ABSTRACT

Title of Document:	UNDERSTANDING THE IMPACT OF INCIDENTS AND INCIDENT MANAGEMENT PROGRAMS ON FREEWAY MOBILITY AND SAFETY
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Despite significant technological achievements over past decades, and institutional support for Intelligent Transportation System (ITS), it is not possible to prevent all traffic incidents. Numerous incidents occur every day along U.S. freeways and traffic incident management (TIM) programs have been proposed and implemented to mitigate their impact. This dissertation proposes various tools to aid in the evaluation of proposed TIM programs, contributing, thus, to the general study area of freeway incident management. In addition, moving violations specific to concurrent flow lane operations are conceived as a type of transient incident. Their impact on mobility and safety is considered. Techniques to address four key areas are proposed. First, a methodology that considers the dynamics of incident impact given a primary incident's properties and prevailing traffic conditions for identifying secondary incidents from a database is proposed. This method is computationally efficient and overcomes deficiencies of other existing techniques, with utility in any context in which the study of secondary incidents is warranted. A

three-stage time-saving process is developed for conducting TIM program benefit evaluations. The process aids in sampling a relatively small set of good quality incident scenarios that can represent historical incident data and overcomes the computational burden encountered when evaluating TIM program's benefit by simulation. Modeling techniques are proposed for simulating violations associated with the operation of concurrent flow lanes. Results from a case study show significant impact to mobility that grows nonlinearly with increasing violation rate. Such illegal traffic maneuvers contribute to increased speed variation and congestion, ultimately affecting safety. Finally, diversion strategies that exploit existing capacity of managed lanes for the purpose of reducing the impact of an incident in the general purpose lanes are evaluated. Simulation modeling methodologies were developed for modeling freeway incidents and studied diversion strategy implementations. Experimental findings indicate benefits of diversion that are contrary to qualitatively developed recommendations in the literature.

Understanding the Impact of Incidents and Incident Management Programs on Freeway Mobility and Safety

By

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Chapter 1: Introduction

1.1 Motivation and Objectives

Due to complex interactions between vehicles operating within a roadway facility, the occurrence of incidents along these facilities is unavoidable. Such incidents can involve a collision between vehicles, vehicles that become disabled, appearance of debris that interferes with smooth traffic flow, or other event that might impede normal traffic operations. Unfortunately, such events are not rare. In fact, in the small state of Maryland between 2002 and 2007, there were between 32,000 and 42,000 incidents involving a collision or disabled vehicle in which assistance was requested arising along the major freeways and a subset of arterials (Chang and Rochon, 2008). In a study of a 3-lane, 10-mile stretch (both directions) of the I-287 freeway in New York State, more than seven incidents occurred daily (Chou et al., 2010). Once an incident occurs, it may reduce roadway capacity, induce traffic congestion and degrade service quality. The magnitude of impact depends on the incident properties and prevailing traffic conditions. In a widely cited study by Lindley in 1987, 60% of the non-recurrent congestion on the freeway was caused by various kinds of incidents (Lindley, 1987). The induced traffic congestion may also cause secondary incidents. One study shows that nearly 15% of all collisions are secondary to a primary incident (Raub, 1997). The impact of incidents on the operation of roadway facilities can be considered not only from mobility and safety perspectives, but also from the standpoint of energy usage and environment impact. As travel delay increases, so do the rates of fuel consumption and emissions (Greenwood et al., 2007).

Traffic incident management (TIM) programs can be implemented to mitigate the deleterious impact of incidents. These programs include Freeway Service Patrol (FSP),

Automatic Incident Detection (AID), ramp metering, incident site management, Variable/Dynamic Message Sign (VMS/DMS) advisory assistance, and route diversion. Some TIM programs seek to quickly restore normal traffic flow. For example, freeway service patrol trucks can be dispatched or automatic incident detection devices can be applied to rapidly identify and respond to incidents. A site management program, by contrast, narrows the impact area to increase traffic capacity. Other TIM programs, such as the VMS system and route diversion, tend to control the traffic demand by detouring or warning the approaching vehicles. These TIM programs can be integrated or stand alone.

As traffic demand increases world-wide, particularly in and around the world's cities, congestion on roadways has substantially increased. To address this, the use of High Occupancy Vehicle (HOV) lanes and Express Toll Lanes (ETLs), or similarly functioning High Occupancy Toll (HOT) lanes, have been proposed as a possible solution to achieve more effective use of existing roadway capacity (Collier and Goodin, 2002). HOV lanes have been part of the roadway landscape for the past two or three decades, however, only recently, perhaps due to improvements in required technologies for toll collection, have HOT lanes been thought of as a viable option. Few incident management programs, thus, have been studied for mitigating the impact of incidents arising in facilities with managed lanes, such as HOT lanes. As many states add new HOT lane facilities or begin conversion of their HOV lane facilities to HOT lanes, the import of developing and studying incident management programs designed specifically for such facilities has increased. Additionally, poor handling of incidents arising along such roadways will undermine public support for these facilities and jeopardize revenues. In 2004, the Texas Transportation Institute hypothesized several possible approaches for addressing incidents in facilities involving managed lanes (Ballard, 2004), including a strategy based on traffic diversion.

These approaches, by and large, have not been quantitatively analyzed.

Driving violations in concurrent flow lane operations can lead to excessive car following and lane changing maneuvers and cause steady traffic oscillating. (Zielke at al, 2008). They can be conceived of as a type of transient incident. The national average annual violation rate associated with HOV and HOT lanes for the 2005-2006 period in the U.S. is estimated to involve between 10 and 15 percent of all vehicles using managed lanes (Martin et al., 2005). While numerous studies have indicated that violations are of significant concern for HOT lane facilities, the impact of various violation types on mobility, safety and other performance metrics in both the managed and general purpose lanes has not yet been quantitatively analyzed.

While TIM programs have, in general, been shown to provide significant benefit in terms of mitigating the impact of incidents on roadway congestion and other negative externalities, in the current climate of budget shortfalls, many TIM programs are facing cuts or outright termination. Thus, benefit evaluation studies of existing or proposed TIM programs are commonplace. Nonetheless, several issues associated with benefit evaluations remain unresolved. For example, while several studies mentioned the benefit of TIM programs from a safety perspective in terms of savings in secondary incidents, how such incidents can be identified as secondary is still unclear. In addition, for studies that use a simulation approach for such evaluation, it is unclear how many incidents and with what characteristics to replicate in deriving accurate benefit estimates.

Driven by the needs and research challenges described above, this dissertation has the following four objectives:

(1) Develop a reliable methodology for filtering secondary incidents from an incident database. In additional to being computationally efficient, the developed methodology must consider the

dynamic impact of incidents in time and space. Such a methodology will overcome the weaknesses of existing methods, most of which rely on static thresholds.

(2) Create an efficient methodology for simulation-based assessment of TIM program benefits. The developed methodology will design a set of incident scenarios, with incident properties, from historical incident data for use in conducting simulation-based evaluation studies of existing and proposed TIM programs. The developed technique seeks to overcome the deficiencies of prior studies in which either too few, and not necessarily representative, incidents were replicated to ensure valid results or too many incidents were replicated, requiring enormous computational effort and time for output synthesis.

(3) Assess impact of traffic violations on the mobility and safety of concurrent flow lane freeway facilities. To address this issue, violation data associated with concurrent flow lane freeway facilities are reviewed and analyzed. Various types of driving violations will be identified. The impact of violations must be assessed from both safety and mobility standpoints. A simulation platform and specific modeling techniques for use in analyzing the impact of driving violations must be developed. The potential negative impact of driving violations to the operation of concurrent flow lane facilities will be quantified.

(4) Propose and assess diversion strategies for non-barrier separated concurrent flow lane facilities for mitigating incident impact. Strategies are developed that consider temporarily allowing nonpermitted vehicles to use managed lanes, possibly crossing the buffer in the non-barrier separated concurrent flow lane facilities, to relieve traffic congestion in the event of an incident. A platform for assessing such strategies must be created and the effects of proposed

diversion strategies must be quantified. The developed strategies fill a need for systematically designed and assessed strategies for incident management in facilities containing managed lanes adjacent to general purpose lanes (concurrent flow lanes).

Off-the-shelf traffic simulation tools were used extensively in this dissertation work. Novel modeling techniques were developed to apply these tools as the needs of this effort often required capabilities that were not directly provided. The platform employed in each portion of the dissertation was chosen based on the functionality of the platform and its suitability for the given study purpose.

1.2 Specific Problems Addressed and Contributions

To achieve the objectives of this dissertation, the following problems are addressed.

1.2.1 A Simulation-Based Secondary Incident Filtering Method

To identify secondary incidents, numerous approaches have been proposed in the literature. The majority of these approaches employ static temporal and spatial thresholds related to the primary incidents and filter secondary incidents from the archived incident database. Such thresholds are unchanged regardless of incident properties or prevailing traffic conditions. As such, they often erroneously identify incidents as secondary, thus, over-estimating their occurrence. In this dissertation, a geometric-based filtering method with dynamic thresholds, referred to as the Simulation-Based Secondary Incident Filtering (SBSIF) method, is proposed that visually identifies the corner points of the incident impact area over space and time within traffic speed contour maps developed from results of simulation runs. The shape of the impact area of each incident varies as a function of incident properties, such as incident duration and severity, and

prevailing traffic conditions. Regression models for estimating the x- and y- coordinates of each corner point are developed to aid in delineation of the incident impact area boundaries. Any incident falling within these boundaries is considered as a secondary incident. This approach, thus, facilitates computer-based impact area recognition and secondary incident identification.

The SBSIF method is computationally efficient and overcomes deficiencies of existing techniques. Tests involving incident data from a six month period along a segment of I-287 in New York State show that the proposed method has a significantly reduced misclassification rate (e.g. a reduction of 58 percentage points and greater) as compared with static methods commonly used in practice, despite that it requires comparable computational effort. Details of the SBSIF method and results of assessment based on real-world data are presented in Chapter 4.

1.2.2 A Time-Saving Approach to Simulation Modeling for TIM Program Evaluation

Many studies rely on microscopic simulation techniques in evaluating the benefits of TIM programs. These studies nearly always replicate either too few, and not necessarily representative, incidents to ensure valid benefit estimates or too many incidents, requiring enormous computational effort and time for output synthesis. A three-stage time-saving analysis process is proposed herein for use in TIM program benefit analyses. This process relies on the developed Property-Based Incident Generation (P-BIG) procedure. The P-BIG procedure is designed to assist in generating a set of incident scenarios that are representative of the historical incident data set and simultaneously not overly large in number so as to induce extensive computational burden. This is accomplished through the estimation of incident property distribution functions based on historical data. These distributions are integrated with a non-stationary Poisson random

variate generation process to produce a relatively small set of representative incidents for simulation and derivation of benefit estimates.

The three-stage analysis process involving the P-BIG procedure is applied along with comparable procedures employing all historical incidents and sets of randomly chosen incidents from this historical incidents in evaluating the benefits of a TIM program, the New York State H.E.L.P. Program, for the purpose of assessing the proposed procedure's predictive power. Results of these experiments show that the three-stage process employing the P-BIG procedure results in benefit estimates within 5% of the value derived employing all historical incidents, while requiring only 18% of the computational effort. By contrast, when a similar procedure is applied using randomly selected incident scenarios, nearly double the number of incidents must be replicated to achieve comparable estimates. Details of the three-stage process and embedded P-BIG procedure, incident property analyses and assessment of the simulation results are provided in Chapter 5.

1.2.3 The Impact of Violations in Computational Assessment of Non-barrier Separated Managed Lanes

Concurrent flow lanes employing non-barrier separation methods permit nearly unlimited improper ingress/egress to/from the managed lanes. These violations impact the free-flow speeds of both managed and general lanes. Additionally, violations have a negative impact on revenue. To assess the impact of traffic violations, frequently observed types of violations along such freeway facilities as non-barrier separated managed lanes are considered: (1) carrying fewer people than the minimum occupancy required (i.e. vehicle occupancy violations); (2) abruptly merging out from the managed lane to the general purpose lane where such a merging maneuver

is prohibited to avoid paying a toll or an area of police enforcement; and (3) entering or leaving the HOT lane at points where access is denied. The importance of violations has been mentioned in many concurrent flow lane studies. However, the impact on mobility, safety and other performance metrics has not yet been quantitatively analyzed. To address this issue, simulation techniques for analyzing violation behavior are developed and implemented on an existing simulation platform, a seven-mile I-270 freeway segment in Maryland with non-barrier separated concurrent flow lane design. The impact of violations on traffic mobility and other performance metrics are quantified.

To assess the impact of violations on safety, particularly as it relates to the potential for collision between vehicles in the system, a technique is developed that relies on the time-space contour map of traffic flow. The contour maps are applied to identify possible locations of increased collision likelihood. These locations are expected to arise along regions of discontinuity in traffic flow along the freeway. The relationship of congestion to increased likelihood of incident as a consequence of violations is developed by analyzing speed time-space contour maps based on simulation runs. Findings from this analysis also contribute to the selection of enforcement strategies. Details of this violation analysis, simulation modeling techniques, and quantitative analyses of violation impact on mobility, safety, and other performance metrics are presented in Chapters 6 and 7.

1.2.4 Development and Analysis of Traffic Diversion Strategies for Concurrent Flow Lane Operations in the Event of an Incident

When incidents occur along a freeway where concurrent flow lanes are operated, diversion strategies may be required. When a serious incident occurs within the general purpose (GP) lanes,

queues will build. If vehicles (regardless of classification in terms of managed lane usage permission) driving in the GP lanes are permitted to temporarily use the managed lane, greater capacity for discharging the queues can be attained, thus mitigating incident impact. Additionally, in the event of an incident arising in a non-barrier separated HOV and HOT lane facility, it is also possible to permit vehicles in the managed lane(s) to cross buffers, thus, diverting traffic from the managed lane(s) to the GP lanes at locations other than normally permitted access points. These and other diversion strategies are studied. A simulation-based platform is developed to assess the proposed strategies. This platform builds directly on an already developed and fully calibrated set of models of existing and proposed managed lane facilities along a segment of I-270 in Maryland. Given different incident properties and prevailing traffic conditions, the effects in terms of savings in travel delay due to the diversion strategies are quantified. Additionally, degradation in service level incurred by traffic using the managed lanes as a consequence of the implementation of a proposed diversion strategy is predicted, allowing trade-offs in performance of GP and managed lanes to be identified. The proposed diversion strategies, evaluation framework, and assessment results are provided in Chapter 8.

In addition to these main considerations, contributions of this dissertation are also derived from a comprehensive study of literature on incident impact, incident management programs and their benefit analyses (Chapter 2), as well as application of such concepts to the study of an actual TIM program, the H.E.L.P. freeway service patrol program in New York State, and six months of incident data from four freeways (Chapter 3).

1.3 Dissertation Organization

The remainder of this dissertation proposal is organized in seven chapters. Chapter 2 presents a literature review of methodologies for incident impact and delay analyses, various TIM programs, and related benefit evaluation studies. These concepts are employed and illustrated in a comprehensive study of incident data and benefits of an actual TIM program in Chapter 3. Chapter 4 proposes the SBSIF method for filtering secondary incidents. In Chapter 5, the three-stage time-saving analysis process for conducting benefit evaluations of TIM programs is described. In Chapters 6 and 7, the impact of violations on mobility and safety in non-barrier separated freeway facilities is analyzed, respectively. Chapter 8 proposes traffic diversion strategies and a structure for their analysis (along with its application on an actual roadway segment) for concurrent flow lane facilities in the event of an incident. Conclusions and extensions are provided in Chapter 9.

Chapter 2: Literature Review

Incidents have negative impacts on roadway facilities; TIM programs are widely implemented as a means of mitigation. To explain the role of incidents, Section 2.1 provides an overview, including: a general discussion of their possible causes, the rate at which they occur, and their impact on safety and mobility. TIM programs can manage this impact from various perspectives, such as reducing incident duration, controlling traffic demand around the incident scene, and increasing discharge capacity for the affected traffic in queue. To understand the mechanism by which TIM programs mitigate the impact of incidents, state-of-the-practice TIM programs are reviewed in Section 2.2. Various benefits that can be achieved through the implementation of a TIM program, together with a synopsis of the methodologies used to estimate incident delay, are reviewed in Section 2.3.

2.1 Overview of Freeway Incident

2.1.1 Incident Definition and Classification

Freeway incidents are non-recurrent events that cause a reduction of roadway capacity or an abnormal increase in traffic demand, such as collision accidents (fatalities, personal injury or property damage), stalled vehicles (overheating, flat tire or out of gas), debris, fire, construction and sporting events (FHWA, 2000). Various criteria, such as planned/unplanned, emergency/non-emergency, severity level, incident type or duration, have been used to classify incident events in the literature. The commonality across these incident classifications is that incidents will impede normal traffic operation. Thus, any event that will impede the stability of traffic operations can be viewed as an incident. From this standpoint, an event as short as a

moving violation (e.g. improper lane change, aggressive or unexpected maneuver) or as long as a work zone along a freeway can be viewed as an incident. Moving violations lead to excessive lane changing and car following maneuvers in traffic flow. Such maneuvers will lead a steady state of traffic flow operation oscillating (stop and go or slow and go traffic conditions) (Zielke at al, 2008). Work zones often block certain portion of the traffic lane for a period of time and cause the traffic demand exceeding the capacity. Typically, people associate freeway incidents with accidents and disabled vehicles along the freeway. In fact, these two incident classes compose more than 90% of incidents along the freeway (FHWA, 2000).

