehicles; for instance, incidents occurring on freeways during the peak-hour period affect many more vehicles than those occurring on local roads during off peak hours. On the other hand, the severity determines the number of lanes closed and duration of the lane closure. Lane closure leads to the reduction of road capacity; the latter decreases far out of proportion to the number of lanes blocked. Blocking one lane out of three on a freeway reduces approximately 50% of capacity and blocking two lanes out of three reduces capacity by almost 80% (U.S. DOT, 2007). Duration of lane closure is another key factor to determining the impacts of incidents. Each additional minute of lane closure requires a longer time for traffic to be restored. In general, each minute of lane closure causes four to five minutes of congestion during off-peak conditions, and up to fifty minutes during peak periods (Dia et al., 2004).

In this study, we assume that an incident occurs on I-66 westbound during the evening peak hour period. The incident location is shown in Figure 8. The road segment where the incident occurs has four lanes operating during the peak hours, including the adjacent median HOV lane, two general purpose lanes, and the hard shoulder. Four scenarios representing different severities of the incident, described in Table 1, are tested in this study.

Table 1 Description of Tested Incident Scenarios

Scenario No	Severity of the Incident
Scenario 1	Blocking the right hand lane out of four lanes for 20 minutes
Scenario 2	Blocking the right hand lane out of four lanes for 40 minutes
Scenario 3	Blocking two right hand lanes out of four lanes for 20 minutes
Scenario 4	Blocking two right hand lanes out of four lanes for 40 minutes

Figure 8 Illustration of Incident Location

4.4 Strategy Description and Implementation

Incidents happen occasionally at random locations, and thereby cause the capacity of those road sections to suddenly decline for a short period. To achieve the objective of incident congestion mitigation, we introduce four strategies, involving a high-occupancy vehicle (HOV) lane, variable speed limits (VSL), variable message sign (VMS) guidance, and en route routing.

For each strategy, the next step is to determine how it is implemented, e.g., where and when the strategy takes effect, or how many vehicles follow the guidance. These parameters affect traffic performance improvement significantly or insignificantly, depending on what the strategy is and what the parameter is. For instance, for the strategy involving VSL, where the speed limits start to be reduced, how much reduction is required, and how long the new speed limits last, will determine whether the strategy will work. If speed limits are reduced far away from the incident location, or if the reduced speed limits last too long after the incident is cleared, the network performance may be deteriorated. In this study, several cases associated with different implementations are tested to make comparisons.

The following are the descriptions of these four strategies and assumptions of their implementations.

4.4.1 Strategy 1: opening HOV lane to all traffic

HOV lanes are restricted to vehicles with at least two persons. HOV lanes are initially implemented to encourage commuters to share rides during rush hours, therefore, improving traffic efficiency since HOV lanes can move more people per lane per unit time compared to general purpose lanes. When congestion occurs, HOV lanes provide a higher speed due to carrying a lower number of vehicles than general lanes.

The strategy involving HOV lanes is to temporarily open HOV lanes to all traffic while congestion caused by incidents occurs, until the network is recovered. Signs upstream of the incident location would indicate when the HOV lane is open to all traffic. In this case, HOV lanes will lose their initial design intent and are used as another general lane. This operation is feasible and theoretically useful, because incident congestion has higher priority than improving commuter efficiency. Without guiding vehicles to pass the incident bottleneck quickly, larger areas will be affected and traffic efficiency will be decreased within those areas.

This strategy is suitable to where incidents occur on a freeway with HOV lanes in effect during rush hours, and cause only lane closure, not closure of the whole road. In this study, an incident is assumed to occur during evening peak hours on I-66 westbound, outside the Beltway, where the far-left lane is reserved for HOV-2 (vehicle occupancy has to be 2 or more). Upstream of the incident, the HOV lane is assumed to open to all traffic from the time of incident occurrence until the end of the simulation. This strategy is tested for the incident to find whether and to what extent it improves network performance.

4.4.2 Strategy 2: smoothing traffic flow by VSL

A speed limit on freeways or arterials is usually fixed to a certain number. However, a fixed speed limit only represents the appropriate speed for normal situations. VSL adjusts road speed limits for unusual situations, such as bad weather, work zones, or incidents, and aims to improve road safety and increase efficient use of the highway.

The strategy of variable speed limits in this study involves adjusting speed limits on freeways in order to improve traffic flow and reduce the possibility of secondary incidents and thereby mitigate congestion. The normal speed limit of I-66 is modeled to be distributed within a range of 55 to 65 mph for the base scenario in the study area. To reflect various driving behavior, the speed limits are set to be a distribution within a range instead of a certain number.

Theoretically, the performance of VSL relies on the sign locations, the speed reduction, and the effective period. VSL is assumed to be displayed by portable roadside message signs. Speed limits are reduced by 10 mph around 8000ft upstream of the incident location ("*VSL (45-55mph)*" shown in Figure 9), and return to normal speed limits after passing the incident location ("*VSL (55-65mph)*" shown in Figure 9). This strategy is implemented from incident occurrence until the end of the simulation. The location of VSL signs is shown in Figure 9. Additionally, all drivers passing though the VSL signs are assumed to obey the speed limits. This assumption leads to optimistic results, and can be considered as the optimal situation.

Figure 9 Locations of VSL Signs

4.4.3 Strategy 3: diverting traffic by en route rerouting

Usually, drivers decide their routes to destinations before they start their trips based on past experience or other resources. The strategy of en route rerouting aims to reroute vehicles during their trips by providing current road traffic information to drivers through in-vehicle electronic devices, guiding them to avoid the congested highway segments and therefore mitigating congestion. This strategy differs from the VMS routing strategy in that it is not restricted to fixed locations, while the latter is. The potential devices to implement this strategy include cell-phones, Internet, and in-vehicle route guidance systems.

In this study, the vehicles are modeled to be rerouted in fixed time intervals of ten minutes, i.e. in every 10 minutes, the best routes of the vehicles that will be rerouted are searched from the current vehicle locations to the destinations, based on the traffic situation data collected 5 minutes ago (offset). Other than using current data, offset is introduced in this model to reflect the data processing time of a hypothetic route guidance system. A five-minute offset means it takes five minutes from when the raw traffic data are collected by loop detectors on the roads until alternative routes are available to drivers. (PTV AG, 2005).

VISSIM's simulation of the en route rerouting strategy is not completely consistent with the real-world application of this strategy. First, in reality, drivers depart (or enter the study area) and search traffic information at individual times, therefore, they will not update their route choice at the same time, as VISSIM does. Secondly, not all the drivers have implemented devices to receive en route guidance information in reality, and among vehicles equipped with the required devices, not all the drivers will follow the guidance; however, the VISSIM simulation model assumes all vehicles can receive road traffic information and follow en route guidance as well. This inconsistency will cause the simulation outputs to deviate from the reality; as a consequence, the results are not directly transferable to the real world but may offer insights and suggest directions for future study.

4.4.4 Strategy 4: diverting traffic via VMS

A variable message sign is an electronic traffic sign installed along the roadside or above a highway, to provide real-time travel information on a specific highway segment, such as warnings of congestion, incidents, accidents, work zone or speed limits. The strategy involving VMS in this study is to provide dynamic travel information, i.e. real-time travel time, congestion situation and alternative routes, to the drivers encountering it under incident congestion. The signs are intended to guide a portion of them around the incident location and therefore reduce the pressure of incident congestion. One of the advantages of the VMS strategy is that it is more implementable than providing in-vehicle navigation systems in every vehicle.

Both highway and relevant segments of arterial road are assumed to be installed with VMS that publishes route guidance information to drivers. As we study the scenarios with incidents occurring on I-66, an access limited freeway, VMS is assumed to be located 1500 ft ahead of the entry or exit ramp of I-66, so that drivers have time to decide whether they want to follow the guidance or not, and have distance to change lanes.

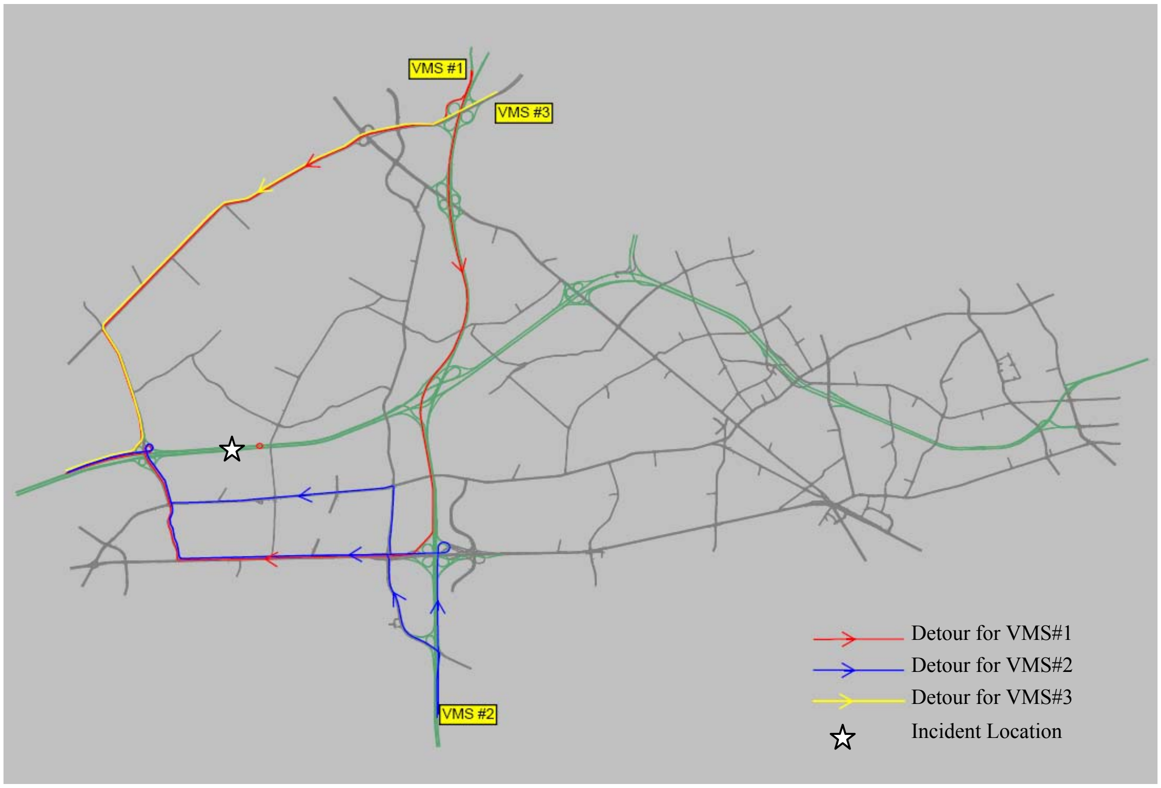

Figure 10 VMS Locations and the Detours

The location of VMS and the detours are predetermined based on knowledge of the travel demand pattern within the studied area, as shown in Figure 10. Three VMSs are located upstream of the incident, (1) on I-495 southbound, (2) I-495 northbound, and (3) Route 123. A total of six detours are displayed though the three signs; VMS#1 indicates two detours displayed as the red lines in Figure 10; VMS#2 indicates three detours displayed as the blue lines in Figure 10; and VMS#3 indicates one detour displayed as the yellow lines in Figure 10. The portion of vehicles following a detour is assumed to be 10%, 15% and 20% for different cases. This strategy is assumed to be implemented from incident occurrence until 20 minutes, 40 minutes and 0 minutes after incident clearance. Nine cases of different diversion rate combined with different implementation period are tested, as described in Table 2.

Table 2 Description of Different Cases for the Strategy of Diverting Traffic via VMS

	Description
Case 1: 20min/10%	The strategy is implemented from incident occurrence until 20 minutes after incident clearance; For each detour, 10% of all involved traffic is diverted for each detour.
Case 2: 40min/10%	The strategy is implemented from incident occurrence until 40 minutes after incident clearance; For each detour, 10% of all involved traffic is diverted for each detour.
Case 3: 0min/10%	The strategy is implemented from incident occurrence until incident clearance; For each detour, 10% of all involved traffic is diverted for each detour.
Case 4: 20min/20%	The strategy is implemented from incident occurrence until 20 minutes after incident clearance; For each detour, 20% of all involved traffic is diverted for each detour.
Case 5: 40min/20%	The strategy is implemented from incident occurrence until 40 minutes after incident clearance; For each detour, 20% of all involved traffic is diverted for each detour.
Case 6: 0min/20%	The strategy is implemented from incident occurrence until incident clearance; For each detour, 20% of all involved traffic is diverted for each detour.
Case 7: 20min/15%	The strategy is implemented from incident occurrence until 20 minutes after incident clearance; For each detour, 15% of all involved traffic is diverted for each detour.
Case 8: 40min/15%	The strategy is implemented from incident occurrence until 40 minutes after incident clearance; For each detour, 15% of all involved traffic is diverted for each detour.
Case 9: 0min/15%	The strategy is implemented from incident occurrence until incident clearance; For each detour, 15% of all involved traffic is diverted for each detour.

4.5 Traffic Demand

4.5.1 Traffic Demand Estimation

The traffic demand for the study area was estimated based on the average daily traffic volume (AADT) on interstate, arterial, and primary routes for 2002 to 2005 published by the Virginia Department of Transportation (VDOT, 2002-2005).

According to VDOT, the average peak hour traffic volume along the segment of I-66 within the study area was estimated to be roughly 8000 vehicles per hour, and ninety-nine percent of the traffic volumes are made up of motorcycles, passenger cars, vans and pickup trucks (VDOT, 2005).

Having traffic counts on studied freeways and arterial roads, we estimated the OD matrix for the study area according to the following steps, illustrated in Figure 11.

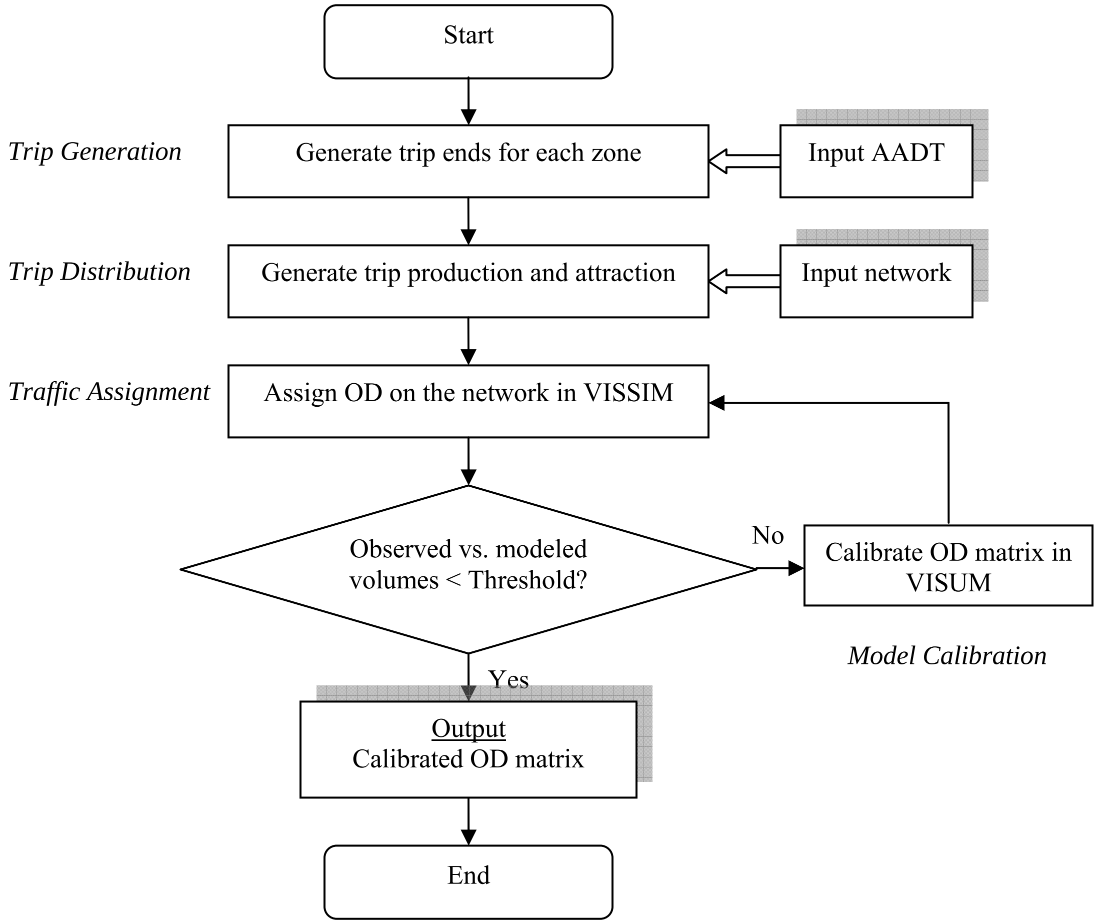

Figure 11 Flow Chart of Traffic Demand Estimation (PTV AG, 2005)

Step 1. Convert AADT to peak-hour and off peak-hour traffic volumes for selected sections of freeways and arterial roads.

Step 2. Use peak-hour traffic counts to estimate trip ends (production and attraction) for traffic analysis zones (TAZ) in the peak-hour direction, and use off peak-hour traffic counts to estimate trip ends (production and attraction) for off peak-hour direction zones. (In this study case, a total of 23 TAZ are defined, wherein 15 are external zones and 8 are internal zones.)

Step 3. Use the gravity model to complete trip distribution for internal-internal traffic and external-internal traffic and output the corresponding estimated OD matrix. The travel time matrix is used to indicate impedance between each pair of zones in the gravity model. VISUM, part of PTV Vision traffic analysis package, provides a module called MUULI with the gravity model built in, which is adopted in this study. VISUM also provides the capability of correcting the OD matrix that will be used in the following step. External-external traffic comprises of a large portion of demand, which cannot be accurately estimated by the gravity model; here, we estimate this part of the OD matrix based on our knowledge of driver patterns of the studied area.

Step 4. Load the estimated OD matrix on the network in VISSIM and perform simulation to achieve traffic volumes on all roads. For the purpose of model calibration, select road sections with heavy traffic or highly related to the assumed incident location, and output traffic volumes on those sections.

Step 5. Check whether the ratios of the estimated traffic counts to the observed traffic counts are within a predetermined threshold for those selected sections of roads; if they are, output the OD matrix as the final estimation and end the procedure, otherwise, calibrate the OD matrix in VISUM and update the OD matrix. Using the new OD matrix, repeat Steps 4 to 5 until the procedure ends.

This demand estimation approach leads to some deviation from reality. Conducting site travel surveys was outside the scope of this project. Internal zones are simplified while coding the network, which causes some intrazone traffic to be overlooked, accordingly arterial roads or local roads are less loaded compared with the real-world situation.