Incidents have both temporal and spatial characteristics. From the temporal point of view, incidents arise over time and may vary in number and type as a function of the season, day-of-week, and time-of-day. A general incident timeline figure (e.g. provided in the Freeway Management and Operation Handbook as depicted in Figure 2-1) reveals that incident durations can typically be separated into verification, response, clearance and recovery time periods by recording timestamps at various stages of an incident (FWHA, 2003). From a spatial perspective, incidents arise on each of the roadways. They arise at various locations along these roadways and may lead to the blockage of one or more lanes of traffic.
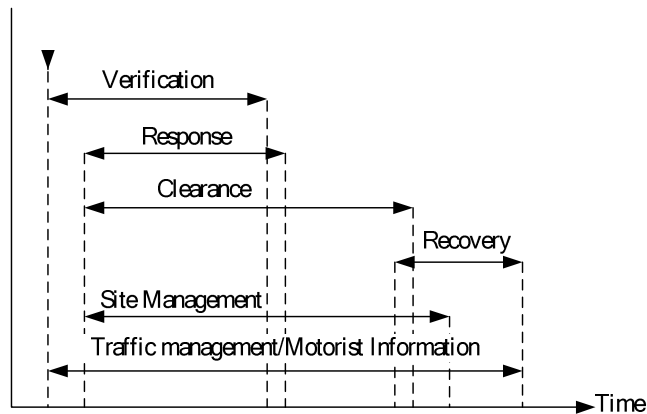
Figure 2-1: Incident and TIM program timeline (source: FHWA, 2003)

2.1.2 Incident Frequency and Distribution

The frequency and distribution of incidents, including their severity level, type, and duration, varies from one roadway to another and from state to state. For example, in the small state of Maryland between 2002 and 2007, there were between 32,000 and 42,000 incidents involving a collision or disabled vehicle in which assistance was requested arising along the major freeways and a subset of arterials (Chang and Rochonm, 2008). In a study of a 3-lane, 10-mile stretch (both directions) of the I-287 freeway in New York State, more than seven incidents occurred daily (Chou et al., 2009). Although the total number of incidents that occur nationwide annually is not reported in the literature, those cases involving fatalities are better documented (FARS's website, 2009). Statistics show that 37,261 fatal collisions occurred during 2008. Applying nationwide the 0.6% of fatal incident class distributions among three types of accidents involving collision (i.e. fatality, injury and property-damage-only (PDO)) found in Kansas and Nebraska State in 2003, the estimation for incidents involving collision might be more than 6.2 million. Note that the fatal, injury, and PDO collisions accounts for 0.6%, 31.7% and 67.7% in Nebraska, respectively (NDOR, 2003) and 0.6%, 22.7% and 76.7% in Kansas State (2003). As accidents only represented 10% of total recorded incidents, and recorded incidents 70% of all incidents (FHWA, 2000), an estimation of total incidents nationwide would rise to 80.6 million. The estimation can be updated through the distribution tree as depicted in Figure 2-2.

Sources:
1:Freeway Management Handbook, 2000
2:Kansas Department of Transportation, 2003
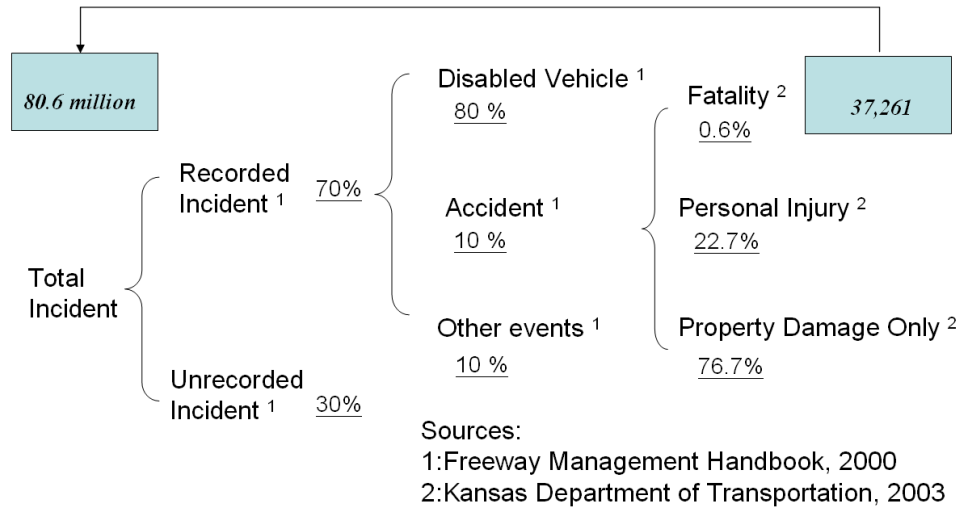
Figure 2-2: Estimation of total incidents in the U.S.

2.1.3 Causation of Incidents

Incidents result from complex interactions among driving behavior, vehicle mechanical fatigue, environmental factors and their combined effects. Rumar (1985) analyzed British and American crash reports data and found that 57%, 3% and 2% of crashes were due solely to driver, roadway and vehicle factors, respectively. The remaining 38% of crashes were due to compound factors, including 27% driver and roadway, 6% vehicle and driver, 1% roadway and vehicle, and 3% combined roadway, driver and vehicle factors as depicted in Figure 2-3.
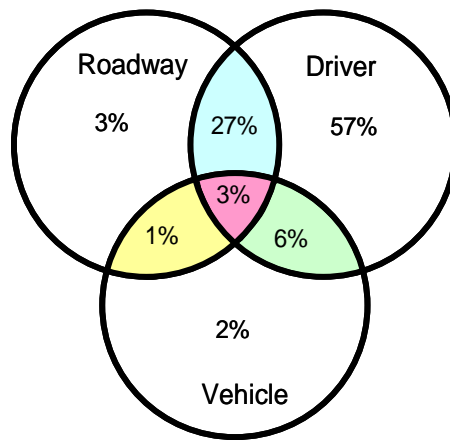
Figure 2-3: Incident factor compositions (Source: Rumar, 1985)

2.1.3.1 Driving Behavior

Driving behavior contributes to 94% of all accidents. Many factors related to the reduction of driving capability and the modulation of risk-taking while driving are identified by Petridou and Moustaki (2000) through a comprehensive review of human factors in the causation of road traffic crashes. For example, inexperience, old age, disease and disability, drug and alcohol, drowsiness, and fatigue are factors affecting driving capability. The overestimation of driving capacity, habitual speeding and disregard for traffic regulations, aggressive driving behavior, motor vehicle crime, suicidal behavior and compulsive acts are also considered high-risk activities. These factors affect driving behavior and are associated with higher probability of crash occurrence.

2.1.3.2 Equipment Failure

Although the occurrence of equipment failure contributes to only 12% of all accidents, it is a main factor leading to disabled vehicles along the roadway system, which accounts for 70% of all reported incidents along the roadway system (FHWA, 2000). Common mechanical failures include the loss of brakes, tire blowouts, tread separation and steering/suspension failure.

2.1.3.3 Roadway Design and Environment

Driving involves a series of driver reactions to roadway design and the traffic environment. There are numerous studies focusing on the accident rate and its relationship to roadway design or environment. From the environmental standpoint, inclement conditions can lead to reduced visibility or difficulty breaking. Thus, snow, ice, wind, rain or foggy weather affects accident rate (Elvik, 2006). A broader concept of roadway design includes not only the geometry or pavement of a facility, but also various traffic control devices (e.g. signal, marking, signs and speed control

bumpers). In addition, roadway design is part of a compound factor leading to traffic incidents, as it intersects with vehicle factors and driver behavior. Thus, proper maintenance, such as removing debris along the roadway or filling potholes in the road, is critical for improving safety.

2.1.4 Incident Impact

Once an incident occurs, it may reduce roadway capacity, induce traffic congestion and degrade service quality. The induced traffic congestion may also cause secondary incidents. In addition, from the standpoint of energy usage and environmental impact, as travel delay increases, so do the rates of fuel consumption and emissions.

2.1.4.1 Mobility Impact

When a freeway incident occurs, roadway capacity is reduced. The level of change in the quantity of capacity reduction depends on the number of lanes blocked. Estimated capacity reduction for a given lane blockage scenario is shown in Table 2-1(HCM, 2000).

Table 2-1: Percentage of available freeway capacity

Number of lanes	Shoulder (disabled vehicle)	Shoulder (collision)	1 lane blocked	2 lanes blocked	3 lanes blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

The severity of mobility impact due to the reduction of capacity is a function of travel demand. Not until the traffic demand exceeds the capacity (i.e. V/C ratio greater than one) will motorists encounter obvious mobility impact. Statistically, in the United States, non-recurrent

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congestion caused by various incidents is estimated to be as high as 60% (Lindley, 1987) of total congestion. While this estimate varies by roadway and city, as well as the measurement technique employed for its computation, its significance has been noted in numerous studies (see also Skabardonis et al., 2002; Schrank and Lomax, 2007). A recent report on urban mobility shows that this estimate ranges from 52 to 58% of total congestion (TTI, 2009).

For short event incidents, such as moving violation or unexpected driving maneuver, that do not involve lane blockage, a traffic flow characteristic map can be applied to identify their impact on mobility. Such impact might not be obvious at the location where the maneuver is taken place, but will propagate to the upstream traffic and become obvious. For example, Sugiyama et al. (2008) conducted an experiment showing that a short breaking event in a stable traffic environment will have impact on the upstream traffic, propagating congestion as depicted in Figure 2-4.
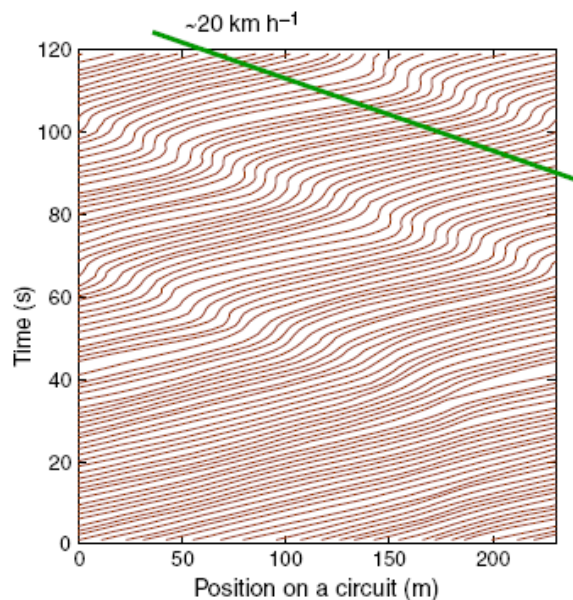
Figure 2-4: Impact from sudden break to upstream traffic (Source: Sugiyama et al., 2008)

2.1.4.2 Safety Impact

Safety concerns apply both to the personnel who handle incidents and to secondary crashes. In 2002, approximately half of police, emergency medical service (EMS), and firefighter fatalities occurred as a result of transportation incidents. Vehicles striking workers represented about 10% of firefighter and nearly 8% of police officer deaths (NTIMC, 2002). In addition, 2% of total fatalities (i.e. 720 out of 37,261) in motor vehicle crashes nationwide in 2008 were associated construction/maintenance zones (workzonesafety.org, 2009).

When incidents disturb steady state traffic conditions and create traffic oscillations, the likelihood of crashes increases (Zheng, 2009). Secondary incident are collisions resulting from abrupt changes in traffic flow conditions caused by prior traffic incidents. A study conducted by Raub (1987) shows that about 15% of crashes may have been caused by an earlier incident. Secondary incidents cause approximately 18% of all freeway deaths according to Brach (2008).

2.1.4.3 Environment

Vehicle emissions account for approximately one-half of total hydrocarbons (HC) and nitrogen oxide (NO) emissions, and two-thirds of total carbon monoxide (CO) emissions (Rouphail et al., 2001), which negatively impact the environment. A large portion of this total may be incident-related, because vehicle emissions increase dramatically during the time period when incidents exist and cause queueing of traffic congestion. Salimol (2007) estimated that an incident on average would result in increases of 138% in CO, 500% in VOCs (i.e. volatile organic compounds), 26% in NO_x (i.e. oxides of nitrogen) and 43% in $PM_{2.5}$ (i.e. particulate matter less than 2.5 microns) emissions relative to those produced during normal traffic operations. Several studies have provided measures or models for converting traffic performance

metrics or travel delay to equivalent emissions or fuel consumption. For example, the Environmental Protection Agency developed a regional-based MOBILE6 model for converting vehicle emission and fuel consumption to emissions of reactive organic gases (ROG), CO, and NO_x as a function of ambient temperatures, travel speeds, operating modes, fuel volatility, and mileage accrual rates (US EPA, 2010). MOBILE6 was used in estimating the benefit and cost of a TIM program in Virginia (Dougald, 2007). CHART provided a set of simplifying conversion factors to compute HC, CO and NO emissions: 13.073, 146.831, and 6.261 grams per hour delay, respectively (Chang and Rochon, 2006).

2.1.4.4 Other

In addition to the common effects described previously, some types of incidents have other economic impacts. Blincoe et al., (2000) divided the total economic impact of crashes into several components: 26% in market productivity, 26% in property damage, 14% of medical care, 11% in travel delay, 9% in household productivity, 7% in insurance administration, 5% in legal cost, 2% in workplace cost and about 1% in emergency services.

2.2 Traffic Impact Management (TIM) programs

Because the occurrence of traffic incidents on freeways is unavoidable, traffic incident management (TIM) programs are launched to mitigate the impact of incidents and have been widely employed throughout the world. In Section 2.2.1, examples of TIM programs are introduced. Different means of mitigating incident impacts are summarized in Section 2.2.2.

2.2.1 Various TIM Programs

Examples of TIM programs include: Freeway Service Patrol (FSP), automatic incident detection, ramp metering, incident site management, variable/dynamic message sign (VMS/DMS) advisory assistance and route diversion. Such programs aim to mitigate incident impact through quick response, thereby shortening incident duration, or controlling traffic demand around the incident scene. These programs can be integrated or stand alone.

2.2.1.1 Freeway Service Patrol

Freeway service patrols (FSPs) are continuously roving vehicles whose purpose is to quickly respond to incidents along freeway segments by providing necessary assistance, such as changing a tire, providing coolant for overheated vehicles, or assisting with minor repairs, and to make primary notification of an incident requiring troopers or another emergency service response. Thus, FSP programs, in addition to assisting distressed motorists, aid in mitigating the impact of traffic incidents on traffic flow by shortening incident duration. Additionally, FSP vehicles act as probe vehicles, providing feedback on traffic conditions.

2.2.1.2 Automatic Incident Detection

Automatic incident detection (AID) systems employ detectors and a mathematical algorithm to detect the occurrence of incidents. Though AID systems continuous to evolve, the five major types developed during the 1970s and 1980s persist: (1) pattern recognition, (2) statistical processing, (3) catastrophe theory, (4) neural networks, and (5) video image processing (Sheu, 2002). The aim of AID systems is to detect incidents in the earliest possible stage.

2.2.1.3 Ramp Metering

Although ramp metering is typically used in dealing with recurrent congestion, it is also beneficial to the management of incidents. This method works by temporarily closing selected upstream freeway on ramps and reducing traffic demand in the vicinity of the incident scene. Key issues in implementing ramp metering for incident management are how many ramps should be closed and the closure duration (Boyles et al., 2009). Once ramps are closed, traffic demand upstream can be controlled and incident impact can be decreased.

2.2.1.4 Incident Site Management

Site management at the incident scene is a process of coordinating and managing resources to handle incidents. Several activities need to be conducted at the incident scene, including accurately assessing incidents, properly establishing priorities, notifying and coordinating appropriate agencies and organizations, using effective liaisons to other responders, and maintaining clear communications (FHWA, 2000). While incidents block freeway main lanes, and collision investigations or emergency services are in process, the impact area can be controlled/managed to ensure the functionality of the roadway facility at a higher service level through the use of appropriate incident site management strategies.

The "Move-it" program (I-95 Corridor Coalition, 2008) is applied in several states at incident sites. This program requires or encourages drivers involved in a minor accident (i.e. with no injuries) to remove vehicles involved in a crash and associated debris out of the roadway so that the roadway can remain functional. Another similarly titled program is the "Move-over" law. It has been found to be effective in many states. The law requires motorists to yield right-of-way for emergency vehicles and to slow down while approaching or passing a traffic incident scene.

Thus, it ensures quicker response by emergency services to incident sites and also enhances the safety of the personnel and drivers involved in incident remediation (NTIMC website, 2010).

2.2.1.5 Variable/Dynamic Message Signing (VMS/DMS) and Media Advisory Assistance

VMS and Highway Advisory Radio (HAR) systems send critical roadway information on congestion, incidents, work zones, and speed limits to roadway users. For incident management, VMS systems, equipped with mobile or fixed units along roadways, send incident information to roadway users who are at the incident scene, approaching the scene or are planning to use an affected route. HAR broadcasts such information by radio. These programs can reduce traffic demand around the incident scene. Huo and Levinson (2006) compared the detector output for a VMS study and found that approximately 13 to 15% of travel demand can typically be diverted. In addition, numerous local internet resources provide real-time traffic incident information to assist motorists in planning trips, such as 511.org, for the San Francisco Bay area in California and chart.state.md.us for the State of Maryland.

2.2.1.6 Route Diversion

When incidents severely limit the roadway capacity, motorists will naturally find alternative routes to divert around the incident once they are given information pertaining to the incident. Preplanned diversion strategies typically utilize arterials extending parallel to the freeway or concurrently operated lanes, such as toll way and /or a high-occupancy vehicle facility. A detailed discussion of types of diversion scenarios, planning processes, selection criteria for choosing alternative routes, deployment decisions for developing a diversion plan, methods to detect incidents, resources to inform and guide motorists, and benefits associated with route diversion across the nation can be found in a survey by Dunn et al. (1999).

2.2.2. Effects of TIM Programs

Different TIM programs seek to tackle the impacts of incidents from various perspectives, such as reducing incident duration or detection time, and controlling traffic demand around the incident scene. Table 2-2 summarized the effects of TIM programs in reducing incident impact.

Table 2-2: TIM program effects

TIM program	Main effects
Freeway Service Patrol	Reduce Incident duration
Automatic Incident Detection	Reduce Incident duration
Ramp Metering	Control traffic demand
Incident Site Management	Reduce incident duration and control the number of lane blockage
Variable/Dynamic Message Sign and Media Advisory Assistance	Control traffic demand
Route Diversion	Control traffic demand

2.3 Methodology for Estimating Incident Delay

Incidents have various impacts as described in Section 2.1.4. As TIM programs can tackle incident impacts through reducing incident duration, reducing affected traffic demand, or increasing discharged capacity at the incident site, the benefits of TIM programs can be assessed by the reduction in such impact that the program achieves. For example, many FSP programs evaluated their programs' benefits in terms of savings in travel delay, fuel consumption and emissions, or extended such analyses to include safety benefits of reducing potential secondary incidents (e.g. Chang and Shrestha, 2000; Guin et al., 2007; Latoski et al., 1999; and Yang et al., 2007). Many of these benefits can be derived through computing and converting the travel delay affected by an incident. As delay is the key component in understanding incident impact, in this section, three typical methodologies that are widely used for estimating incident delay are reviewed.

2.3.1 Queueing Models

Figure 2-5 depicts a fundamental queueing diagram for computing incident delay (May, 1998). The area between the arrival and departure curves represents delay. Several inputs, including traffic demand, incident duration, and original and affected freeway capacities, are needed to compute delay. Note that such inputs are assumed to be constant in the figure. This model does not consider the stochastic attributes of traffic. Once the affected capacity changes as time evolves (e.g. a portion of the closed lanes re-opens), the queueing model approach for estimating travel delay needs further reversion. (see Li et al. (2006) for more detail).
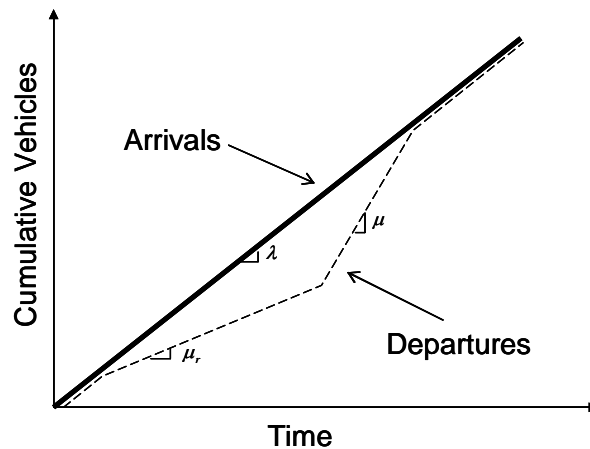
Figure 2-5: Queueing model for computing incident delay

2.3.2 Travel Time (Speed) Difference Models

Skabardonis et al. (1995) proposed a method to compute delay based on the difference in travel time between incident and incident-free scenarios. This method relies on deploying loop detectors at close intervals along a freeway as depicted in Figure 2-6. Three various sources are discussed in (Skabardonis et al., 1998) to capture the speed profile during an incident: (1) loop detector measurement of speed and flow, (2) probe vehicle speeds and loop detector flows, and

(3) probe vehicle travel time-based delay. Input for implementing this method include: (1) incident location, (2) incident duration, and (3) incident influence area identification.
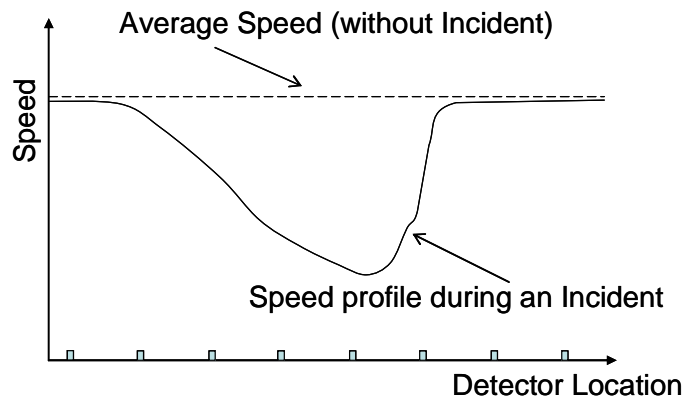
Figure 2-6: Speed difference approach for computing incident delay

The accuracy of delay estimation depends on the increment of the analysis slice in time and space. The choice for incident-free average speed, which is used for comparison, also affects the estimation results.

2.3.3 Simulation Approaches

Simulation techniques are often applied to evaluate traffic operations. Macroscopic, mesoscopic and microscopic models examine traffic operations on different scales. Macroscopic models capture the relationships between flow, speed and density characteristics of traffic, but do not characterize individual vehicle movements. Microscopic techniques apply car-following and lane-changing behavior models to replicate the decisions and movement trajectories of individual vehicles and their response to other vehicles, incidents and geometric design. Mesoscopic models capture traffic operations between macro and micro levels. Among these techniques, microscopic simulation models are particularly popular in many traffic operation studies, because they

provide a user-friendly interface to revise traffic attributes, and the results are often easily understood by experts and laypeople alike. Several studies that analyze the impact of TIM programs adopt simulation-based techniques to estimate travel delay (e.g. CHART (Chang and Rochon, 2006) and FIRST (MNDOT, 2004) program evaluations). To apply the technique, a simulation platform with calibrated parameters must be developed to fit local traffic operations. Once the simulation model is developed and calibrated, it is relatively easy to conduct a sensitivity analysis of affected factors as compared to other methodologies. Simulation models typically cover a wider range of study area and can capture impacts upstream of the incident. On the other hand, the queueing and travel time difference models, confine incident impact to a relatively small area (i.e. only the vicinity of the incident). Although simulation is a popular approach for estimating incident delay, it can be quite time-consuming. Thus, many studies utilize results from a set of simulation runs to develop regression models. Both linear and non-linear regression models developed from simulation results have been proposed (e.g. Chang et al. (2000) and Cambridge Systematics Inc. (1998)) for estimating incident delay.

2.4 Summary

To achieve the goals of this dissertation, comprehensive details of a case study are presented in Chapter 3. While specific to one TIM program, this case study is provided to illustrate the various aspects of TIM program evaluation, as well as the significance of incident occurrence and the import of quick response. As illustrated in the case study of Chapter 3, evaluation of TIM programs requires a methodology for estimating travel delay due to incidents and a method for identifying secondary incidents from incident archives. The Simulation-Based Secondary Incident Filtering (SBSIF) methodology is proposed in Chapter 4 for identifying secondary

incidents from a database. In Chapter 5, a technique that reduces the computational burden associated with estimating travel time delay impacts of incidents, and reductions in their impact due to incident response and management via microscopic simulation, is proposed. The dissertation also considers incidents and incident management strategies associated with concurrent flow lane operations. In particular, moving violations specific to concurrent flow lane operations are conceived as a type of transient incident. Their impact on mobility and safety is considered through the study of lane changing and car following maneuvers in a simulated freeway environment. No attempt was previously made to quantify their impacts. In Chapters 6 and 7, the mobility and safety impacts from moving violations along a freeway operating concurrent flow lanes were investigated. The role of a TIM program that exploits excess capacity in managed lanes to mitigate general purpose-lane incident impact is explored in Chapter 8.

Chapter 3: Benefit-to-Cost Analysis of a FSP program - An Illustrative Case Study

3.1 Introduction and Background

In the United States, it is estimated that nearly 60% of non-recurrent freeway congestion is caused by incidents (Lindley, 1987). Incidents cause most of the non-recurrent freeway congestion in the United States. This non-recurrent congestion negatively impacts safety and mobility. It induces enormous delay for travelers and results in secondary incidents, which cause approximately 18% of all freeway deaths according to Brach (Brach, 2008). Moreover, traffic congestion results in the unnecessary use of fuel and the emission of dangerous pollutants. To mitigate the impact of incidents along freeways, Freeway Service Patrol (FSP) programs have been introduced nationwide.

Ideally, to evaluate the benefits of a FSP program, a "before-and-after" study would be conducted. However, in most locations, the necessary data to establish a "before" benchmark is not available. Thus, most studies of these programs are completed through comparisons between responses to incidents involving or not involving (i.e. with and without) FSP vehicles. Examples include, among others, evaluations conducted in Minnesota (2004), Florida (2005), Maryland (2006), Georgia (2007) and Northern Virginia (2008).

Deterministic queueing models were employed to study travel delay savings due to the Traffic Incident Management (TIM) program in Georgia (Guin et al., 2007). The estimated savings in travel delay provided input for analytical models developed to estimate corresponding savings in emissions, fuel consumption and secondary incidents. This queueing modeling approach to FSP program evaluation requires data pertaining to traffic volumes prior to, during,

and after each traffic incident for travel delay estimation. The Freeway Service Patrols Evaluation (FSPE) package used a macroscopic approach to evaluate the benefits of the Road Ranger and Northern Virginia Safety Service Patrol (NOVA SSP) programs in Florida (Hagen et al., 2005) and Virginia (Dougald and Demetsky, 2008) in terms of savings in travel delay, fuel consumption and pollution.

Where required traffic volume data are unavailable or detailed analysis is needed, microscopic simulation-based methods may be preferred. Such methods can predict performance while modeling real-world variability in problem parameters. If real-time traffic data had been collected just prior to and throughout the recovery period of each incident in the study period, actual travel delay can be estimated. Since such real-time data are not typically available, simulation is often used to approximate actual conditions. For example, regression models for estimating travel delay and fuel consumption were created from simulated runs (employing the CORridor SIMulator (CORSIM) simulation platform) of a chosen set of 120 of 1,997 incidents stored in a data archive to study the Coordinated Highways Action Response Team (CHART) program in Maryland (Chang and Shrestha, 2000). The authors provide few details of the simulation technique or the selected 120 incidents. Savings in emissions were estimated based on travel delay savings. The emissions rates as a function of travel delay were provided by the Maryland Department of Transportation (Chang and Rochon, 2006).

Hundreds of simulation runs of representative incidents with varying incident duration (0 to 40 minutes) and lane blockage characteristics were completed using the Paramics simulation platform to analyze Minnesota's Freeway Incident Response Safety Team (FIRST) program (MNDOT, 2004). Total delay and volume computed from the simulation runs were plotted against each other to establish how one varies with the other. This plot was used to estimate

delays resulting from actual incidents in an archive of incident data and resulting savings in delay due to the FIRST program. Reduction in environmental pollution and secondary incidents resulting from this program were estimated based on rates of pollution and secondary incidents as a function of travel delay and total incidents, respectively, provided in the literature.

Haghani et al. (2006) proposed a similar simulation-based methodology using the CORSIM simulation platform to estimate savings in travel delay, fuel consumption, pollution emissions and secondary incidents. They conducted a sensitivity analysis of performance measures and key parameter settings, such as incident duration, traffic volume, car-following sensitivity factors, and rubbernecking effects, and developed regression models to predict the benefit-to-cost ratio as a function of volume-capacity ratio, rubbernecking effect, and potential reduction in total incident duration. A key finding of their work is that a traffic flow rate of at least 1,500 vehicles per lane per hour provides a significant indicator for the benefits of the FSP program to outweigh its costs.

A simulation-based methodology that builds on the general technique developed in (Haghani et al., 2006), as well as other simulation-based works (Chang and Shrestha, 2000; MNDOT, 2004), to estimate the benefits of a FSP program is employed herein. This methodology is used to assess a FSP program, the Highway Emergency Local Patrol (H.E.L.P.) program, operating within New York State. The H.E.L.P. program runs service patrol vehicles along a portion of the I-95 Corridor in the Lower Hudson Valley region of New York. It operates eight hours per day (during weekday morning and evening peak periods). Segments of four roadways, I-287, I-684, the Taconic State Parkway and the Sprain Brook Parkway, were considered within the analysis. Incidents arising along these roadway segments during a six-month period (January 1, 2006 through June 30, 2006) were studied. The reduction in

incident duration due to the execution of the H.E.L.P. program was estimated through a statistical comparison of incident durations resulting from response by troopers or H.E.L.P. vehicles. Hundreds of incidents that arose along a segment of I-287 were replicated and benefits in terms of reduced travel delay, fuel consumption, emissions, and secondary incidents were estimated. The monetary equivalent of these savings was computed to obtain an estimate of the benefit-to-cost (B/C) ratio. A set of B/C ratios are provided for a range of average incident duration savings that might result from a comparable FSP program operating on a roadway with similar geometric characteristics to that considered in the study. Haghani et al. (2006) conducted a related, but significantly less comprehensive, study of this H.E.L.P. program. Their findings provided an initial starting point for this work.

This analysis provides (1) important findings from statistical analyses of nearly 10,000 incidents arising along four roadway segments over a six-month period in a major metropolitan area within the United States, including estimated savings in incident duration due to the responsible FSP program; (2) details associated with the proper handling of key parameters of the simulation model; and (3) benefit-to-cost estimates by potential average incident duration savings for the studied roadway with sufficient detail to permit other programs operating along roadways with similar geometry to complete similar estimates for their own programs. Description of the procedure employed herein is limited to the specific details that are unique to this study and facets of the approach required to provide comprehensive depiction of the steps of this work.

3.2 Incident Data Analysis and Incident Duration Savings

FSP programs exist in New York State. Figure 3-1 shows the service regions and constituent beat

formations for the Hudson Valley area. This study considers portions of Beats 8-2, 8-3, and 8-5. Incident data pertaining to freeway segments along which the H.E.L.P. program operates are stored and maintained in three different databases: HTECAD (HTE's Computer-Aided Dispatch (CAD)), ATMS (the Traffic Management Center's Transcommander software from Northrup Grumman), and TWAY (Thruway's Tiburon CAD). Consequently, the data reporting procedures and information recorded under each incident varies as a function of which database it is entered in. Incidents reported in more than one database were identified, incident attributes were combined (since different information was stored in each database), and the duplicate data were removed. The technique of matching the data across databases required buffers in both time and space, because a single incident may be recorded at a slightly different location or time as a function of the database to which it was entered and device used in entering the data. After extensive experimentation, buffers of 30 minutes and 0.3 miles were employed in creating a single, integrated database. Table 3-1 summarizes the frequency of incidents along segments of Taconic State Parkway, Sprain Brook Parkway, I-684 and I-287 after removing 2,968 duplicated incident records. During the study period, 9,765 incidents involving disabled vehicles and collisions arose along the study roadway segments, of which 5,919 (61% of all incidents) arose during H.E.L.P. hours of operation and 4,732 were assisted by H.E.L.P. vehicle drivers.

While the H.E.L.P. vehicle drivers sometimes assisted with incidents that arose outside normal hours of operation, only those events arising during the H.E.L.P. hours of operation (i.e. during the rush hours) were considered in performance analysis of the H.E.L.P. program. The potential savings from the H.E.L.P. program were estimated by comparing incidents between categories of "H.E.L.P. only," "Police only," and "Both," results of which are shown in Table 3-2.