However, OD estimation is considered as an input, not the objective of this study. The key purpose of this study is to evaluate the impacts of certain strategies on incident congestion in a certain area and with a certain pattern of demand.

Figure 12 shows the results of model calibration. The overall difference between observed and modeled traffic counts is 1.8%.

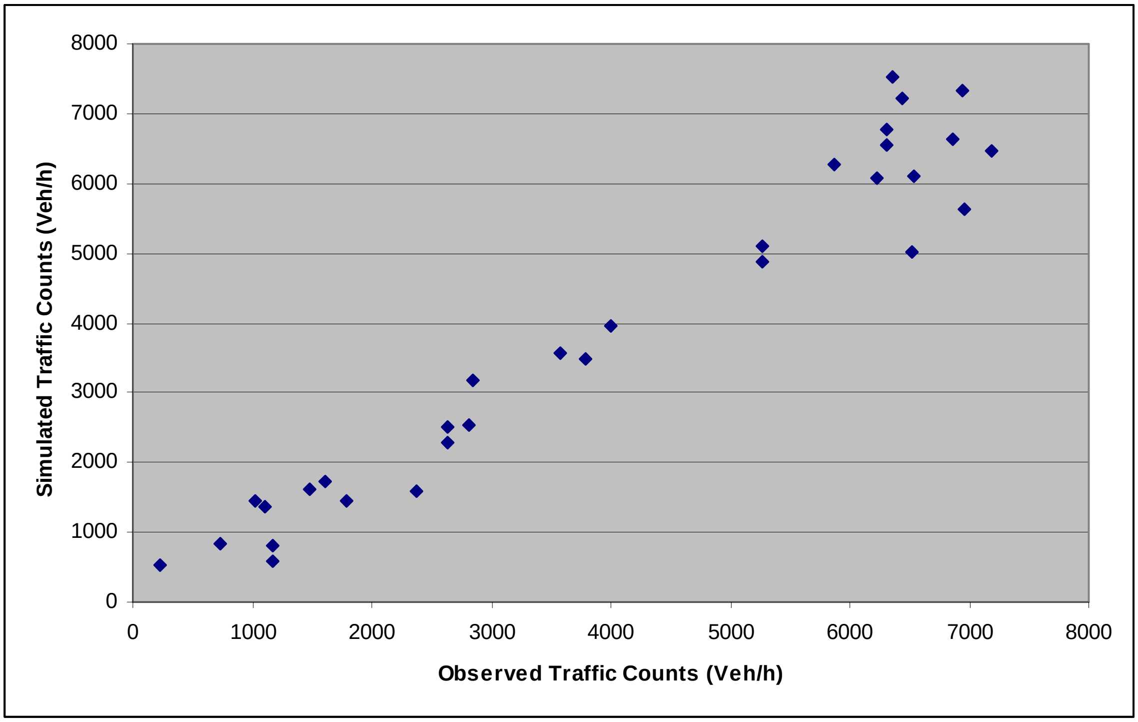

Figure 12 Calibration Results between Observed and Modeled Traffic Counts

The following sections describe the primary travel-demand related assumptions adopted in this study.

4.5.2 Deterministic Demand Assumption

In reality, travel demand is time-dependent and the distribution of demand is affected by implementing a certain congestion mitigation strategy. Nonetheless, in this study we assume demands to be deterministic over the simulation period, 5:00PM-7:00PM of a weekday, by determining an expected traffic flow rate based on historical traffic counts.

The reason to assume that traffic flow rate is constant over the simulation period is that we concentrate on average performance of incident congestion mitigation strategies; that is also why we test only one incident occurring at 5:30 PM of a weekday.

The study focuses on the strategies only effective to vehicles en route to their destinations, e.g., VSL and VMS signs will not affect traffic until drivers reach the location of the signs, therefore, demand shifts over time and modes are not taken into consideration in this study. As a consequence, implementation of the proposed strategies will result in better performance than that obtained through these simulations.

4.5.3 Vehicle Mix and HOV Lane Usage

In this study, heavy vehicles including buses and trucks are assumed to make up 1% of total traffic on I-66, 5% on I-495 and 2% on other roads such as Route 29 and Route 50. The proportions are based on a review of historical road traffic counts published by VDOT (VDOT, 2005). In addition, as the model involves an effective HOV lane, we have to determine the proportion of HOVs. The HOV Enforcement report (VDOT, 2003) concluded that approximately 20% of traffic on I-66 outside the Beltway is comprised of HOVs, by conducting a one day site survey. Based on this conclusion, we assume that HOVs make up 20% of the total traffic.

This chapter demonstrates the road network, the incident scenarios and the proposed strategies. It includes travel demand estimation method used in this study and describes assumptions related to travel demand. The following chapter analyzes the outputs of the simulation.

Chapter 5 Result Analysis

Micro simulation is performed based on the information provided in the previous chapter. This chapter defines the performance measures first, and then analyzes the simulation results in terms of those defined performance measures.

5.1 Performance Measures

Two sets of measures of effectiveness (MOEs) are defined to evaluate traffic performance from the perspectives of travel time and queue length.

5.1.1 Travel time measures

Travel time measures include total vehicle hours traveled (VHT) of the overall network, average travel speed on freeways (ATSF) and average origin-destination travel time (ODTT). Data collection points are placed every half a mile along the freeways to collect travel speed. Definitions of these measures are shown in equations (4)-(6).

$$VHT = \sum_{i,j} \sum_{k} t_{ij}^{k} \tag{4}$$

$$ATSF = \frac{\sum_{m} \left[\left(\sum_{k} v_{mk} \right) / N_m \right]}{M} \tag{5}$$

$$ODTT_{ij} = \left(\sum_{k} t_{ij}^{k} \right) / N_{ij} \tag{6}$$

Where,

t_{ij}^{k} : the travel time of the k^{th} vehicle from origin i to destination j

v_{mk}: travel speed of the k^{th} vehicle when passing the data collection point m

N_m: the number of vehicles passing though the data collection point m in a given simulation period

M: the number of data collection points

N_{ij}: the number of modeled vehicles that have completed the trips between origin i and destination j in a given simulation period

5.1.2 Queue measures

Maximum queue length (MQL) is used to measure the queue. In this study, a vehicle is counted as in the queue condition when its speed drops below 2.0 km/h, and once the speed exceeds 5.0 km/h, the vehicle is no longer counted as in the queue. VISSIM measures upstream queue length every simulation time step, and the maximum is computed from these values during a given time period to gain MQL (PTV AG, 2005).

5.1.3 Resilience with respect to MOEs

As previous mentioned in Chapter 1, evaluating traffic performance in terms of network resilience to incident congestion is one of the main objectives of this study. Resilience generally refers to the ability of a system to resist and recover from a disturbance; here, it refers to the ability of the transportation system to resist and recover from congestion once an incident occurs. Currently, no strict or clear definition of resilience or its measurement exists in the field of transportation (Murray-Tuite, 2006). Here, we define transportation network resilience with respect to a certain MOE as Equation (7).

$$R_{MOEi} = \begin{cases} \dfrac{MOE_{DoNothing} - MOE_i}{MOE_{DoNothing} - MOE_{NoIncident}} & for \quad MOE_{DoNothing} \geq MOE_{NoIncident} \\ \dfrac{MOE_i - MOE_{DoNothing}}{MOE_{NoIncident} - MOE_{DoNothing}} & for \quad MOE_{DoNothing} < MOE_{NoIncident} \end{cases} \tag{7}$$

Where, R_{MOEi} is resilience with respect to MOE with implementation of strategy i

MOE_i is MOE with implementation of strategy i

$MOE_{DoNothing}$ and $MOE_{NoIncident}$ are MOEs of do-nothing and no-incident cases

Resilience with respect to MOEs is expressed as a unitless number or a percentage value. A R_{MOEi} equal to 0.20 can be explained as, among 1 unit of a MOE's decrease or increase caused by the occurrence of an incident, 20% is recovered when implementing a certain strategy, while 80% still remains.

No strict upper or lower limits of R_{MOEi} exist. A R_{MOEi} equal to 1 indicates that traffic under the incident conditions is totally recovered to the no-incident situation due to a certain strategy. The higher the value of R_{MOEi} is, the better the strategy works. If $MOE_{DoNothing}$ is equal to $MOE_{NoIncident}$, R_{MOEi} is infinity, which represents the situation that incident occurrence does not affect road traffic at all, most likely when road traffic is very small. When R_{MOEi} is infinity, no strategy is needed. Negative R_{MOEi} means that the corresponding strategy deteriorates traffic performance in terms of the MOE. A R_{MOEi} corresponds with a certain time period, and a different time period results in a different value of R_{MOEi}.

The advantage of introducing the concept of resilience to evaluate incident congestion mitigation strategies is that the measure combines the no-incident case, do-nothing case and Strategy case into one indicator. As the resilience measure includes the total reduced performance with no strategy as the denominator, it can be compared among different incident scenarios, and therefore it can demonstrate whether the strategy is stable or sensitive with characteristics of incidents.

5.2 Results Analysis

Random seeds determine the profile of arriving traffic, specifically the stochastic variation of input flow arrival times (PTV AG, 2005). Different random seeds change the simulation results, even though the input files are identical. In this study, four different random seeds, 10, 20, 30 and 42, are tested with the identical inputs. The results shown in the following tables are the average value of simulation outputs across these different random seeds.

5.2.1 MOE#1: Overall network performance: Total vehicle hours traveled (VHT)

VHT is selected to evaluate the traffic performance for the whole network. VHTs for different scenarios with different strategies are shown in Tables 3-4. Resilience with respect to VHT, R_{VHT}, for different scenarios with different strategies are also included in Tables 3-4 and illustrated in Figures 13-14.

Table 3 Total Vehicle Hours Traveled with the Different Strategies Implemented

	Scenario 1 One lane blocked for 20min		**Scenario 2** One lane blocked for 40min		**Scenario 3** Two lanes blocked for 20min		**Scenario 4** Two lanes blocked for 40min	
	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}
No-incident	8190.1	-	8190.1	-	8190.1	-	8190.1	-
Do-nothing	8847.7	-	10465.5	-	10616.7	-	12452.3	-
Strategy 1: Opening HOV lane to all traffic	8228.6	0.94	8348.2	0.93	8659.6	0.81	10394.9	0.48
Strategy 2: Smoothing traffic flow by VSL	8971.7	-0.19	10448.3	0.01	10711.7	-0.04	12490.2	-0.01
Strategy 3: Diverting traffic by en route rerouting	8657.5	0.29	9957.9	0.22	11281.0	-0.27	13020.8	-0.13
Strategy 4: Diverting traffic via VMS **- Case 1** (20min/10%)	8610.4	0.36	9718.5	0.33	10154.1	0.19	12215.7	0.06

Note: The values of Strategies 1-3 in this table are the average for random seeds 10, 20, 30 and 42. As the difference of MOEs between the case of random seed 42 with the average case are found within 3%, strategy 4 is only run for the random seed =42 for the purpose of simplification of the study. The same note applies to the following tables.

Table 4 Total Vehicle Hours Traveled under Different Cases for the Strategy of Diverting Traffic via VMS

	Scenario 1		Scenario#2		Scenario 3		Scenario 4		Average R_{VHT}
	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}	VHT (h)	R_{VHT}	
Case 1: 20min/10%	8610.4	0.36	9718.5	0.33	10154.1	0.19	12215.7	0.06	0.23
Case 2: 40min/10%	8649.0	0.30	9726.8	0.33	10116.3	0.21	12203.6	0.06	0.22
Case 3: 0min/10%	8616.7	0.35	9758.6	0.31	10581.2	0.02	12213.1	0.06	0.18
Case 4: 20min/20%	9321.9	-0.72	9846.2	0.27	9787.4	0.34	12103.8	0.08	-0.01
Case 5: 40min/20%	9580.8	-1.12	9955.3	0.22	10032.7	0.24	12132.1	0.08	-0.14
Case 6: 0min/20%	8834.6	0.02	9574.1	0.39	10230.4	0.16	12197.3	0.06	0.16
Case 7: 20min/15%	8873.8	-0.04	9954.7	0.22	9746.2	0.36	12240.1	0.05	0.15
Case 8: 40min/15%	9047.2	-0.30	10009.4	0.20	9792.0	0.34	12219.4	0.06	0.07
Case 9: 0min/15%	8684.7	0.25	9879.5	0.26	10375.2	0.10	12324.1	0.03	0.16

The above table shows that Case 1 of Strategy 4, diverting 10% of all involved traffic from incident occurrence until 20 minutes after incident clearance, achieves the highest average R_{VHT} (taken over all scenarios) among all cases of Strategy 4. Therefore, Case 1 of Strategy 4 is selected to compare with other strategies in this study.

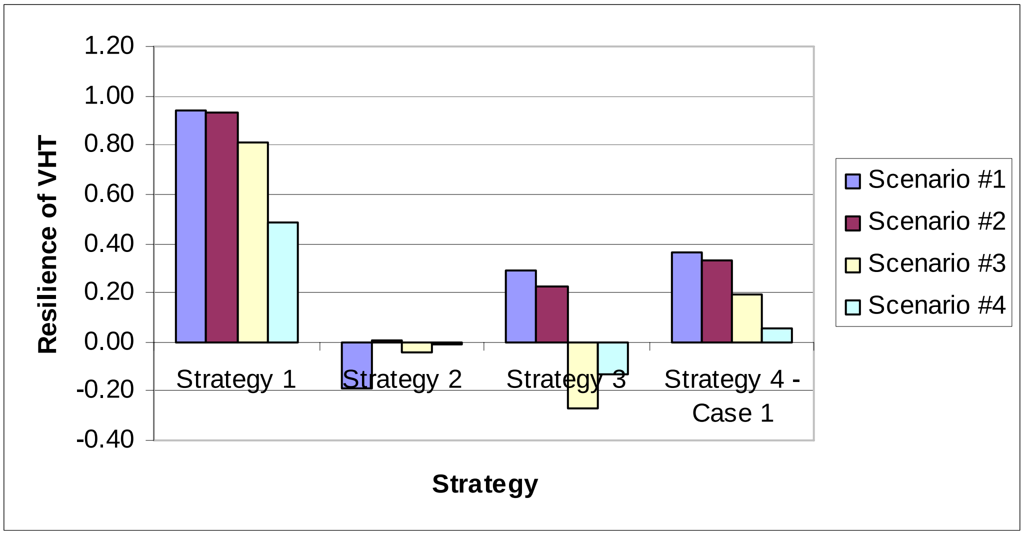

Figure 13 Resilience with respect to VHT for all Strategies

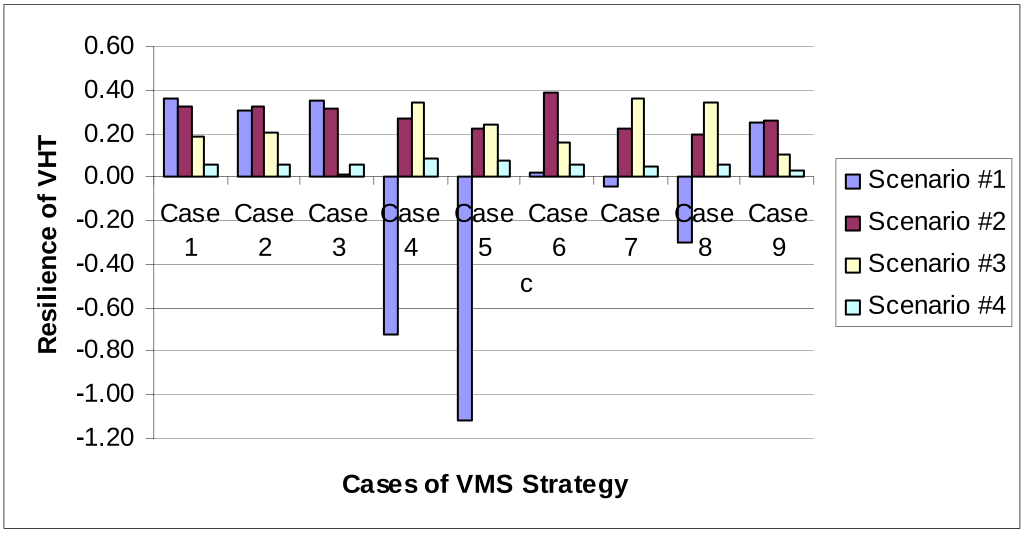

Figure 14 Resilience with respect to VHT for all Cases of VMS Strategy

The above tables and figures indicate that from the perspective of overall network performance, opening the HOV lane to all traffic (Strategy 1) is the most effective way among all proposed strategies to recover network performance in case of incident congestion. Diverting traffic via VMS (Strategy 2) is the second most effective strategy, and other two strategies are sensitive to the incident scenarios and can deteriorate the overall performance for some scenarios.

The observations are consistent with our expectations for all these strategies. Opening the HOV lane to all traffic is essentially increasing road capacity; diverting traffic via VMS is decreasing demand through the incident location. However, implementing VSL may slow down traffic in broader space and time than required, and the en route rerouting strategy involves vehicles that may not be influenced by incidents; therefore, both strategies could cause negative effects for the overall network.

It is also observed that the strategies involving the HOV lane and VMS are stable with the duration of incidents in terms of overall network performance, but sensitive with severity of incidents (i.e. number of lanes blocked). For instance, the HOV strategy leads to approximately the same VHT resilience, around 0.9, for the one-lane blocked incident with different durations; however, lower values are found for the two-lane blocked incident, which suggests that more severity causes lower resilience for a certain strategy. Besides high severity, a limited simulation period also partially contributes to lower values of resilience for the two-lane blocked incident, as resilience corresponds with a time period.

The definition of resilience provides constant value only when its corresponding time period covers the whole traffic recovery period, in other words, the simulation period should last at least until traffic has totally recovered, otherwise, resilience is variable and follows the trends that the longer time period it covers, the higher the value is. Figures 17-20 illustrate that by the end of simulation, traffic has not been totally recovered and the results are somewhat pessimistic. Therefore, comparison of resilience within the same scenario provides more quantitatively reliable information than comparing resilience among different scenarios in this study.

In addition, 0.3-0.4 VHT resilience can be achieved by adopting the VMS diverting strategy for the one-lane blocked incident, and a lower number is achieved for the two-lane blocked incident with the possible reason stated previously.

5.2.2 MOE#2: Average Travel Speed on Freeways (ATSF)

ATSF is chosen to represent traffic performance over freeways. Tables 5-6 show ATSFs for different incident scenarios with different strategies. Figures 15-16 illustrate resilience with respect to ATSF, R_{ATSF}, for different scenarios with different strategies. Case 1 of Strategy 4 is selected to be compared with other strategies.