Figure 3-1: H.E.L.P. program Beat 8 operation area
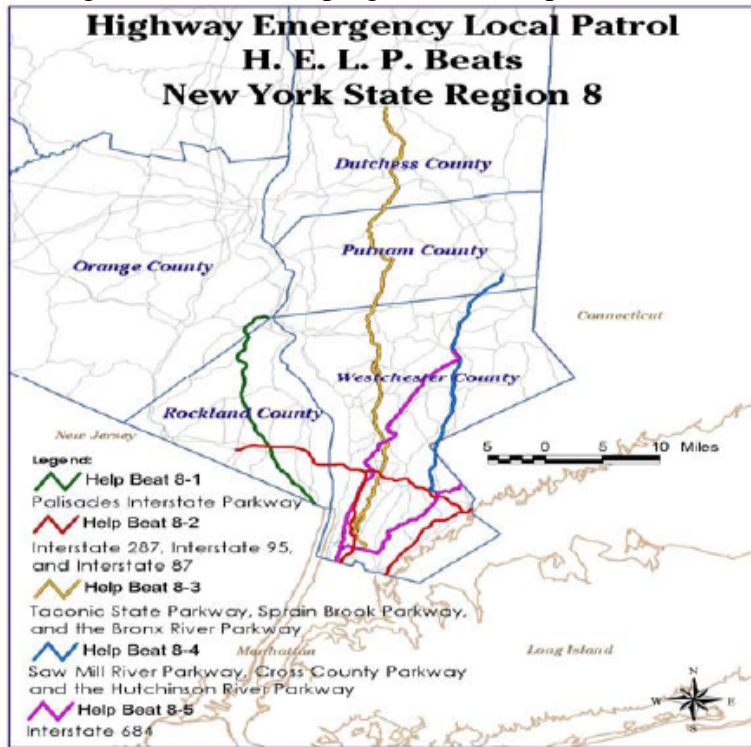
Table 3-1: Incident frequency

	H.E.L.P. only	Police only	Both	Total
Taconic State Parkway (34 miles in each direction)	1,311	2,057	123	3,491
Sprain Brook Parkway (14 miles in each direction)	1,445	1,097	121	2,663
I-684 (29 miles in each direction)	881	1,242	158	2,281
I-287 (10 miles in each direction)	642	637	51	1,330
Total	4,279	5,033	453	9,765

* "Police only" calls received response only from state troopers. "H.E.L.P. only" calls received assistance only from H.E.L.P. vehicle drivers. "Both" calls received assistance from both H.E.L.P. vehicle drivers and troopers.

Table 3-2: Incident duration comparison for responding groups

	H.E.L.P. only			Police only			Both		
	Total Freq.	Avg. duration	%	Total Freq.	Avg. duration	%	Total Freq.	Avg. duration	%
MV accident	251	32.72	20%	654	53.47	53%	322	53.5	26%
Disabled vehicles	3,855	16.55	82%	748	35.12	16%	89	37.57	2%
Total	4,106	17.53	69%	1,402	43.68	24%	411	50.05	7%

One of the main roles of the H.E.L.P. program is to assist in incidents involving disabled vehicles. It was noted that on average more than 82% of these incidents arising during the H.E.L.P. hours of operation were handled by H.E.L.P. vehicle drivers alone. The remaining such incidents were handled by state or local troopers or both H.E.L.P. vehicle drivers and troopers. The program also assisted more than 46% of the incidents involving collision. In a comparison of average times to assist in incidents across the studied roadway segments between cases handled by either only H.E.L.P. vehicle drivers or only troopers, average savings of approximately 20 minutes in incident duration for incidents involving a collision and 19 minutes for incidents involving a disabled vehicle were found when the incidents were handled by the H.E.L.P. vehicle drivers. These average values ranged from 7 to 45 minutes for incidents involving a collision and 11 to 33 minutes for incidents involving disabled vehicles over the four roadway segments. While significant, it must be noted that the incidents handled by H.E.L.P. vehicle drivers require less assistance duration than typical incidents handled by troopers alone.

3.3 Simulation-Based Methodology for Travel Delay and Fuel Consumption Estimation

The CORSIM simulation platform is a discrete-time and stochastic based microscopic simulation platform designed specifically to model traffic operations. It estimates travel delay through travel time comparisons of traffic operating at free flow speeds as compared with speeds resulting from vehicle interactions that result from congestion. It also estimates fuel consumption by tracking the performance of individual simulated vehicle speed and acceleration rates with a standard fuel consumption rate table developed by Oak Ridge National Laboratory (Davis, 1999). As is the case with most simulation tools, behavior that cannot be predicted with certainty is replicated

from random variates employed to model stochasticity in the behavior. Multiple replications must be conducted. Five replications were used herein, consistent with recommendations in (Haghani et al., 2006). As the CORSIM simulation model is run and traffic conditions are replicated, a set of traffic measures, including incident properties and associated factors (incident onset and duration, location, capacity reduction and lanes impacted as a consequence of the rubberneck effect, warning sign location (e.g. a flare), and lane closure status) are recorded.

To analyze the impact of an incident on travel delay and fuel consumption in this simulation platform, four stages are considered, as portrayed in Figure 3-2. In the first stage, prior to the incident, traffic flow is assumed to be stable. At the onset of the incident (stage 2), shoulder and/or freeway lanes may become blocked and capacity along these lanes is nearly instantaneously impacted. In stage 3, it is assumed that a warning sign is set up for warning the upstream traffic (or that the upstream traffic can discern that an incident has arisen a short distance prior to coming into contact with the incident). Drivers passing by the incident scene may reduce their speed to observe the incident, creating the so-called rubbernecking phenomenon. Upon clearance of the incident, normal traffic flow conditions are re-established. Details of specific components of this four-stage incident modeling approach to evaluate the benefits of the H.E.L.P. program are presented in the following subsections.
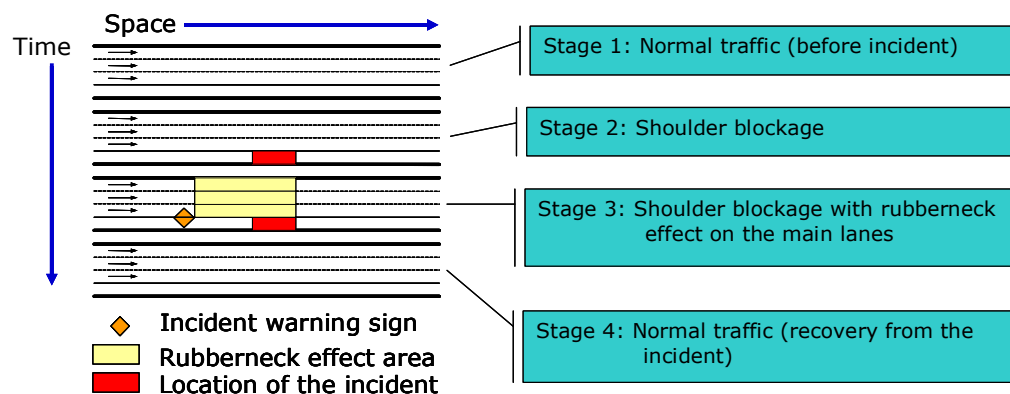
Figure 3-2: Procedures for modeling an incident

3.3.1 Experimental Design

To estimate savings in travel delay and fuel consumption that resulted from the program's impact on incident duration, a set of simulation runs were designed for the incidents that received services from the H.E.L.P. program. Incident durations reported in the data archives are significantly impacted by the existence of the H.E.L.P. program. The impact on traffic under similar circumstances assuming that such a program did not exist, where incident durations would be longer, must be compared to the impact under existing conditions. Thus, actual incident durations replicated directly from the incident data represent the "base case," where it is assumed that the H.E.L.P. program existed. To estimate the savings that were achieved as a consequence of this program, another set of replications were run where incident durations were lengthened by between 5 and 25 minutes (in 5-minute increments). These replications are meant to model circumstances assuming that such a program were nonexistent. Thus, for example, an incident with 10-minute duration that arose during the study period would be modeled with 10-minute duration in the base case, but with 15-, 20-, 25-, 30-, and 35-minute durations in additional runs. Such additional time is based on average savings expected from such a program. The addition of 5 minutes, thus, is employed to estimate the additional travel delay and fuel consumption that would have been incurred had a FSP program with average incident duration savings of 5 minutes not been in place. Thus, the difference in performance measurements between the base case and each extended case provides the savings in such performance metrics that are estimated to have resulted from the FSP program. For each incident, traffic is modeled from a period of time just prior to the incident through at least 30 minutes (longer for longer incident durations) past the time of incident resolution.

693 incidents arising in a 10-mile (in each direction), three-lane study segment with

right-side shoulder of I-287 for the study period that received assistance from the H.E.L.P. program were simulated within the CORSIM platform using the incident properties and estimates of likely prevailing traffic conditions. The simulation time for each run was set as a function of the incident duration. The incidents with duration less than 90 minutes were simulated for two hours, while the incidents with duration of more than 90 minutes (only nine such incidents arose during the study period) were simulated for three hours. The excess time beyond the incident duration was required to ensure that prevailing traffic conditions could be reestablished before concluding the run. Each incident scenario was replicated five times using different random seeds and average performance metrics over these runs were obtained. This ensures that if circumstances that are randomly chosen in a given replication are significantly different from ordinary that they contribute to, but do not dominate, the final measurements. A total of 20,790 replications were designed, requiring more than 41,580 simulation hours.

3.3.2 Critical Simulation Settings

When a freeway incident occurs, roadway capacity is reduced and non-recurrent delay is induced. The level of change in these quantities depends on incident properties. Estimated capacity reduction for given lane blockage status is shown in Table 3-3a (Highway Capacity Manual, 2000).

Table 3-3a: Percentage of available freeway capacity

Number of lanes	Shoulder (disabled vehicle)	Shoulder (collision)	1 lane blocked	2 lanes blocked	3 lanes blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

Table 3-3b: Computed rubberneck effect value for different lane blockage scenarios

	Lane blockage scenario on a 3-lanes freeway segment				
	Shoulder blocked (disabled vehicle)	Shoulder blocked (collision)	1 lane blocked	2 lanes blocked	3 lanes blocked
Residual capacity	99%	83%	49%	17%	N/A
Capacity reduction	1%	17%	51%	83%	N/A
REP(%)	1	17	26	49	N/A
Computed reduction	1%	17%	50.67%	83%	N/A

To achieve the desired capacity reduction, a rubberneck effect parameter (REP) within the CORSIM simulation model can be set. This parameter affects the acceptable gap between leading and lagging vehicles. Within the CORSIM software manual (CORSIM User's Manual, 2000), a technique is supplied for setting the rubberneck effect parameter to achieve varying levels of capacity reduction for given roadway geometries. Within this technique, the contribution of each lane to overall capacity reduction is computed as a function of a chosen rubberneck effect parameter value. The capacity reduction is directly proportional to the remaining capacity of each lane, which is determined through the rubberneck effect parameter setting. For example, consider a three-lane freeway segment with a 25% rubberneck factor for two lanes and the remaining lane completely blocked. By the approach suggested in (CORSIM User's Manual, 1998), reduced capacity (RC) by 50% would be estimated,

$$RC = (100\%) \times \frac{1}{3} + (25\%) \times \frac{1}{3} + (25\%) \times \frac{1}{3} = 50\% .$$

This technique of setting the rubberneck effect parameter to achieve a known level of capacity reduction as determined through the Highway Capacity Manual was employed within this work. From Table 3-3a and the rubberneck effect parameter setting technique, appropriate rubberneck effect parameter values were estimated for incidents with varying numbers of lanes blocked for a three-lane freeway segment. The results are given in Table 3-3b.

To illustrate how Table 3-3b can be employed in the setting of the rubberneck effect parameter for the three-lane study segment, assume that one lane has been blocked by an incident. The rubberneck effect parameter should be set to 26% to yield a 51% reduction in capacity. Note that different parameter settings are given for incidents involving disabled vehicles as opposed to a collision for the case that only the shoulder is blocked.

Once an incident occurs, it is assumed that a warning sign, flares, arrowboards or other methods of signage are set up to warn the upstream traffic of the incident. Since guidelines suggest that the optimal location for a warning sign is 500 feet behind the incident along a highway (Guidelines for Emergency Traffic Control, 2006), a distance of 500 feet was set in this study. Note that this provides the driver with approximately five seconds between passing the warning sign and passing the incident scene assuming a speed of 65 miles per hour. In the CORSIM model, the rubberneck effect parameter is applied to the stretch of roadway between the warning sign and the incident scene. For additional details concerning these and other related parameters and techniques employed within the CORSIM model, see (CORSIM User's Manual, 1998).

The impact of any particular incident will depend on prevailing traffic conditions at the time of the incident. It is, therefore, desirable to have knowledge of such prevailing conditions when studying savings in incident impact resulting from the existence of the H.E.L.P. program.

Since the necessary traffic volume data did not become available in the study area until after the study period, traffic volume data for the study roadway segment was employed for the same period, but in the following year. Specifically, reports from six detectors (three in each direction) along I-287 were made available through Transcom. Average weekday and weekend hourly traffic volumes by month were computed from the available data. The average weekday hourly volume data by month for 2007 was employed in the simulation runs. For a given incident, the average hourly volumes determined at the nearest detector for the time period in which the incident impacted traffic was employed.

3.4 Estimating the Benefits of the H.E.L.P. Program

Once the rubberneck effect parameters were set, traffic volumes were estimated, and the set of simulation runs were designed for estimating incurred travel delay and fuel consumption, the 693 incidents could be replicated. Note that the impact on traffic in the opposite direction was not considered. Five runs of each of the 693 incidents were conducted and the results were aggregated into 12 categories as a function of traffic volume (between 0 and 2,000 vehicles per lane per hour in increments of 500 vehicles per lane per hour) and lane closure (shoulder, one-lane blocked or two-lanes blocked). For each group, the total savings in terms of performance measures of travel delay and fuel consumption were computed. Savings were estimated based on the difference between the performance measure as measured on the base case and each incident duration extended case:

$$\sum_{i \in j} (pm_i^{e,k} - pm_i^b)_j \qquad \text{(3-1)},$$

where

i : Incident i;

j : One of 12 categories classified by volume and lane blockage properties, $j = (1, \ldots, 12)$;

k : One of five incident duration extension cases, $k = (5, 10, 15, 20, 25)$;

$pm_i^{e,k}$: Average performance measure of incident i with k-minute incident duration extension; and

pm_i^{b} : Average performance measure of incident i with actual incident duration as in the base case.

In the following subsections, estimated savings in travel delay, fuel consumption, emission pollution and secondary incidents are given.

3.4.1 Travel Delay

Table 3-4a (Page 53) shows the results of total savings in travel delay (in vehicle-hours) for each of the 12 categories. These savings are computed by first averaging over the set of five runs under each incident and then taking the sum of differences between these averages for the base and extended case pairs. For example, there were 31 H.E.L.P. incidents under the category of one lane-blocked and volume level of 1,000 to 1,500 vehicles per lane per hour. For this category, the total savings in travel delay was computed to be 1026.4 vehicle-hours assuming that the H.E.L.P. program saved 5 minutes in average incident duration (i.e. as compared with the five-minute extended case). Thus, an average of 33.1 vehicle-hours savings in travel delay per incident was estimated, inferring that the H.E.L.P. program would save approximately 33 vehicle-hours in travel delay under similar prevailing traffic conditions for the given 5-minute incident duration savings. Savings in travel delay are most notable at higher traffic volumes and where one or more travel lanes are blocked, as one would expect.

3.4.2 Fuel Consumption

Table 3-b (Page 54) provides results of the simulation runs in terms of savings in fuel consumption (in gallons). The same categories and computational approach (Equation (3-1)) as employed in estimating savings in total and average travel delay are employed. For example, assume a five-minute incident duration reduction is estimated for the H.E.L.P. program. Then, the 31 incidents categorized under one lane-blocked and volume level between 1,000 and 1,500 vehicles per lane per hour contributed to a total savings of 128.5 gallons of fuel consumed, or an average savings in fuel consumption for each incident of 4.2 gallons. The greater the traffic volume, incident duration and savings due to the program, the great the savings in fuel consumption.

3.4.3 Pollution Causing Emissions

Emissions are estimated with the use of empirically derived equations that can be used to quantify levels of certain pollutants as a function of travel delay. Once savings in travel delay are estimated, rough estimates of savings in pollution causing emissions, specifically in hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxide (NO), can be estimated using the following factors: 13.073, 146.831, and 6.261 grams per hour delay, respectively (Chang and Rochon, 2006). A similar emission estimation approach was employed in (Guin et al., 2007). By using these rates multiplied by the total delay savings found in Table 3-4b, the savings in terms of emissions for different incident duration extension cases can be estimated as shown in Tables 3-4c through 3-4e (Page 55-57).

3.4.4 Secondary Incidents

A critical element in estimating the benefits of FSP programs is the savings in secondary incidents. It is difficult, though, to estimate savings in secondary incidents, because such savings can only be concluded from incidents that did not occur, which cannot be documented. Several studies for estimating savings in secondary incidents assume a linear function of the number of secondary incidents and the total savings in incident duration (Guin et al., 2007; Chang and Rochon, 2006). However, total delay may be more pertinent than incident duration, because it reflects not only the temporal properties of the incident impact area, but also the spatial properties. Thus, to estimate such savings in secondary incidents that would result from the H.E.L.P. program, Equation (3-2) is proposed. This equation assumes that the number of secondary incidents is linearly correlated with total delay resulting from the primary incidents.

$$N^{e,k} = \frac{N^b \times TD^{e,k}}{TD^b} \tag{3-2}$$

where

N^b : Number of secondary incidents found in the database;

$N^{e,k}$: Number of secondary incidents for k-minute incident duration extension case, $k = (5, 10, 15, 20, 25)$;

TD^b : Total delay for the base case (no extension for incident duration); and

$TD^{e,k}$: Total delay for k-minute incident duration extension cases, $k = (5, 10, 15, 20, 25)$.