Table 5 Average Travel Speed on Freeways (ATSF) with the Different Strategies Implemented

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}
No-incident	57.1	-	57.1	-	57.1	-	57.1	-
Do-nothing	55.3	-	52.1	-	52.3	-	49.4	-
Strategy 1	57.0	0.94	56.5	0.87	55.9	0.74	52.6	0.41

Strategy 2	54.2	-0.55	51.2	-0.19	51.5	-0.15	48.9	-0.07
Strategy 3	55.8	0.31	53.6	0.30	54.0	0.37	50.9	0.19
Strategy 4 - Case 1	56.5	0.67	54.3	0.43	53.4	0.23	50.3	0.12

Table 6 Average Travel Speed on Freeways (ATSF) under Different Cases for the Strategy of Diverting Traffic via VMS

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}	ATSF (mph)	R_{ATSF}
Case 1: 20min/10%	56.5	0.67	54.3	0.43	53.4	0.23	50.3	0.12
Case 2: 40min/10%	56.6	0.69	54.4	0.45	53.7	0.30	50.4	0.12
Case 3: 0min/10%	56.4	0.59	54.2	0.40	52.5	0.05	50.3	0.11
Case 4: 20min/20%	56.9	0.87	56.2	0.82	55.9	0.74	51.9	0.32
Case 5: 40min/20%	56.9	0.89	56.3	0.83	56.0	0.77	52.0	0.33
Case 6: 0min/20%	56.8	0.81	56.0	0.77	53.9	0.34	51.4	0.26
Case 7: 20min/15%	56.7	0.77	54.7	0.52	55.0	0.56	51.0	0.20
Case 8: 40min/15%	56.7	0.79	54.7	0.52	55.3	0.63	51.1	0.22
Case 9: 0min/15%	56.4	0.63	54.4	0.45	53.5	0.26	50.8	0.18

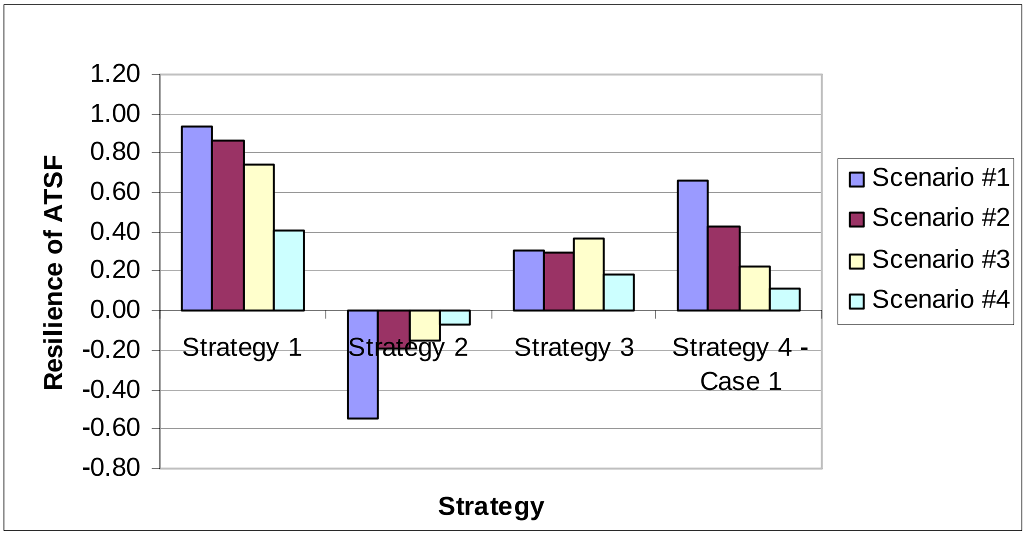

Figure 15 Resilience with respect to ATSF for all Strategies

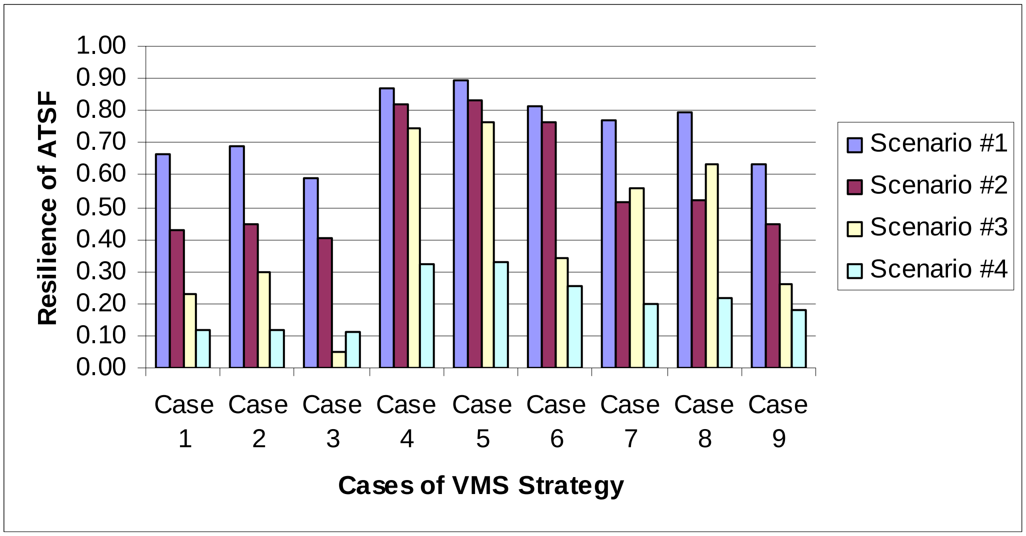

Figure 16 Resilience with respect to ATSF for all Cases of VMS Strategy

The simulation results show that all strategies except the one involving VSL improve the freeway traffic performance in terms of average travel speed under the situation of incidents, among which the HOV strategy is found to make the greatest improvements, followed by the VMS strategy and en route rerouting strategy. For instance, for the one-lane blocked incident lasting 20 minutes, 0.95, 0.65, and 0.30 resilience of ATSF result from implementing the strategies involving HOV lane, VMS, and en route rerouting, respectively. Furthermore, the observations of strategy stability in terms of freeway traffic performance measured by ATSF are found to be approximately the same as those in terms of overall network performance measured by VHT.

VSL is implemented to smooth traffic flow and also avoid a vehicle approaching an incident location with a high speed to decrease the possibility of secondary incidents. This very nature of VSL suggests that average highway travel speed will be reduced, which is consistent with the results of this study. The potential benefits of VSL are reducing congestion queue length and decreasing the possibility of secondary incidents. The evaluation of queue length is discussed in section 5.2.4.

The improvements achieved for freeway performance are found to be greater compared with those for overall network performance; the finding is consistent with the intention of the proposed strategies that is to improve freeway performance where incidents are assumed to occur by sacrificing performance on other roads. For example, the en route rerouting strategy achieves up to 0.36 of resilience for freeway traffic performance for the two-lane blocked incident, but causes negative effects for the whole network performance.

The VSL strategy causes slight negative effects for both freeways and overall network performance for most incident scenarios. It is essentially different from the other strategies with the fundamental idea of smoothing traffic flow rather than increasing capacity or decreasing relevant demand. Optimization of traffic flow by dynamically changing speed limits is hard to achieve and influenced by many factors such as the reduction of speed limits, location of dynamic speed limits signs, and proportion of drivers complying. Based on the simulation results and analysis, the VSL strategy is not recommended for nonrecurring congestion mitigation.

Figures 17-20 illustrate the change of ATSFs over time under four different incident scenarios.

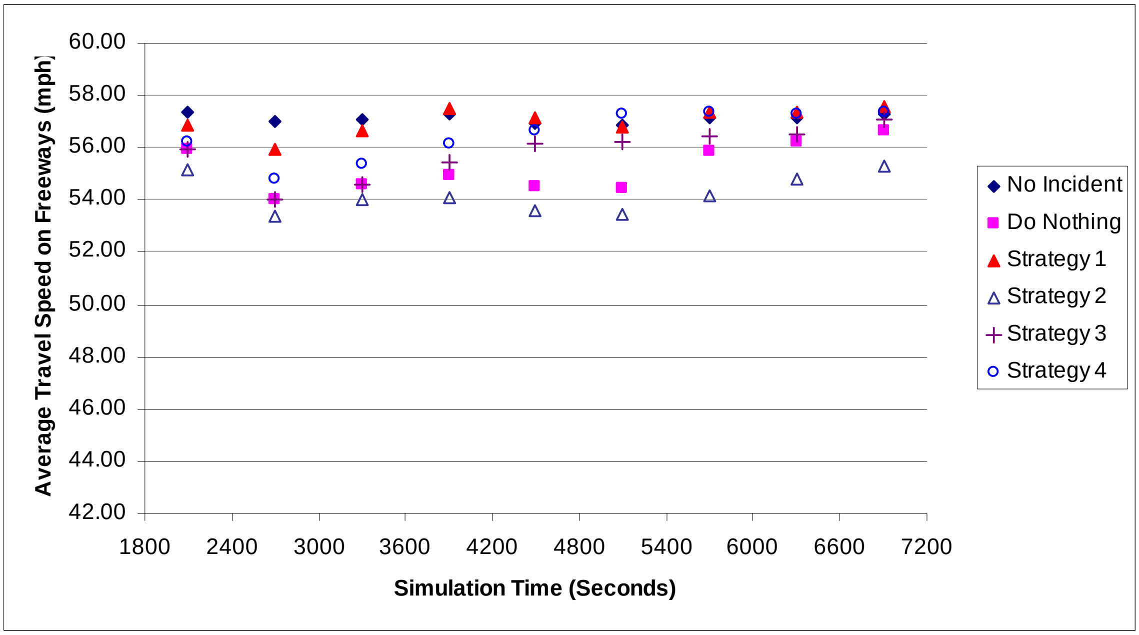

Figure 17 Average Travel Speed on freeways over time with different strategies under Incident Scenario #1