To classify secondary incidents from the archived database, this study employed a Simulation-Based Secondary Incident Filtering (SBSIF) method proposed by Chou and Miller-Hooks (2009). The SBSIF technique explicitly considers the dynamics related to temporal and spatial properties of traffic in estimating the incident impact area of a given incident. Any second incident falling within the impact area is identified as a secondary incident. This

geometry-based method was applied to the I-287 incident database and 27 secondary incidents were identified to have resulted from the 693 incidents that received assistance from the H.E.L.P. program.

Chou and Miller-Hooks (2009) compared results of existing secondary incident static filtering and SBSIF methods with visual inspection and found that a significantly greater rate of misclassification existed for the static methods as compared with the SBSIF method. In fact, the static methods erroneously identified nearly double the number of incidents (i.e. up to nearly 96%) as secondary as identified by visual inspection. By contrast, the SBSIF method erroneously identified only 12.5% additional incidents as secondary.

The simulation-based methodology described previously was employed to estimate total delay based on the base case and extension cases, TD^b and $TD^{e,k}$, respectively. That is, the 693 incidents served by H.E.L.P. vehicle drivers that arose along the study roadway segment during the study period were replicated to obtain an estimate of total delay due to the incidents. The estimated numbers of secondary incidents under varying incident duration extension cases are shown in Table 3-5.

Table 3-5: Number of secondary incidents under varying incident duration extension cases

Incident duration extension case	Base case	5 minutes	10 minutes	15 minutes	20 minutes	25 minutes
Total delay (vehicle-hours)	36,374	38,932	41,803	45,007	48,557	53,178
Number of secondary incidents	27	29	31	33	36	39

Table 3-5 indicates a savings in secondary incidents of between 2 (29 as compared with 27) and 12 (39 as compared with 27) incidents as a result of the H.E.L.P. program assuming between 5- and 25-minute reductions in incident duration, respectively. Note that these estimates

are likely to be conservative, because the actual duration of these 693 incidents would have been greater had the H.E.L.P. program not been in place and a greater number of secondary incidents would be expected than were actualized.

3.5 Estimating the B/C Ratio for the H.E.L.P. Program

A widely employed method for assessing the benefits of FSP programs around the country involves the estimation of equivalent monetary savings from savings in travel delay, emission pollution, fuel consumption and secondary incidents (see FIRST and TIM Evaluations, 8 and 3, respectively, for example). In this section, such a methodology is used in conjunction with operating cost estimates in assessing the B/C ratio of the H.E.L.P. program.

3.5.1 Benefits

Let B_{pm}^k denote the total benefit in terms of a given performance measure, pm, for $pm \in \{$travel delay; fuel consumption; HC, CO, and NO emissions; secondary incidents$\}$, assuming a k-minute incident duration reduction for $pm \in \{$travel delay; fuel consumption; HC, CO, and NO emissions$\}$, or a k-minute incident duration extension for $pm \in \{$secondary incidents$\}$. Extending Equation (3-1) for estimating the savings in performance measure $pm \in \{$travel delay; fuel consumption; HC, CO and NO emissions$\}$ for each of 12 categories ($j \in \{1,2,\ldots,12\}$) of traffic level and lane blockage scenarios, B_{pm}^k can be computed as given in Equation (3-3).

$$B_{pm}^k = \sum_{\forall j} \sum_{i \in j} (pm_i^{e,k} - pm_i^b)_j \qquad (3\text{-}3).$$

Savings in the number of secondary incidents were estimated in Equation (3-2) by taking the difference in the number of secondary incidents identified in the data archives (i.e. the base case), denoted N^b, and the number estimated given the additional travel delay that would be incurred in the k-minute incident duration extension cases, $N^{e,k}$. B^k_{pm} for $pm \in \{secondary$ incidents$\}$ can be expressed as in Equation (3-4).

$$B^k_{pm} = N^{e,k} - N^b$$ (3-4).

Let P_{pm} be the monetary equivalent for each unit of savings in performance measure $pm \in \{travel delay; fuel consumption; HC, CO and NO emissions; secondary incidents\}$. The total savings, TB^k, in all performance measure categories (travel delay, fuel consumption, emissions and secondary incidents) from the program given k-minute incident reductions or extensions as appropriate can be estimated by Equation (3-5).

$$TB^k = \sum_{\forall\, pm}(P_{pm} \times B^k_{pm})$$ (3-5).

Results in terms of total benefits, TB^k, for the I-287 study segment and given study period are provided in Table 3-6. The monetary equivalent rates (i.e. P_{pm}) assumed in this study are given in the table. These values were selected to be consistent with similar rates used in the literature. The monetary savings of $1,706 per secondary incident avoided is reported in (Haghani et al., 2006), which was determined by converting a 1994 estimate from the National Highway Safety Administration to 2006 dollars. Similarly, value of time estimates from Latoski et al. (1999) were converted for use in estimating the monetary equivalent of one-hour of travel delay savings per person (i.e. $15/hour) as per (Haghani et al., 2006). Monetary equivalents for

savings in emissions predicted here were obtained from (Chang and Rochon, 2000). Similar rates were employed in evaluating the TIM program (Guin et al., 2007). Note that these rates are based on 2006 values and are quite conservative.

The results indicate that, assuming an average reduction in incident duration of 20 minutes (i.e. k = 20), the H.E.L.P. program led to an equivalent savings of $215,000, or an annual savings of $430,000, for the 10-mile study segment and six-month study period. These savings were driven by estimated annual savings of:

(a) 24,000 vehicle-hours in travel delay;

(b) 2,900 gallons of fuel consumed;

(c) 0.32 ton of hydrocarbon (HC);

(d) 3.6 tons of carbon monoxide (CO);

(e) 0.2 ton of nitrogen oxide (NO); and

(f) 18 secondary incidents.

3.5.2 Costs

The total cost, TC, is a function of the number of roving FSP trucks along the study segment, hourly operating cost per truck, number of working hours, and number of workdays in the study period, as expressed by Equation (3-6).

$$TC = c \times n \times hr \times day \qquad (3\text{-}6),$$

where

TC	:	Total cost for operating the FSP program in dollars;
c	:	Cost per truck-hour;
n	:	Number of roving trucks;
hr	:	Number of working hours in each day; and
day	:	Number of workdays in the study period.

Cost estimates of $40 and $50/truck-hour were provided by H.E.L.P. program personnel. Two roving trucks operated within the study roadway segment with an eight-hour workday. These trucks operated during 126 workdays within the study period. Thus, by Equation (3-6), the operational costs, including the costs of fleet maintenance and personnel, along the study roadway segment during the study period were estimated at $80,640 and $100,800 for $40 and $50/truck-hour, respectively.

3.5.3 The B/C Ratio

Results of benefit and cost estimates can be combined to assess the B/C ratio for the H.E.L.P. program for the study area and study period for each k-minute incident reduction or extension case. These results, given in Table 3-6 (Page 58), indicate that, even using exceptionally conservative monetary equivalent rates, the program operates with a B/C ratio of 2.68 assuming a cost of $40/truck-hour for operating the H.E.L.P. program or a 2.14 B/C ratio assuming a cost of $50/truck-hour for a k-value equal to 20 minutes. Thus, the H.E.L.P. program is cost effective and provides a sizable return on the public's investment.

To determine the point at which the program breaks even, where the cost of operation is equivalent to the savings achieved by the program, the B/C ratios for each k-minute incident reduction or extension case are plotted against the average estimated incident duration savings in Figure 3-3. This plot shows that breakeven points were reached at eight and 11 minutes for $40 and $50/truck-hour operating cost rates, respectively. That is, if the cost of operating a H.E.L.P. vehicle is assumed to be $40/truck-hour, the program must save, on average, more than eight minutes in incident duration for the benefits to outweigh the costs. Note that the average savings in incident duration estimated for the H.E.L.P. program (approximately 20 minutes) far exceeds this breakeven point even for the assumed higher operational rate of $50/truck-hour.
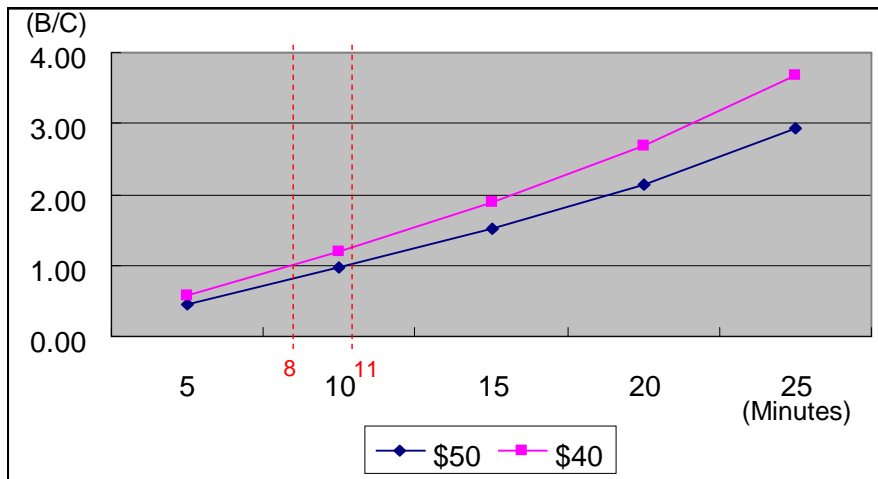
Figure 3-3: B/C versus incident duration reduction by cost

3.6 Summary

In this chapter, key findings in terms of incident reduction savings due to the implementation of a FSP program of extensive statistical analyses of nearly 10,000 incidents arising in the Hudson Valley region of New York State, a suburb of New York City, are given. A simulation-based methodology, including details for setting key simulation parameters, for assessing the impact of these savings on savings in travel delay, fuel consumption, emissions and secondary incidents is presented. Using this methodology, the H.E.L.P. program's B/C ratio was estimated and tables including sufficient detail to permit other FPS programs operating along roadways with similar geometry to complete similar estimates for their own programs are provided. Estimates employing the provided tables require only the number of incidents under varying categories of incident properties and information on prevailing traffic conditions.

The B/C ratio for the H.E.L.P. program and associated tables with greater utility were developed from data associated with only a three-lane, 10-mile stretch of I-287. The study described herein can be repeated for roadway segments with varying roadway geometries to

provide more accurate benefit estimates for programs operating on roadways with different roadway configurations.

The rates employed in estimating the monetary equivalent of savings in the various performance measures are very conservative, particularly for the location in which the H.E.L.P. program operates. No details of traffic composition or passenger occupancy were available for this study. Thus, traffic was assumed to consist entirely of passenger cars with only one passenger per vehicle. The New York Metropolitan Transportation Council (Hrabowska and Chandra, 2008) reported an average occupancy of 1.29 passengers per passenger car in Manhattan for 2006. An average occupancy of approximately 1.15 passengers per passenger car has been computed for a stretch of a suburban freeway in the Washington, D.C. metropolitan region. Commercial vehicles may make up a substantial portion of traffic in a region such as studied herein. The data from the Washington, D.C. metropolitan region indicates that during the morning peak period, commercial vehicles make up between three and six percent of traffic. Smalkoski and Levinson (2005) report an average rate of approximately $49 per commercial vehicle-hour delay based on data for Minnesota. Thus, the assumed rate of $15 per vehicle-hour delay is quite low and a much higher rate would be required to account for truck and commercial vehicle traffic.

A cost of $1,706 estimated per secondary incident is also seemingly very low. The National Highway Traffic Safety Administration (NHTSA) (Blincoe et al., 2002), Parry (2004) and Hanley (2005) report that the average cost of a traffic incident involving only property damage was $2,532 nationally in 2000, $3,447 in 2004 (for Washington, D.C.) and $6,500 in 2005 (for Wisconsin, Connecticut and several other states), respectively. The NHTSA reports average costs of nearly $1.1 million for incidents involving persons in critical condition and

nearly $1 million where a fatality is involved (based on 2000 data). A slightly higher figure is estimated in (Hanley, 2005) for several states across the U.S. Even greater costs may be incurred where commercial vehicles are involved, particularly if significant damage to the civil infrastructure results.

This chapter shows that the H.E.L.P. program operates with better than two-to-one benefit-to-cost ratio (2.68 and 2.14 for $40 and $50/truck-hour operating cost rates, respectively) under these very conservative assumptions. With an average occupancy of 1.15 (instead of 1) passengers per vehicle, traffic composition with 5% commercial vehicles (instead of zero) with a rate of $49 per commercial vehicle-hour delay, and a cost of $6,500 (instead of $1,706) per avoided secondary incident, all else unchanged, the benefit-to-cost ratio would be 4.2 and 3.4 for $40 and $50/truck-hour operating cost rates, respectively. With only one fatal incident avoided at a savings of $1,000,000, this ratio would increase to between 16.5 and 13.2.

Additional savings incurred by drivers, including costs of towing, changing of tires or minor repairs, as well as savings to the local community in terms of reduced fatality rates, and thus, reduced lawsuits, roadway closures and the use of forensic teams, for example, might also be included in the B/C ratio estimates. Additional savings may also be realized that were not considered in this study. For example, drivers of disabled vehicles or vehicles involved in a collision may not need to pay for towing and savings may be incurred by local police agencies, where the H.E.L.P. vehicles are able to respond to incidents in place of troopers. Additionally, the troopers can spend their time on more urgent business for which they were trained. Such factors require additional study. The appropriate factors and rates to use in freeway service patrol benefit analyses is the subject of future research by the authors.

A rather extensive set of simulation runs were conducted in this study in quantifying the

benefits of the H.E.L.P. program and the ultimate B/C ratio with accompanying general-use tables. This approach required enormous simulation run time. While the approach applied within this study can be directly extended for use in studying any roadway for which the necessary data is available, a less computationally burdensome technique can be created for generating an adequate number of random incidents instead of replicating all of the historical incidents. Such a technique is the focus of continued work by the authors and would not only require significantly reduced effort, but would also permit study of much larger roadway segments or networks.

Table 3-4a: Savings in travel delay (vehicle-hours)

Travel Delay (vehicle hours)			5 minutes reduction		10 minutes reduction		15 minutes reduction		20 minutes reduction		25 minutes reduction	
	Volume	Freq.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.
Shoulder	< 500	37	1.06	0.03	0.64	0.02	1.13	0.03	0.87	0.02	0.63	0.02
	500-1000	312	23.54	0.08	24.00	0.08	25.11	0.08	26.98	0.09	30.97	0.10
	1000-1500	221	63.23	0.29	78.20	0.35	87.84	0.40	97.11	0.44	121.89	0.55
	>1500	30	180.29	6.01	391.28	13.04	631.53	21.05	889.75	29.66	1,168.63	38.95
One Lane	< 500	7	0.18	0.03	0.61	0.09	0.55	0.08	0.69	0.10	0.41	0.06
	500-1000	45	12.30	0.27	22.74	0.51	36.08	0.80	50.90	1.13	66.60	1.48
	1000-1500	31	1,026.35	33.11	2,254.95	72.74	3,684.56	118.86	5,330.75	171.96	7,459.18	240.62
	>1500	4	557.75	139.44	1,194.70	298.68	1,854.17	463.54	2,558.43	639.61	3,496.60	874.15
Two Lanes	< 500	0	0	-	0	-	0	-	0	-	0	-
	500-1000	5	508.54	101.71	1,048.93	209.79	1,650.09	330.02	2,293.78	458.76	3,252.08	650.42
	1000-1500	1	184.69	184.69	412.76	412.76	661.48	661.48	933.22	933.22	1,207.25	1,207.25
	>1500	0	0	-	0	-	0	-	0	-	0	-
Total		693	2,557.93		5,428.81		8,632.54		12,182.48		16,804.24	

Table 3-4b: Savings in fuel consumption (gallons)

Fuel Consumption (gallons)			5 minutes reduction		10 minutes reduction		15 minutes reduction		20 minutes reduction		25 minutes reduction	
	Volume	Freq.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.
Shoulder	< 500	37	2.35	0.06	4.79	0.13	4.66	0.12	4.19	0.11	2.24	0.06
	500-1000	312	38.49	0.12	39.00	0.12	51.34	0.16	51.18	0.16	58.66	0.19
	1000-1500	221	57.99	0.26	66.93	0.30	74.33	0.34	88.96	0.40	106.35	0.48
	>1500	30	36.86	1.23	73.02	2.43	119.64	3.99	161.24	5.37	209.22	6.97
One Lane	< 500	7	0.20	0.03	0.45	0.06	0.37	0.05	0.26	0.04	0.59	0.08
	500-1000	45	8.51	0.19	14.54	0.32	21.69	0.48	27.75	0.62	35.85	0.80
	1000-1500	31	128.51	4.15	271.42	8.76	435.60	14.05	627.21	20.23	780.57	25.18
	>1500	4	69.14	17.28	144.97	36.24	199.78	49.95	244.12	61.03	292.14	73.04
Two Lanes	< 500	0	0	-	0	-	0	-	0	-	0	-
	500-1000	5	37.51	7.50	74.74	14.95	119.25	23.85	161.31	32.26	171.39	34.28
	1000-1500	1	19.28	19.28	42.65	42.65	63.83	63.83	84.83	84.83	103.74	103.74
	>1500	0	0	-	0	-	0	-	0	-	0	-
Total		693	398.84		732.51		1,090.49		1,451.05		1,760.75	

Table 3-4c: Savings in HC (grams)

Emission - HC (grams)			5 minutes reduction		10 minutes reduction		15 minutes reduction		20 minutes reduction		25 minutes reduction	
	Volume	Freq.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.
Shoulder	< 500	37	13.81	0.36	8.31	0.22	14.72	0.39	11.35	0.30	8.24	0.22
	500-1000	312	307.76	0.99	313.75	1.01	328.24	1.05	352.66	1.13	404.82	1.30
	1000-1500	221	826.55	3.74	1,022.33	4.63	1,148.33	5.20	1,269.47	5.74	1,593.44	7.21
	>1500	30	2,356.88	78.56	5,115.18	170.51	8,256.02	275.20	11,631.65	387.72	15,277.50	509.25
One Lane	< 500	7	2.33	0.33	7.92	1.13	7.24	1.03	9.05	1.29	5.41	0.77
	500-1000	45	160.77	3.57	297.28	6.61	471.67	10.48	665.36	14.79	870.69	19.35
	1000-1500	31	13,417.47	432.82	29,478.96	950.93	48,168.31	1,553.82	69,688.92	2,248.03	97,513.86	3,145.61
	>1500	4	7,291.47	1,822.87	15,618.37	3,904.59	24,239.62	6,059.90	33,446.38	8,361.60	45,711.03	11,427.76
Two Lanes	< 500	0	0	-	0	-	0	-	0	-	0	-
	500-1000	5	6,648.14	1,329.63	13,712.61	2,742.52	21,571.57	4,314.31	29,986.64	5,997.33	42,514.44	8,502.89
	1000-1500	1	2,414.48	2,414.48	5,396.06	5,396.06	8,647.55	8,647.55	12,199.93	12,199.93	15,782.43	15,782.43
	>1500	0	0	-	0	-	0	-	0	-	0	-
Total			33,439.66		70,970.77		112,853.27		159,261.41		219,681.86	

Table 3-4d: Savings in CO (grams)

Emission - CO (grams)			5 minutes reduction		10 minutes reduction		15 minutes reduction		20 minutes reduction		25 minutes reduction	
	Volume	Freq.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.
Shoulder	< 500	37	155.05	4.08	93.38	2.46	165.33	4.35	127.45	3.35	92.50	2.43
	500-1000	312	3,456.70	11.08	3,523.94	11.29	3,686.63	11.82	3,960.91	12.70	4,546.77	14.57
	1000-1500	221	9,283.54	42.01	11,482.48	51.96	12,897.64	58.36	14,258.17	64.52	17,896.94	80.98
	>1500	30	26,471.57	882.39	57,451.74	1,915.06	92,728.48	3,090.95	130,642.29	4,354.74	171,591.11	5,719.70
One Lane	< 500	7	26.14	3.73	88.98	12.71	81.34	11.62	101.61	14.52	60.79	8.68
	500-1000	45	1,805.73	40.13	3,338.94	74.20	5,297.66	117.73	7,473.11	166.07	9,779.24	217.32
	1000-1500	31	150,700.00	4,861.29	331,096.56	10,680.53	541,008.22	17,451.88	782,719.65	25,249.02	1,095,238.86	35,330.29
	>1500	4	81,894.99	20,473.75	175,419.58	43,854.90	272,250.22	68,062.56	375,657.13	93,914.28	513,408.98	128,352.25
Two Lanes	< 500	0	0	-	0	-	0	-	0	-	0	-
	500-1000	5	74,669.44	14,933.89	154,014.85	30,802.97	242,283.78	48,456.76	336,798.60	67,359.72	477,506.16	95,501.23
	1000-1500	1	27,118.51	27,118.51	60,606.55	60,606.55	97,126.06	97,126.06	137,025.04	137,025.04	177,262.31	177,262.31
	>1500	0	0	-	0	-	0	-	0	-	0	-
Total			375,581.67		797,117.00		1,267,525.36		1,788,763.96		2,467,383.66	

Table 3-4e: Savings in NO (grams)

Emission - NO (grams)			5 minutes reduction		10 minutes reduction		15 minutes reduction		20 minutes reduction		25 minutes reduction	
	Volume	Freq.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.	Total	Avg.
Shoulder	< 500	37	6.61	0.17	3.98	0.10	7.05	0.19	5.43	0.14	3.94	0.10
	500-1000	312	147.40	0.47	150.26	0.48	157.20	0.50	168.90	0.54	193.88	0.62
	1000-1500	221	395.86	1.79	489.62	2.22	549.97	2.49	607.98	2.75	763.14	3.45
	>1500	30	1,128.77	37.63	2,449.79	81.66	3,954.02	131.80	5,570.70	185.69	7,316.79	243.89
One Lane	< 500	7	1.11	0.16	3.79	0.54	3.47	0.50	4.33	0.62	2.59	0.37
	500-1000	45	77.00	1.71	142.38	3.16	225.90	5.02	318.66	7.08	417.00	9.27
	1000-1500	31	6,425.98	207.29	14,118.24	455.43	23,069.06	744.16	33,375.84	1,076.64	46,701.93	1,506.51
	>1500	4	3,492.07	873.02	7,480.04	1,870.01	11,608.98	2,902.25	16,018.34	4,004.59	21,892.20	5,473.05
Two Lanes	< 500	0	0	-	0	-	0	-	0	-	0	-
	500-1000	5	3,183.97	636.79	6,567.33	1,313.47	10,331.19	2,066.24	14,361.38	2,872.28	20,361.27	4,072.25
	1000-1500	1	1,156.36	1,156.36	2,584.32	2,584.32	4,141.54	4,141.54	5,842.87	5,842.87	7,558.62	7,558.62
	>1500	0	0	-	0	-	0	-	0	-	0	-
Total			16,015.13		33,989.75		54,048.38		76,274.43		105,211.36	

Table 3-6: Benefit and cost estimation of the H.E.L.P. program for six-month operation along I-287

BENEFIT											
Duration reduction		5 minutes		10 minutes		15 minutes		20 minutes		25 minutes	
Saving	P_{pm} ($/unit)	B_{pm}^5 (Savings in original units)	TB^5 (Total savings in dollars)	B_{pm}^{10} (Savings in original units)	TB^{10} (Total savings in dollars)	B_{pm}^{15} (Savings in original units)	TB^{15} (Total savings in dollars)	B_{pm}^{20} (Savings in original units)	TB^{20} (Total savings in dollars)	B_{pm}^{25} (Savings in original units)	TB^{25} (Total savings in dollars)
Delay (vehicle-hours)	15	2,558	38,369	5,429	81,432	8,633	129,488	12,182	182,737	16,804	252,064
Fuel consumption (gallons)	3	399	1,197	733	2,198	1,090	3,271	1,451	4,353	1,761	5,282
HC (tons)	6,700	0.03	224	0.07	476	0.11	756	0.16	1,067	0.22	1,472
CO (tons)	6,300	0.38	2,389	0.80	5,070	1.27	8,061	1.79	11,377	2.47	15,693
NO (tons)	12,875	0.02	206	0.03	438	0.05	696	0.08	982	0.11	1,355
Secondary incidents	1,706	2	3,412	4	6,824	6	10,236	9	15,354	12	20,472
Total saving			45,796		96,436		152,509		215,870		296,337

COST					
	Total Cost $TC = c \times n \times hr \times day$	n Number of roving trucks	hr work hours a day	day work days	c cost per truck hour
COST(1)	100,800	2	8	126	50
COST(2)	80,640	2	8	126	40

B/C RATIOS					
Incident reduction case	5 minutes	10 minutes	15 minutes	20 minutes	25 minutes
B/C ratio (with COST(1))	0.45	0.96	1.51	2.14	2.94
B/C ratio (with COST(2))	0.57	1.20	1.89	2.68	3.67

Chapter 4: Secondary Incident Filtering Model

4.1 Introduction and Background

In the United States, it is estimated that as high as 60% (Lindley, 1987) of non-recurrent freeway congestion is caused by incidents. While this estimate varies by roadway and city, as well as measurement technique employed for its computation, its significance has been noted in numerous studies (Skabardonis et al., 2003; Schrank and Lomax, 2007). This non-recurrent congestion negatively impacts safety and mobility. It produces enormous travel delay and results in secondary incidents (i.e. collisions resulting from abrupt changes in traffic flow conditions caused by prior traffic incidents), which not only induce additional congestion, but cause 18% of all freeway fatalities (Brach, 2008). Consequently, measures that can reduce the number of incidents and their impact, including the occurrence of secondary incidents, have been widely studied and implemented. Typical methods for assessing the benefits of such measures require the ability to quantify the measure's impact on travel delay reduction, secondary incident occurrence, and other factors. This often requires a study of traffic impact and identification of secondary incidents from archived data. Additionally, to study the characteristics of secondary incidents and the specific details of events that cause them, it is necessary to first identify them.

Static threshold filtering methods that employ bounds on time and space in identifying secondary incidents have been widely used, despite that it is commonly known that such methods erroneously identify incidents as secondary when they are, in fact, isolated incidents (MNDOT, 2004). Two prior studies propose dynamic threshold methods that overcome some of the shortcomings of such static threshold techniques; however, these techniques have significant deficiencies or require significant computational effort. A computationally efficient methodology

for accurately identifying secondary incidents from archived incident data is proposed herein.

In the next section, methods from the literature for filtering historical traffic data to identify and classify incidents as secondary incidents are reviewed. In Section 4.3, a geometric-based method, the Simulation-Based Secondary Incident Filtering (SBSIF) method, for classifying secondary incidents from archived incident data that overcomes the deficiencies of existing filtering methods is proposed. In Section 4.4, the proposed methodology is applied to incident data for a segment of I-287 in New York State. Results of this application show that the proposed method produces significantly fewer errors as compared with static threshold methods. Conclusions are given in Section 4.5.

4.2 Review of Secondary Incident Filtering Methods

Numerous methods have been proposed for identifying secondary incidents. One approach to classify incidents as secondary could be to entrust this categorization to police officers or other personnel who record information about incidents to which they respond or employees of traffic management centers, where observations via CCTV monitoring can be employed. Such methods would, however, require human judgment and wide visual perspective.

Numerous automated approaches to identifying whether or not an incident is secondary to another incident via computer programs that filter data in archived incident databases have been proposed in the literature. The majority of these approaches employ temporal and spatial thresholds related to the primary incidents. For example, Raub (1997) used static thresholds of 1,600 meters and 15 minutes. Any incident arising within 15 minutes of resolution of another incident and within one mile of that incident is defined as a secondary incident. Other works that employ similar static thresholds include: Moore et al. (2004), Hirunyanitiwattana and Mattingly

(2006) and Zhan et al. (2008).

Chilukuri and Sun (2006) proposed the use of a progression curve for identifying secondary incidents involving a spatial threshold that is a nonlinear function of time beginning after the occurrence of a primary incident. The progression curve is constructed from affected distance lengths (defined as the distance from the location of an incident to the back of the developing queue) computed from archived incident data. Incidents are classified as secondary incidents if they fall under the curve. A simulation-based approach for identifying the time-space incident impact area of individual incidents was introduced by Haghani et al. (2006). In their approach, the incident impact area is identified from the shockwave that arises as a consequence of the incident in the simulation model. A set of preselected time intervals, along with occupancy data employed to evaluate queue lengths, are employed in seeking the impact area during a specific time interval for each incident. In each iteration of the procedure, the time-dimension is increased by a constant interval employed in impact area identification. The procedure is repeated until the occupancy data indicates that traffic has returned to pre-incident conditions. Any incident arising in the impact areas identified for each time interval up to the last time interval tested is considered to be a secondary incident. These approaches are summarized in Table 4-1.

Table 4-1: Summary of existing secondary incident identification methods.

Author, Year	Method
Raub, 1997	Static method with thresholds of 1,600 meters and 15 minutes from incident resolution
Moore et al., 2004	Static method with thresholds of two miles and two hours from incident identification
Chilukuri and Sun, 2006	Dynamic method employing progression curves over time and space based on incident queue length information
Hirunyanitiwattana and Mattingly, 2006	Static method with thresholds of two miles and 60 minutes from incident identification
Haghani et al., 2006	Dynamic, simulation-based method employing shockwaves
Zhan et al., 2008	Static method with thresholds of two miles and 15 minutes from incident resolution

The static threshold filtering models assume that the incidents occurring within a defined time period and spatial area are secondary incidents. However, there is no agreement on the threshold values to be employed in defining this timeframe and spatial area. Moreover, the static threshold approaches do not provide scientific-based justification for the threshold values that they employ. These methods, therefore, can lead to misclassification errors, where an incident is mistakenly identified as secondary.

The progression curves proposed by Chilukuri and Sun (2006) compensate for the inadequacies of the static based approaches by establishing thresholds based on queueing information associated with primary incidents. Their approach assumes that queueing information can be gathered from the archived incident database; however, it is often the case that limited queuing information, at best, can be retrieved from such records. Additionally, this method applies an identical function (in the form of a progression curve) over all incidents, regardless of the number of lanes blocked or traffic volume, for identifying secondary incidents.

The simulation method of Haghani et al. (2006) considers the dynamics associated with traffic in the aftermath of an incident. Their approach seeks to estimate the impact area through simulation. The impact area is mathematically represented by rectangles with a dimension in time. The smaller the time interval considered, the greater the accuracy of the estimation method, but the smaller the time interval, the greater the computational effort required to identify secondary incidents from within the archived data.

4.3 The SBSIF Method

A computationally efficient methodology, the SBSIF method, is proposed for efficiently delineating the boundaries of the incident impact area in a time-space contour map of traffic

speeds and employing the outcome in identifying secondary incidents from incident data archives. Unlike existing static threshold filtering techniques and the dynamic technique of Chilukuri and Sun (2006), this method accounts for the dynamic spatial and temporal properties of incident impact given prevailing traffic conditions.

The SBSIF method is composed of two main tasks. The first task identifies the incident impact area that results from each primary incident, i.e. the portion of the time-space traffic speed contour map in which traffic speeds are impacted as a consequence of the incident. The second task employs the impact area to identify the secondary incidents from archived data. The identification of an incident as secondary to a primary incident is illustrated in Figure 4-1. Given the incident impact area created by an incident "A", incident "B" is classified as a secondary incident.
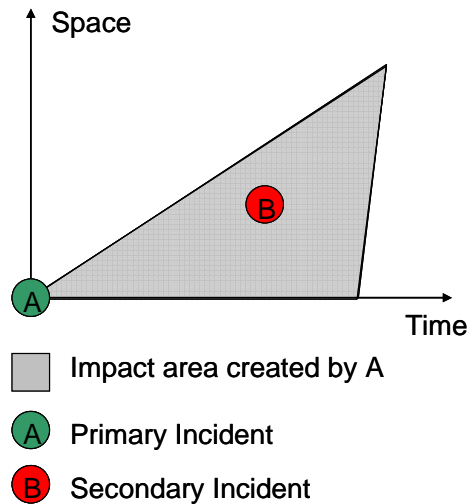
Figure 4-1: Classifying a secondary incident

Direct measurement of the impact area for every incident as is required for the first task is computationally burdensome. Thus, to facilitate this task, an approach that develops regression models from simulating representative incidents for use in estimating the impact area for incidents with given properties under given traffic conditions is proposed. The regression models

were assessed with empirical incident data and can be employed in estimating geometrical properties of the impact area associated with a primary incident that are necessary for delineation of the boundaries of this area. In succeeding subsections, the specific steps of the SBSIF method are described and assessed.

4.3.1 Procedures of the SBSIF Method

The steps of the SBSIF method, assuming that the necessary regression models exist for estimating the corner points for delineation of the impact area boundaries, are given in Figure 4-2. The regression models are described in detail in Subsection 4.3.3.