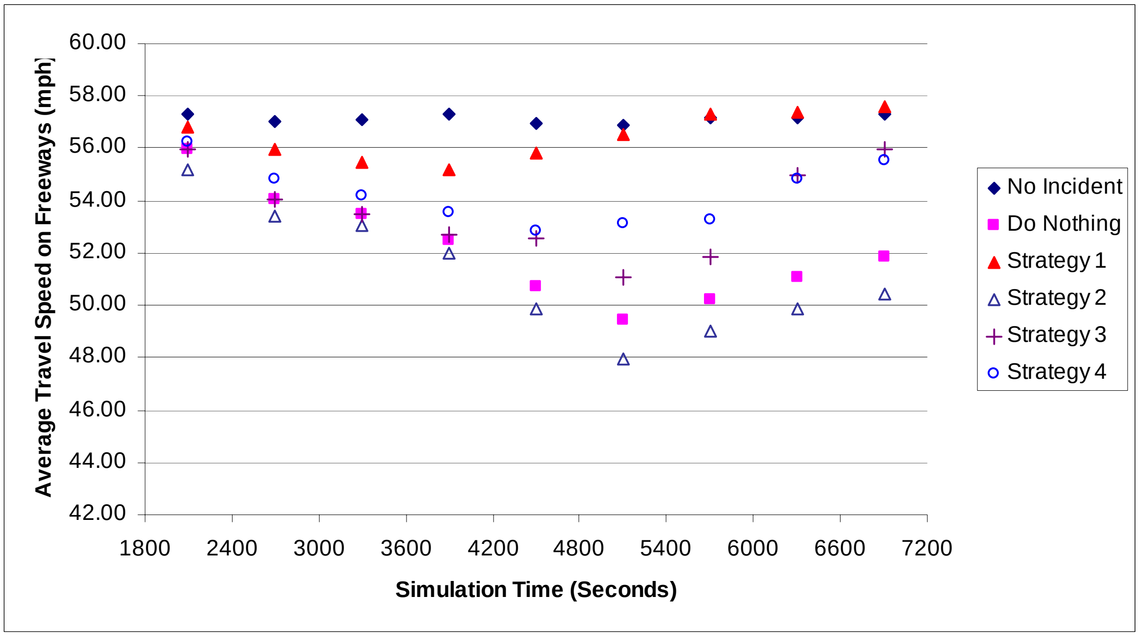

Figure 18 Average Travel Speed on freeways over time with different strategies under Incident Scenario #2

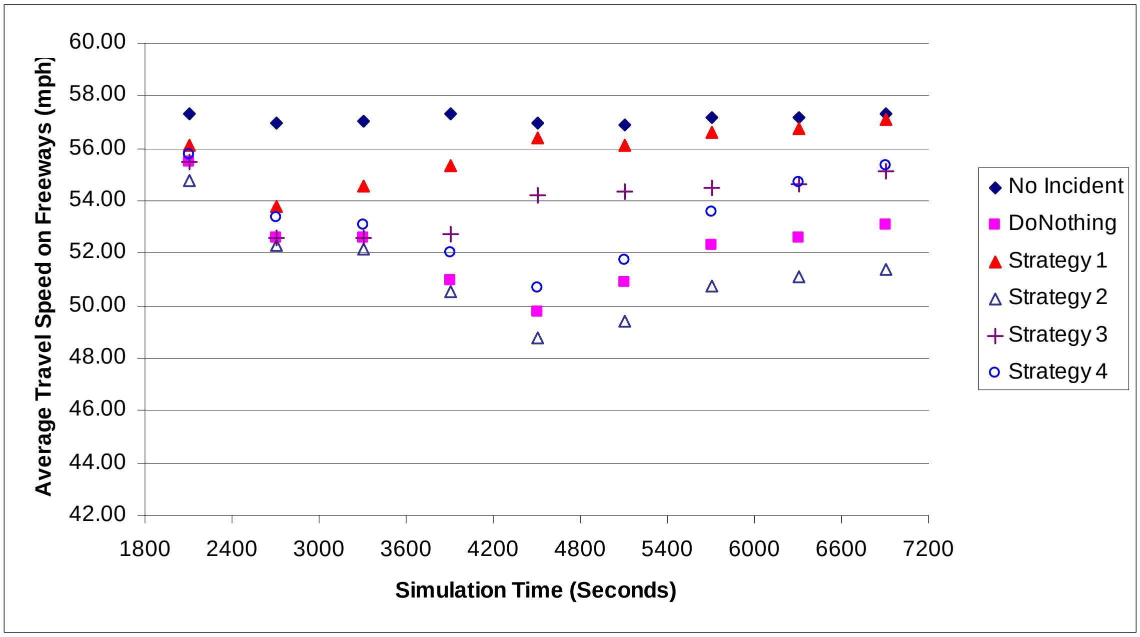

Figure 19 Average Travel Speed on freeways over time with different strategies under Incident Scenario #3

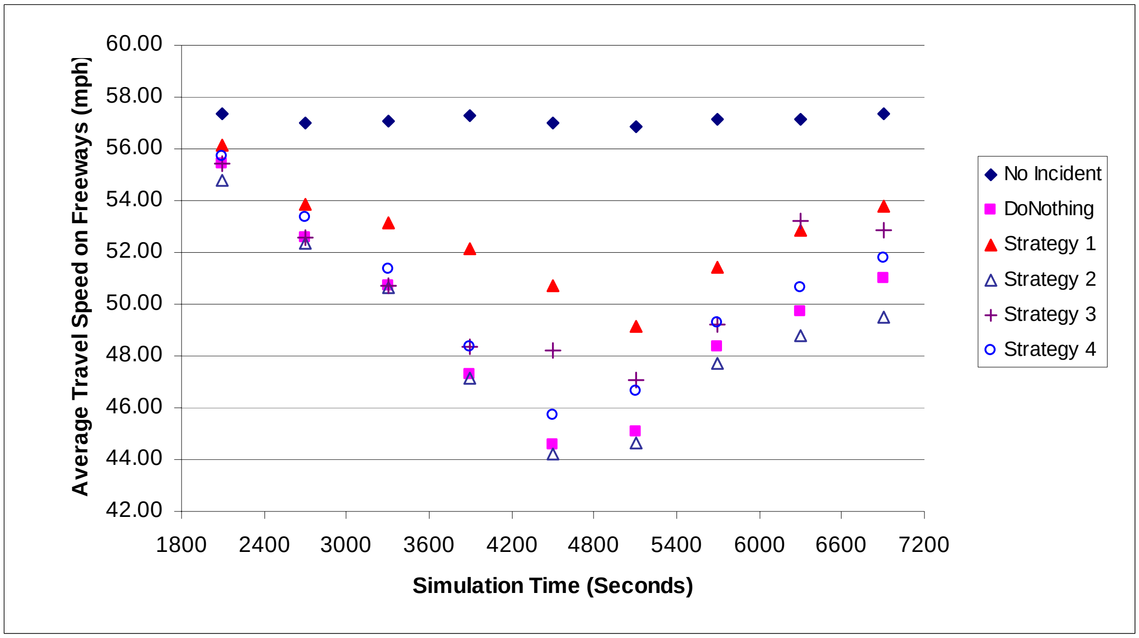

Figure 20 Average Travel Speed on freeways over time with different strategies under Incident Scenario #4

In this study, Scenario #1 is of minor consequence, Scenarios #2 and #3 are moderate and Scenario #4 has major severity. From the above figures, we find that only for the scenario with minor consequence, traffic on freeways starts to recover almost immediately after the clearance of the incident. For all other scenarios with more severity, after incident clearance, traffic continues to deteriorate for 10-30 minutes before it starts to recover (in this study, the incident occurs at simulation time 1800s (20 minutes), and is cleared at simulation time 3000s (40 minutes) or 4200s (60 minutes)).

The figures also illustrate that the strategies have immediate effects; the HOV strategy and VMS strategy improve ATSF over time significantly for the scenarios with one-lane blocked. The strategy of diverting traffic by en route rerouting is found to fluctuate intensely and sensitively for the scenario with major incident severity. Generally, this strategy works better for the scenarios with minor or moderate severity.

5.2.3 MOE#3: OD Travel Time (ODTT)

ODTT refers to the average travel time from the origin to the destination for the relevant group of vehicles. Tables 7-8 display ODTTs for vehicles traveling through the incident location and all vehicles, respectively. Resilience with respect to ODTT, R_{ODTT}, is also included in Tables 7-8.

Table 7 OD Travel Time for Traffic traveling through the Incident Location with the Different Strategies Implemented

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}
No-incident	625.8	-	625.8	-	625.8	-	625.8	-
Do-nothing	668.0	-	765.0	-	777.9	-	1039.8	-
Strategy 1	627.0	0.97	637.9	0.91	660.2	0.77	797.7	0.59
Strategy 2	677.5	-0.23	775.8	-0.08	779.6	-0.01	1042.8	-0.01
Strategy 3	656.8	0.27	741.2	0.17	742.9	0.23	919.4	0.29

Note: Strategy 4 adopts static traffic assignment rather than dynamic traffic assignment used for other strategies, in order to predefine the detours, its effective period and percentage of vehicles following the detours. Vehicle path files that are used to calculate ODTT measure can not be outputted from static assignment modeling, therefore, Strategy 4 is not included in Tables 7-8.

Table 8 OD Travel Time for all Traffic with the Different Strategies Implemented

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}	ODTT (s)	R_{ODTT}
No-incident	534.5	-	534.5	-	534.5	-	534.5	-
Do-nothing	545.3	-	587.4	-	593.4	-	690.3	-
Strategy 1	533.0	1.14	535.2	0.99	542.0	0.87	595.8	0.61
Strategy 2	548.0	-0.24	590.9	-0.07	593.5	0.00	691.7	-0.01
Strategy 3	540.2	0.47	574.6	0.24	595.5	-0.04	654.9	0.23

Figures 21-22 illustrate resilience with respect to ODTT, R_{ODTT}, for traffic travelling through the incident location and all traffic respectively.

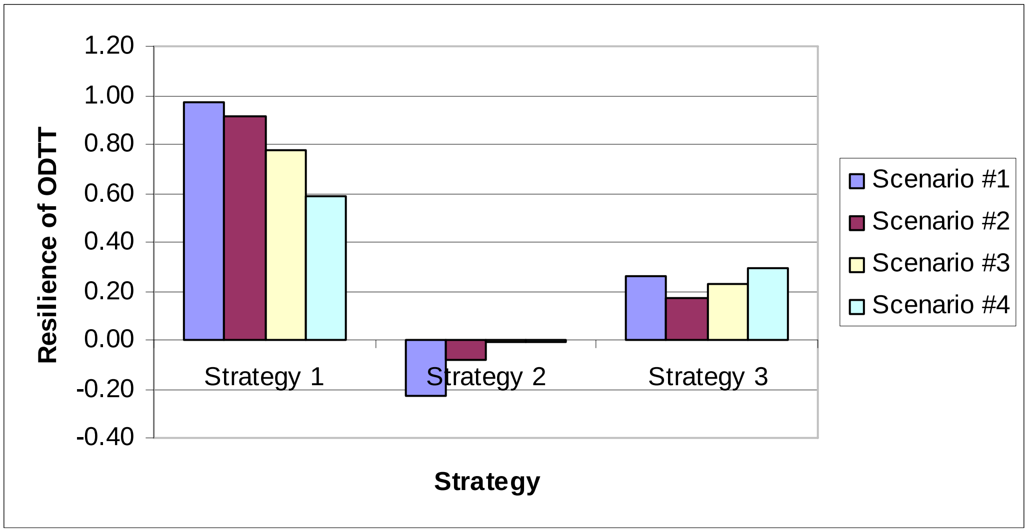

Figure 21 Resilience with respect to ODTT for Traffic traveling through the Incident Location

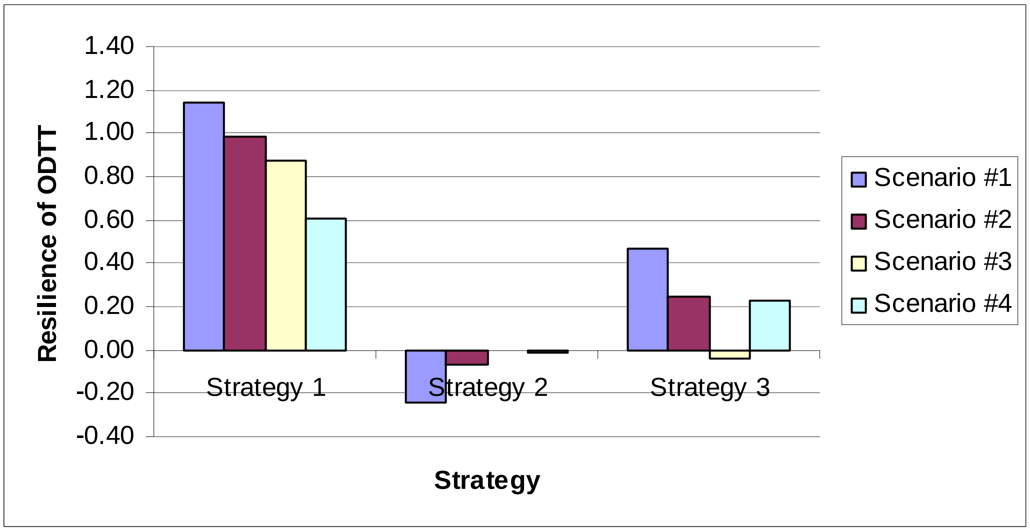

Figure 22 Resilience with respect to ODTT for all traffic

The HOV strategy saves total OD travel time for both the overall network traffic and traffic going through the incident location point to a great extent; the VSL strategy increases the total ODTT for all incident scenarios; and the en route rerouting strategy causes medium reduction of ODTT for almost all incident scenarios.

5.2.4 MOE#4: Maximum Queue Length (MQL)

MQL is used to measure queue length caused by the incident. Tables 9-10 show MQLs and resilience with respect to MQL, R_{MQL} , for different scenarios with different strategies. Figures 23-24 illustrate resilience with respect to MQL.

Table 9 Maximum Queue Length with the Different Strategies Implemented

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}
No-incident	0	-	0	-	0	-	0	-
Do-nothing	6877	-	6971	-	7988	-	8489	-
Strategy 1	2444	0.65	3957	0.43	6813	0.15	6851	0.19
Strategy 2	6878	0.00	6959	0.00	7775	0.03	8462	0.00
Strategy 3	6877	0.00	7415	-0.06	7988	0.00	8781	-0.03
Strategy 4 - Case 1	6272	0.09	6833	0.02	7298	0.09	7986	0.06

Table 10 Maximum Queue Length under Different Cases for the Strategy of Diverting Traffic via VMS

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}	MQL (ft)	R_{MQL}
Case 1: 20min/10%	6272	0.09	6833	0.02	7298	0.09	7986	0.06
Case 2: 40min/10%	6272	0.09	6833	0.02	7298	0.09	7986	0.06
Case 3: 0min/10%	6328	0.08	6833	0.02	7416	0.07	7986	0.06
Case 4: 20min/20%	4633	0.33	5804	0.17	7062	0.12	7318	0.14
Case 5: 40min/20%	4633	0.33	5804	0.17	7062	0.12	7318	0.14
Case 6: 0min/20%	4755	0.31	5957	0.15	7055	0.12	7318	0.14
Case 7: 20min/15%	5834	0.15	6899	0.01	7064	0.12	7809	0.08
Case 8: 40min/15%	5834	0.15	6899	0.01	7064	0.12	7809	0.08
Case 9: 0min/15%	5988	0.13	6897	0.01	7064	0.12	7809	0.08

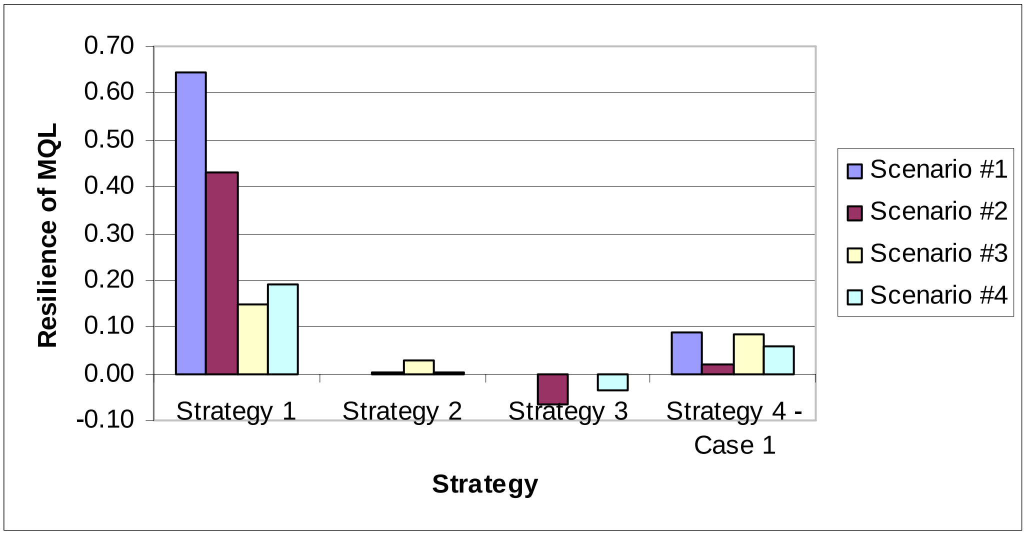

Figure 23 Resilience with respect to MQL for all Strategies

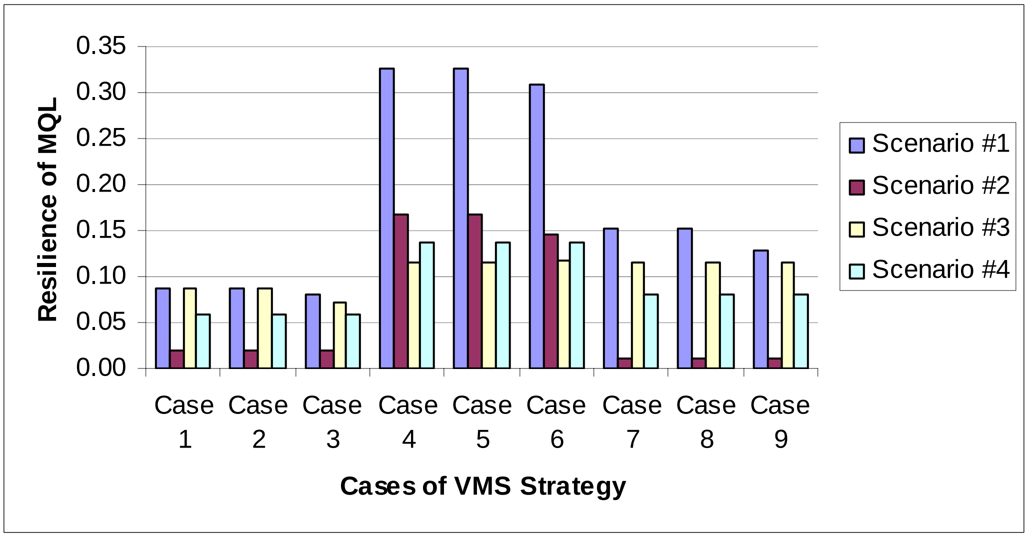

Figure 24 Resilience with respect to MQL for all Cases of VMS Strategy

The HOV strategy and VMS strategy reduce the maximum queue length caused by the incident for all scenarios. The VSL strategy slightly decreases the maximum queue length (less than 0.03 resilience) for the scenarios with major severity or longer duration. Contrarily, en route rerouting strategy slightly increases queue length for the scenarios with long incident duration, and does not change queue length for the scenarios with short incident duration (resilience 0). The VSL strategy also causes 0 resilience of MQL under the scenario of minor severity and short duration. Generally, we conclude that the measure of queue length is only slightly affected or not affected by implementing VSLs or en route rerouting.