Let P denote the set of incidents archived in an incident database arising along a roadway segment during a given study period, $P = \{p_{it} \mid t \in \Gamma = \{1,2,...T\}, i \in (1,2,....n_t)\}$, where p_{it} represents incident i, $i \in (1,2,....n_t)$, of incident type t, Γ is the set of incident types, n_t is the number of incidents of type t, and $\sum_{t \in \Gamma} n_t = |P|$. The initial step of the SBSIF method defines two subsets of incidents in the archived database P: primary incidents and potential secondary incidents, denoted by $Q_p \subseteq P$ and $Q_s \subseteq P$, respectively. The user can select the types of incidents that belong to Q_p. Let $\Omega \subseteq \Gamma$ be the set of types of incidents that belong to Q_p as determined by the user. Ω represents the set of incident types for which the user would like to determine the set of resulting secondary incidents. $Q_p = \{p_{ik} \mid i = (1,2,....n_k), k \in \Omega\}$ and $\sum_{k \in \Omega} n_k = |Q_p|$. For example, a user might be interested to determine the set of secondary incidents from only the collision category, only the disabled vehicle category, both or any other classification of the incidents in an archived database. Moreover, all incidents in the database can

be regarded as primary incidents, in which case all types of incidents would be included in Ω,

i.e. $\Omega = \Gamma$ and $Q_p = P$. Similarly, Q_s is defined as the collection of incidents of type Λ,

$\Lambda \subseteq \Gamma$, where Λ, denotes the chosen classes of incidents to be considered as possible

secondary incidents to incidents in Q_p. $Q_s = \{ p_{ij} \mid i = (1, 2, \ldots n_j), j \in \Lambda \}$ and $\sum_{j \in \Lambda} n_j = |Q_s|$. For

example, an incident of the collision type may be included in Q_s, whereas, incidents of the

disabled vehicle type may not.

The SBSIF Method

Step 0: $S = \phi$. Select and remove p_{ik} from Q_p .

Step 1: Generate a corner point set, $C_{p_{ik}}$, of incident $p_{ik} \in Q_p$ via regression models with traffic conditions and incident properties.

Step 2: Let (x,y)-coordinates of $p_{ik} \in Q_p$ be the point of origin,$(0,0)$. Form an impact area, $IA_{p_{ik}}$,of incident $p_{ik} \in Q_p$ using line functions with the corner point set, $C_{p_{ik}}$.

Step 3: Compute (x,y)-coordinates, $(x, y)_{p_{ij}}$, for a potential secondary incident, $p_{ij} \in Q_s$, with data logs of mile marker and incident start timestamp with respect to $p_{ik} \in Q_p$.

Step 4: If $(x, y)_{p_{ij}} \in IA_{p_{ik}}$ and the traffic flow direction of p_{ij} is the same as p_{ik} , a primary-secondary pair is found, denoted (p_{ik}, p_{ij}) .

Step 5: $S = S \cup \{(p_{ik}, p_{ij})\}$. Repeat Steps 3 and 4 for all $p_{ij} \subseteq Q_s$ and $p_{ij} \neq p_{ik}$.

Step 6: If $Q_p \neq \phi$, select and remove p_{ik} from Q_p and return to Step 1; otherwise, if $Q_p = \phi$, stop. The procedure terminates with the set of secondary incidents and the pairing of secondary incident to primary incidents.

Notation employed:

Q_p : Set of primary incidents consisting of Ω incident types, $Q_p = p_{ik}, \forall i \in (1,2,....n_k), \quad \Omega \subseteq \Gamma$

p_{ik} : An incident, i, of incident type k, $\forall i = (1,2,...n_k), k \in (1,2,...K)$, $p_{ik} \in Q_p$

Q_s : Set of potential secondary incidents consisting of Λ incident types, $Q_s = p_{ij}, \forall i \in (1,2,....n_j), \quad \Lambda \subseteq \Gamma$

p_{ij} : An incident, i, of incident type j, $\forall i = (1,2,...n_j), j \in (1,2,...J)$, $p_{ij} \in Q_s$

S : Set of primary-secondary incident pairs, $S = \{(p_{ik}, p_{ij})\}, \forall p_{ik} \in Q_p, p_{ij} \in Q_s$

(p_{ik}, p_{ij}) : A primary-secondary incident pair, $\forall p_{ik} \in Q_p, p_{ij} \in Q_s$

$C_{p_{ik}}$: Set of corner points of incident $p_{ik}, \forall p_{ik} \in Q_p$

$IA_{p_{ik}}$: Impact area of incident $p_{ik}, \forall p_{ik} \in Q_p$

$(x, y)_{p_{ij}}$: (x,y)-coordinates of incident $p_{ij}, \forall p_{ij} \in Q_s$

Figure 4-2: The SBSIF method

The SBSIF method classifies an incident in Q_s as a secondary incident by determining whether or not the incident falls within the impact area of any incident in Q_p. Multiple regression models are applied in Step 1 to generate a set of corner points, $C_{p_{ik}}$, associated with individual incident properties and prevailing traffic conditions for an incident $p_{ik} \in Q_p$ Detailed description of incident impact area delineation through corner point identification and the use of regression modeling for first identifying the corner points are provided in Sections 4.3.2 and 4.3.3. Alternatively, one can identify the corner points directly through analysis of traffic data. Specifically, one can develop a traffic speed contour map, as in Figure 4-3a of Section 4.3.2, from traffic detector data to capture the impact of an incident given the incident's characteristics and prevailing traffic conditions. As it is often the case that such data is unavailable, simulation can be employed to estimate the required traffic data to develop such contour maps. Since the necessary traffic detector data may not be available and replications of the incidents using a simulation package can be quite time-consuming, the multiple regression modeling approach is proposed. Equations of the line segments formed through neighboring pairs of corner points are determined in Step 2. These equations are used to delineate the boundaries of the impact area, $IA_{p_{ik}}$, of incident $p_{ik} \in Q_p$. The (x,y)-coordinates in time and space of the primary incident, p_{ik}, under consideration are set to origin $(0,0)_{p_{ik}}$.

In Step 3, the temporal and spatial (x,y)-coordinates, $(x, y)_{p_{ij}}$, of each incident p_{ij} in Q_s, are computed with respect to the primary incident's start timestamp and location given by the mile-marker data log. If the (x,y)-coordinates of incident p_{ij} fall within the impact area generated by the primary incident p_{ik}, incident p_{ij} is classified as a secondary incident in Step 4.

A primary-secondary incident pairing is made, denoted (p_{ik}, p_{ij}). This process (Steps 3 and 4) is repeated over all incidents in Q_s (via Step 5). Steps 1 through 5 of the algorithm are repeated over all incidents Q_p. Note that it is possible that more than one secondary incident will be associated with the same primary incident. Moreover, as Q_p may intersect Q_s, this method can help to identify tertiary (i.e. secondary incidents of secondary incidents) and higher orders of incidents.

4.3.2 Impact Area Analysis

An illustrative incident impact area contour map generated from simulation of traffic for a given incident is provided in Figure 4-3a. The shape of the contour map is sensitive to incident properties and prevailing traffic conditions. The impact area can be identified based on user defined performance measures, such as speed, volume or occupancy, and thresholds for level of service. For example, in the figure, existing travel speeds are compared with pre-incident travel speeds in incident impact area identification. One can see the boundary of the discontinuous region of traffic flow in Figure 4-3a, which forms a dynamic region within which an incident can be classified as a secondary incident.

Using a threshold value for average speed from pre-incident conditions, one can form a time-space polygon to represent the impact area. Different threshold values will lead to different polygon representations. The incident impact area for the illustrative example is identified as the area for which a decrease in speed to a value less than 50% or 75% of the average pre-incident speed is noted (shown in the dark shaded or light shaded polygon for 50% or 75% thresholds, respectively, in Figure 4-3b). For a chosen threshold value, any incident occurring within the identified time-space polygon generated by a primary incident can be classified as a secondary

incident. Once the incident impact area speed contour map is obtained, it can be visually inspected and the (x,y)-coordinates of the corner points of the impact area can be identified as shown in Figure 4-3c.
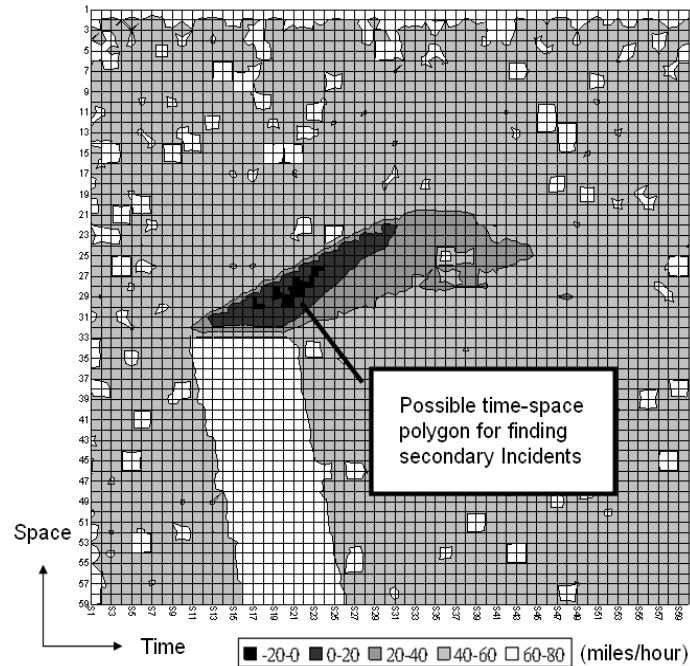
Figure 4-3a: Traffic speed contour map of an incident
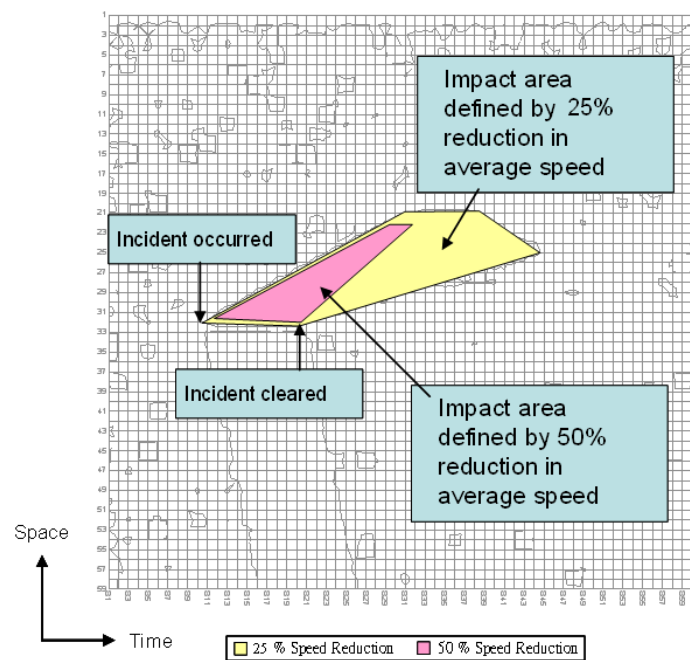
Figure 4-3b: Impact area with two threshold definitions
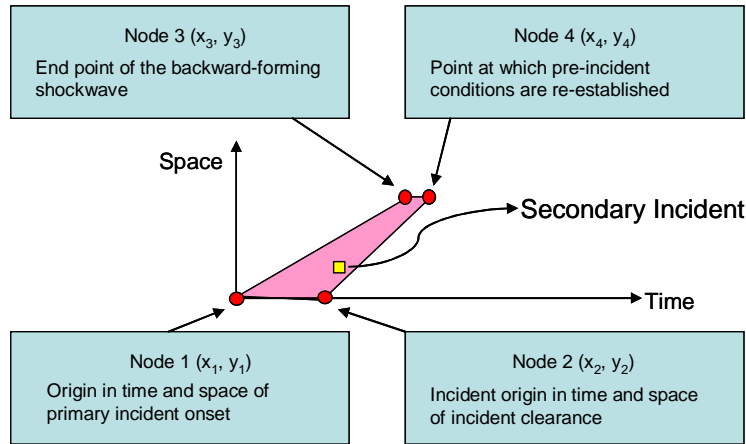
Figure 4-3c: Impact area identification through corner point identification

Typically, four corner points are required to specify the polygon; although, in some situations, the polygon may consist of only 2 or 3 corner points. One can interpret each corner point as follows.

Node 1: Incident Start Point

The first node represents the incident origin at incident onset.

Node 2: Incident End Point

The second node represents the incident origin at the time of incident clearance (i.e. the time at which normal traffic conditions are restored). Thus, this node represents the same location as Node 1, but at a later time.

Node 3: Point of the Shockwave Transition

The third node represents the location and point in time at which the backward-forming shockwave (identified by temporal and spatial boundary conditions that demark a discontinuity in flow-density conditions (May, 1990) terminates.

Node 4: End of Incident Impact

The fourth node represents the location and time at which normal traffic conditions are re-established.

The x-value associated with each corner point is a measure of time and the y-value is a measure of space. With the knowledge of the (x,y)-coordinates associated with each of the corner points, the polygon can be completely specified. The sides of the polygon are computed from the (x,y)-coordinates of their endpoints using the equation of a line; given two corner points (x1,y1) and (x2, y2):

$$y = y_1 + [(y_2 - y_1)/(x_2 - x_1)] \times (x - x_1).$$

Any incident arising at a time and location associated with an (x,y)-coordinate that falls within the polygon formed by the primary incident is classified as a secondary incident. The square in Figure 4-3c illustrates such a secondary incident.

4.3.3 Regression Models for Identifying Corner Points of Incident Impact Areas

Simulation can be employed to create the traffic speed contour map for any given incident and the incident impact area can be identified visually. Since analysis of a historical archive of incident data would require incident impact area identification of hundreds of incidents, this process would be excessively time-consuming. Thus, the use of multiple regression models that, once calibrated, can be employed to identify the impact area of a primary incident given prevailing traffic conditions and incident properties, is suggested herein to facilitate this task. Each of the regression models identifies a corner point of the impact area for an incident with given properties. This approach to incident impact area identification explicitly considers the variability of traffic flow characteristics in the aftermath of an incident, i.e. it is a dynamic approach.

To calibrate the regression models, traffic conditions were simulated using the CORSIM

simulation platform for a model of a 10-mile stretch (two directions) of I-287 in New York State containing three main lanes, a right-side shoulder, and no on- or off-ramps. Additional detail concerning the data archive, specific location and simulation model are provided in (Miller-Hooks and Chou, 2008). 360 representative incidents with a wide range of characteristics under varying traffic conditions were replicated. Specifically, the criteria considered include:

1. Lane blockage: shoulder, 1 and 2 lanes blocked;

2. Incident duration: 10, 20 and 30 minutes;

3. Speed: 55 and 65 miles per hour; and

4. Volume: 400 to 2300 vehicles per lane per hour in 100 vehicle increments.

By using simulated incident data instead of historical data, a wider range of incident characteristics can be captured.

Each of the 360 representative incidents was simulated over a two-hour period and traffic data was collected from the run results. The average speed at one-minute increments was collected over space with 1,000 feet spacing. The incident impact area was identified by first recognizing the stretch of roadway and time intervals for which an average speed reduction by 50% is noted. For each incident, the (x,y) coordinates of the impact area corner points were identified through visual inspection. By connecting the corner points with straight line segments, the impact area was fully delineated. This process is illustrated in Figure 4-4.
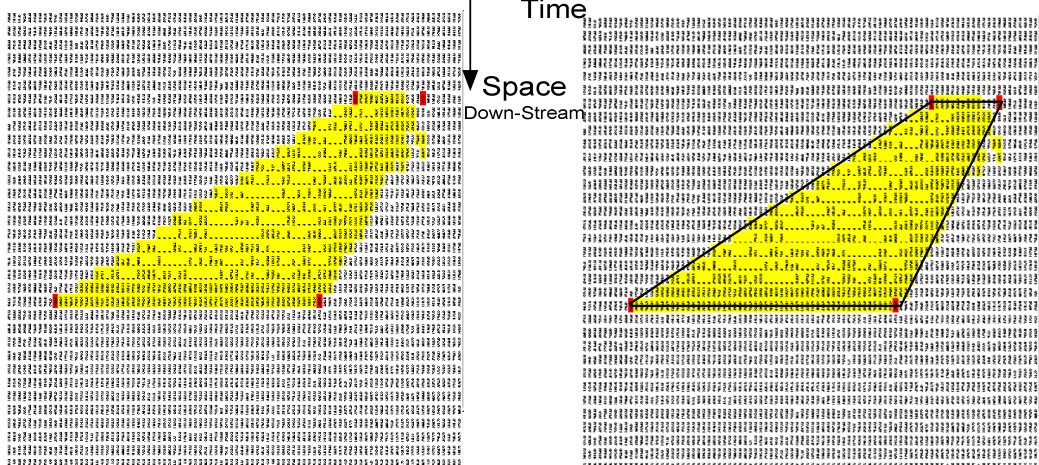
Figure 4-4: Procedures for corner point identification

Data related to 50 of the 360 simulated incidents were discarded, because the resulting impact area expanded beyond the study limits of the 10-mile roadway segment and two hour study period. Thus, it was not possible to obtain the corner points of the impact area associated with these 50 incidents. The final sample size from each scenario classification is provided in Table 4-2.