Notably even though the VSL strategy deteriorates traffic performance with respect to vehicle hours and average travel speed, it slightly reduces the queue length. However, less than 0.03 resilience of queue length does not counteract its negative effect; therefore, we still do not recommend using the VSL strategy to mitigate incident congestion.

Chapter 6 Conclusions

This study used microscopic simulation technology as a tool to evaluate the proposed incident congestion mitigation strategies, i.e., opening HOV lane to all traffic, smoothing traffic flow by VSL, diverting traffic by en route rerouting, and diverting traffic via VMS. Previous work on the currently widely-used strategies and evaluation of these strategies were reviewed. In addition to the evaluation criteria of maximum queue length, average origin-destination travel time, average freeway travel speed, and total vehicle hours, the concept of resilience was introduced and defined as the ratio of recovered performance due to a certain strategy with respect to total reduction of performance in the do-nothing case. A case study using the microscopic simulation tool VISSIM was conducted in an actual medium sized road network located in Northern Virginia.

6.1 Conclusions

The main conclusions of this study are summarized as follows.

- Opening the HOV lane to general traffic (when 20% of traffic is HOV) and diverting traffic via VMS are the two most effective ways to increase transportation system resilience to congestion caused by incidents. In addition, these two strategies are found to be more stable with respect to incident severity than smoothing traffic flow by VSL and diverting traffic by en route rerouting.
- The VSL strategy causes slight negative effects on traffic performance with respect to vehicle hours and average travel speed for most incident scenarios, compared to do-nothing case; however, it does decrease maximum queue length caused by the incident slightly, suggesting that while travel is slower, fewer vehicles are actually queued.

- For the scenario with minor incident consequence, traffic on freeways starts to recover almost immediately after the clearance of the incident; for all other scenarios with more severe incident consequence, after the incident clearance, traffic continues to deteriorate for 10-30 minutes before it starts to recover.
- The HOV strategy and VMS strategy reduce maximum queue length caused by the incident for all scenarios. Contrarily, en route rerouting strategy increases queue length.

The conclusions are also suitable to other non-recurring congestion situations with lane closure, e.g., work-zone and special event. Based on the conclusions, the following preliminary recommendations are made, though future study may be required before directly transferring the results to a particular area.

- Opening the HOV lane to general traffic is highly recommended in the case of incident congestion, provided that the percentage of HOVs is relatively low.
- The VSL strategy is not effective for mitigating congestion caused by incidents and should not be implemented for that purpose.
- The en route rerouting strategy should be further studied due to its inconsistent performance.
- The VMS diverting strategy should be implemented from incident occurrence until 20 minutes after incident clearance and 10% of traffic in that direction should be diverted for each detour.

6.2 Future Work

This study is an initial work and opens the door for several future studies. In the future, more strategies, such as congestion pricing, could be evaluated using the micro simulation tool. Scenarios with different incident locations could also be tested. Finally, dynamic demand and various incident occurrence times could be examined.

References

1. Allen, R.W., Stein, A.C., Rosenthal, T.J., Ziedman, D., Torres, J.F., and Halati, A., (1991) A human factors simulation investigation of driver route diversion and alternate route selection using in-vehicle navigation systems, Proceedings - Society of Automotive Engineers, p9-26

2. Cragg, C.A., and Demetsky, M.J., (1995) Simulation Analysis of Route Diversion Strategies for Freeway Incident Management, Virginia Transportation Research Council, Charlottesville, VTRC-95-R11, 1995, 31p

3. Chiu, Y., Huynh, N., and Mahmassani, H.S., (2001) Determining Optimal Locations for Variable Message Signs Under Stochastic Incident Scenarios, Presented at the 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

4. Chu, L., Liu, H.X., and Recker, W., (2004) Evaluation of potential ITS strategies under non-recurrent congestion using microscopic simulation. In *2004 TRB Annual Meeting*. CDROM

5. Cuneo, D., Jha, M., and Ben-Akiva, M., An Evaluation of Integrated Freeway Traffic Control and Route Diversion using Microscopic Simulation, Massachusetts Institute of Technology

6. Daganzo, C.F., Laval, J., and Munoz, J.C., (2002) Ten Strategies for Freeway Congestion Mitigation with Advanced Technologies, California PATH Research Report

7. Dia, H., and Cottman, N., (2004) Evaluation of Incident Management Benefits Using Traffic Simulation, the University of Queensland, Workshop on Traffic Simulation 5-6 August, 2004

8. Federal Highway Administration (FHWA), (2005) Traffic congestion and reliability: trends and advanced strategies for congestion mitigation, Available via < http://ops.fhwa.dot.gov/congestion_report/>

9. Federal Highway Administration (FHWA), (2001) Regional Traffic Incident Management Programs, Implementation Guide

10. Helman, D.L., (2004) Traffic Incident Management, Public Roads, November/ December 2004, vol. 68, No.3, available via http://www.tfhrc.gov/pubrds/04nov/03.htm

11. Huynh, N., Chiu, Y., and Mahmassani, H.S., (2003) Finding Near-Optimal Locations for Variable Message Signs for Real-Time Network Traffic Management, Transportation Research Board, 1856, pp. 34-53

12. Litman, T., (2006) London congestion pricing, Implications for other cities. Federal Highway Administration, Value pricing pilot program brochure

13. McNally, M.G., Jayakrishnan R., and Cohen M.I., (1993) Simulation of ATIS strategies to mitigate special event congestion, Computing in Civil and Building Engineering, p 583-590

14. Murray-Tuite, P.M., (2006) A Comparison of Transportation Network Resilience under Simulated System Optimum and User Equilibrium Conditions, Proceedings of the 2006 Winter Simulation Conference, p 1398-1405

15. National Audit Office, (2004) Tackling Congestion by Making Better Use of England’s Motorways and Trunk Roads, HC 15, 2004-05

16. Paniati, J., (2004) Operational Solutions to Traffic Congestion, Public Roads, November/ December 2004, Vol. 68, No. 3, available via http://www.tfhrc.gov/pubrds/04nov/01.htm

17. Pearson, R., (2001) Ramp Metering, ITS Decision Report, California Center for Innovative Transportation

18. Peeta, S., and Gedela, S., (2001) Real-time variable message sign-based route guidance consistent with driver behavior, Transportation Research Record, n 1752, 2001, p 117-125

19. Peeta, S., Ramos, J.L., and Pasupathy, R., (2000) Content of variable message signs and on-line driver behavior, Transportation Research Record, n 1725, 2000, p102-108

20. PTV AG., (2005) VISSIM4.10 user manual

21. Rathi, V., (2007) Assessment of Impact of Dynamic Route Guidance through Variable Message Signs, Massachusetts Institute of Technology, Master thesis

22. Robinson, M.D., and Nowak, P.M., (1993) An Overview of Freeway Incident Management in the United State

23. Steel, P., McGregor, R.V., Guebert, A.A., and McGuire, T.M., (2005) Application of variable speed limits along the Trans Canada Highway in Banff National Park. In *2005 Annual conference of the transportation association of Canada Calgary, Alberta*

24. Sundaram, S., (2002) Development of a Dynamic Traffic Assignment Systems for Short-Term Planning Applications, Massachusetts Institute of Technology, Master thesis

25. U.S. Department of Transportation (U.S. DOT), (2007) Traffic Incident Management, available via http://www.oti.dot.gov/tim/index.htm

26. U.S. Department of Transportation (U.S. DOT), (2007) Intelligent Transportation Systems for Traffic Incident Management, Deployment Benefits and Lessons Learned, available via http://www.its.dot.gov/jpodocs/repts_te/14288.htm

27. Virginia Department of Transportation (VDOT), (2003) I-66 multimodal transportation and environmental study

28. Virginia Department of Transportation (VDOT), (2002-2005) Average daily traffic volumes with vehicle classification data on interstate, arterial and primary routes

29. Wikipedia, (2007) http://en.wikipedia.org/wiki/Microsimulation

30. Wunderlich, K., (1998) A simulation-based assessment of route guidance benefits under variable network congestion conditions, Mathematical and Computer Modelling, v 27, n 9-11, May-June 1998, p 87-101