Table 4-2: Simulation scenario and sample size for regression model calibration

Lane Blockage	Incident Duration (minutes)	Speed (mph)	Volume (vplph)	Qualified sample size
Shoulder	10	55	400-2300	20
		65	400-2300	20
	20	55	400-2200	19
		65	400-2200	19
	30	55	400-2000	17
		65	400-2000	17
1 lane blocked	10	55	400-2200	19
		65	400-2200	19
	20	55	400-2000	17
		65	400-2000	17
	30	55	400-1900	16
		65	400-1900	16
2 lane blocked	10	55	400-2100	18
		65	400-2100	18
	20	55	400-1800	15
		65	400-1900	16
	30	55	400-1600	13
		65	400-1700	14

Table 4-3 gives the independent variables employed within the regression models and provides the correlation matrix of incident duration, volume, and average speed from the 310 samples. As the absolute correlation values between the independent variables are low, it is assumed for simplicity that these variables are uncorrelated. Thus, ordinary least squares regression modeling could be applied. Note that the lane blockage status variables are treated as binary variables.

Table 4-3: Correlation matrix for independent and dependent variables

		Incident duration	Volume	Average speed	Shoulder blocked	1 lane blocked	2 lanes blocked
Independent variables	Incident duration	1					
	volume	-0.134	1				
	Average speed	0.045	-0.307	1			
	Shoulder blocked	0.013	0.096	-0.033	1		
	1 lane blocked	-0.068	-0.049	-0.054	-0.574	1	
	2 lanes blocked	0.060	-0.050	0.095	-0.459	-0.465	1
Dependent variables	X_2	0.999	-0.126	0.047	0.009	-0.063	0.058
	X_3	0.760	0.296	-0.106	-0.109	-0.070	0.194
	y_3	0.110	0.675	-0.219	-0.282	-0.026	0.333
	x_4	0.666	0.429	-0.095	-0.202	-0.056	0.279
	y_4	0.080	0.688	-0.228	-0.272	-0.022	0.318

Two ordinary least squares regression models were calibrated for each corner point, one associated with the x-coordinate and the other with the y-coordinate. Node 1 (in the impact area polygon depicted in Figure 4-3c) of each incident impact area is shifted to (x,y)=(0,0). The y-coordinate for Node 2 (from the figure) is zero and, thus, only the x-coordinate of the second node must be estimated. The estimation of the impact area corner points by this method is illustrated in Figure 4-5.
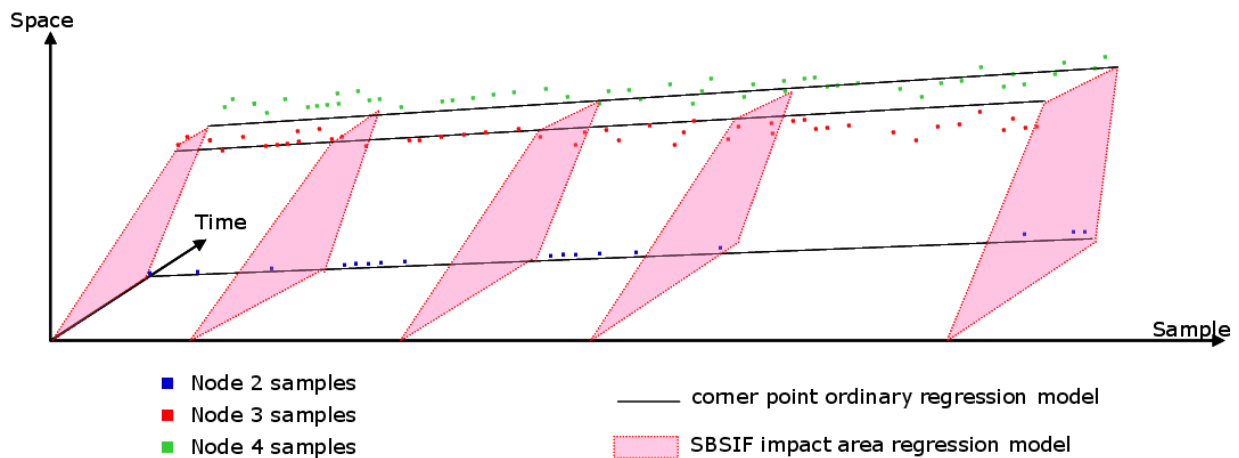
Figure 4-5: Regression models of the SBSIF method

Parameters associated with statistically significant independent variables of the regression models are summarized in Table 4-4. Only the x-coordinates for Nodes 2, 3 and 4 and the y-coordinates for Nodes 3 and 4 require estimation, because x1, y1 and y2 are set to zero. The goodness of fit indicators, R2 and adjusted R2, and P-values, are also provided for each regression model. The smaller the p-value, the greater one's confidence is in its significance. The sign of all significant parameters, with the exception of the constant terms, is positive, which is consistent with expectations for the given independent variables. Note that volume and number of lanes blocked were not statistically significant factors in the regression model for x2 of Node 2. Thus, these factors were excluded when calibrating the final x2 model.

Table 4-4: Multi-regression models of the SBSIF method

Variable	x_2 Coefficient [P-value]	x_3 Coefficient [P-value]	y_3 Coefficient [P-value]	x_4 Coefficient [P-value]	y_4 Coefficient [P-value]
Constant (C)	0.15968 [.000]	-11.4352 [.000]	-13.8086 [.000]	-18.9505 [.000]	-14.0318 [.000]
Incident duration	0.99658 [.000]	1.08343 [.000]	0.170031 [.000]	1.19827 [.000]	0.152125 [.000]
Volume	-	8.90E-03 [.000]	0.010055 [.000]	0.01435 [.000]	0.01061 [.000]
1 lane blocked	-	2.39768 [.001]	3.53768 [.000]	5.06702 [.000]	3.61839 [.000]
2 lanes blocked	-	5.28852 [.000]	7.43028 [.000]	10.4489 [.000]	7.50181 [.000]
R^2	0.99873	0.775601	0.669801	0.811807	0.666523
Adjusted R^2	0.99872	0.772658	0.665471	0.809339	0.66215

4.4 Assessment of the SBSIF Method

To assess both the proposed regression technique for quickly delineating the boundaries of the traffic impact area of archived incidents and the resulting ability of the larger SBSIF method to identify secondary incidents, the SBSIF method employing regression for corner point

identification was tested on archived incident data for the 10-mile segment of I-287 discussed in Section 4.3.3 for a six month period in 2006 (January 1 through June 30). Secondary incidents identified through this SBSIF implementation were compared with those identified through the alternative implementation of the SBSIF method employing visual delineation of the impact areas. These results were further compared with those of commonly used static filtering methods.

4.4.1 The Regression Technique for Corner Point Identification

The proposed regression models for identifying the corner points of the incident impact area were calibrated on a set of artificially created incidents with representative characteristics. To assess the ability of the regression models to identify the corner points of the incident impact areas of incidents from data archives for a particular location, contour maps of the incident impact areas associated with archived incident data for the I-287 study roadway segment were delineated. 693 incidents (for which the most complete information was available) of the 1,303 archived incidents for this roadway segment and study period were considered as potential primary incidents. The 1,303 incidents were classified as either resulting from a collision or a disabled vehicle. Only incidents involving a collision (630 of the 1,303 incidents) were considered to be potential secondary incidents.

To create the contour maps, the 693 incidents with their properties were replicated within the CORSIM simulation platform employing a model of the I-287 study roadway segment under prevailing traffic conditions as estimated from 2007 traffic data. Note that no real-time traffic data could be obtained for the study period in 2006. Thus, average hourly traffic volumes were computed by month and weekday for the same period in 2007 for use herein. Once the traffic speed contour maps were created, the corner points of each incident's impact area were identified.

It was assumed that visual inspection of the contour maps, as illustrated in Figure 4-4 of Section 4.3.3, would yield the most accurate depiction of the traffic impact areas and associated corner points. Thus, visually identified corner points were taken as the truth. The corner points obtained through the regression models were compared with those obtained through visual inspection and differences were noted.

Plots of visually estimated (x,y)-coordinates against regression predicted (x,y)-coordinates of the impact area polygon corner points associated with the backward forming shockwave (Node 3 in the impact area polygon depicted in Figure 4-3c) and re-establishment of pre-incident traffic conditions (Node 4) are provided in Figure 4-3c. The closer each point in the plot is to the diagonal, the closer the predicted value is to the visually estimated value. Resulting corner point coordinates from both visual identification and regression modeling estimation are given in Table 4-5 for a randomly selected sample of incidents chosen from the incident data archives (i.e. from the 693 incidents occurring along I-287). Note that no samples with zero-valued y_3 or y_4 were included in the sample.
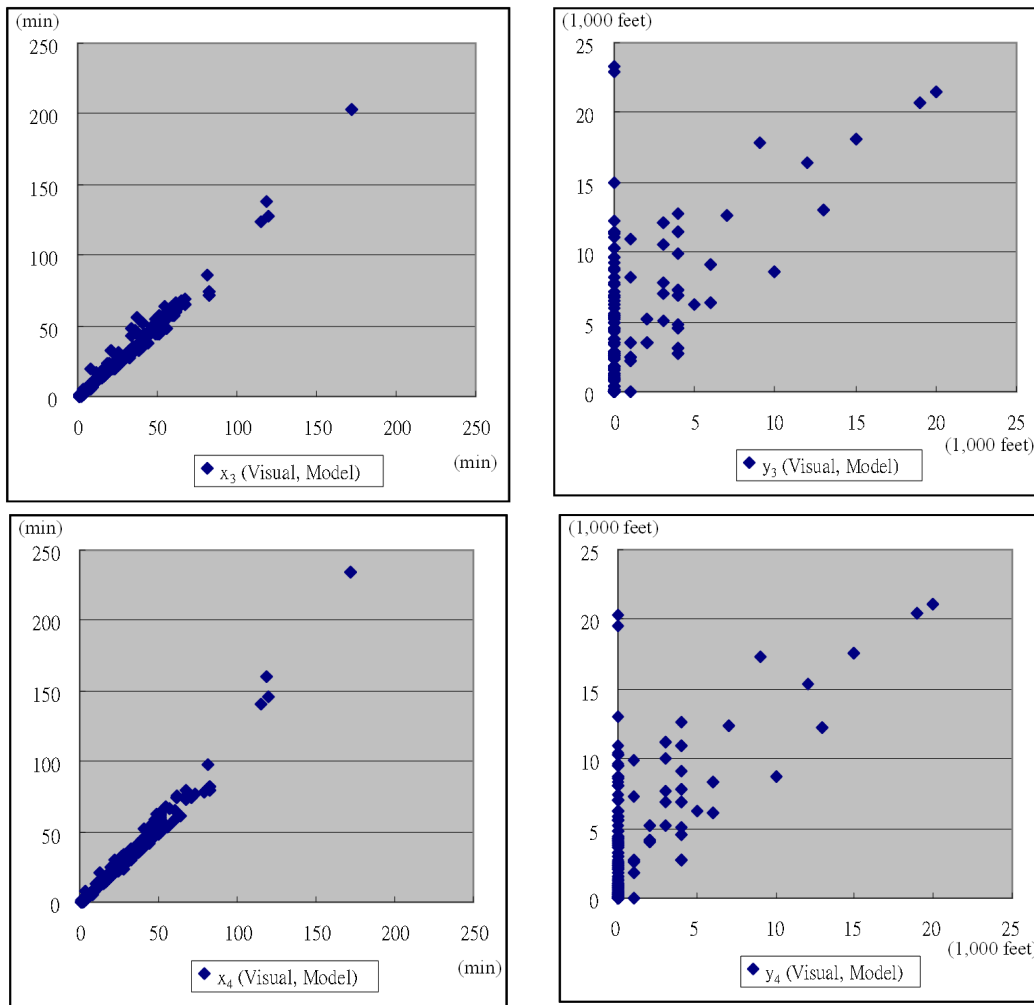
Figure 4-6: Corner point prediction trend via regression modeling

Table 4-5: Comparison of corner point coordinate estimates

Corner Points / Incident Case	Visually Identified Corner Point Coordinates								Regression Model Predictions of Corner Point Coordinates							
	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4
173	0	0	17	0	19	4	23	4	0	0	16	0	21	6	26	6
175	0	0	27	0	26	3	32	3	0	0	26	0	32	8	37	8
187	0	0	10	0	8	1	11	1	0	0	9	0	11	2	13	2
212	0	0	14	0	15	4	20	4	0	0	13	0	19	8	25	8
215	0	0	35	0	21	1	36	1	0	0	34	0	37	6	42	5
248	0	0	51	0	58	15	71	15	0	0	50	0	59	13	68	13
249	0	0	7	0	8	2	10	2	0	0	6	0	11	6	15	6

Note: x_1, y_1 and y_2 are zero by definition.

The results shown in Figure 4-6 suggest that the proposed regression models better predict the temporal impact on traffic speeds of incidents than the spatial impact. Improved fit in terms of the spatial impact might be achieved by developing regression models specific to each incident classification. Unlike predictions from static threshold filtering techniques and the dynamic progression curve approach of Chilukuri and Sun (2006), results of Table 4-5 show that the proposed SBSIF method identifies unique corner points for incidents with different properties and associated prevailing traffic conditions. Results of Table 4-5 also indicate that the regression technique is more likely to slightly overestimate the impact of an incident than to underestimate it, but generally provides reasonable estimates. Once calibrated, this approach requires little computational and data processing effort, on par with the simple static threshold methods.

4.4.2 Assessment of the SBSIF Method

By considering traffic dynamics, the proposed SBSIF method overcomes the deficiencies of the static threshold filtering methods that have been proposed in the literature. These static methods would identify an erroneous impact area and, therefore, would identify erroneous secondary incidents (positive error) or would fail to identify incidents as secondary (negative error). An example from the archived data to illustrate a positive-type error is provided in Figure 4-7, where the static method identifies an incident as secondary that would not be considered secondary if one considers the impact area correctly.
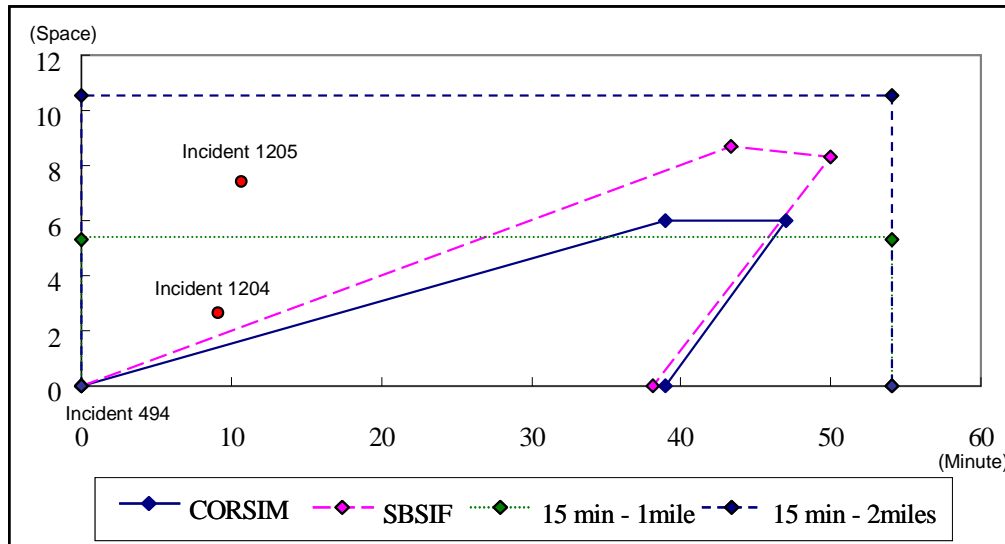
Figure 4-7: Secondary incident classification by static and dynamic methods

The impact area, as determined by both visual inspection and regression models is delineated in the figure. Incident cases 1204 and 1205 would be classified as secondary incidents by the static threshold method using 15-minute and 2-mile thresholds as proposed by Zhan et al., (2008). Similarly, using the more conservative threshold of 1-mile in conjunction with the 15-minute threshold as proposed by Raub (1997), only incident 1204 would be classified as a secondary incident. Neither incident, however, appears to be a secondary incident when the impact area of primary incident 494 is correctly considered.

To assess the effectiveness of the proposed SBSIF method employing regression for impact area corner point delineation and ultimate identification of secondary incidents, the SBSIF method was employed twice for the same 693 incidents considered in the prior subsection. In one run of the method, the corner points from visual inspection were used and Step 1 of the method was omitted. In the other run, the corner points were estimated by regression as indicated in the SBSIF method description. Results of this comparison, as well as a comparison with the static threshold method, are provided in Table 4-6. It is assumed that those incidents falling

within the boundaries established through visual inspection are in fact secondary incidents. With this assumption, the table includes the number of both positive and negative errors.

Table 4-6: Error comparison between SBSIF and other methods

	Filtering method			
	CORSIM (Visual)	SBSIF (Regression)	15 minutes and 1 mile	15 minutes and 2 miles
Positive error	-	3	17	23
Negative error	-	0	0	0
Number of secondary incidents identified	24	27	41	47

Results given in Table 4-6 indicate that the regression implementation of the SBSIF method significantly outperforms the static methods. The SBSIF method identified 24 and 27 incidents as secondary incidents employing the visual and regression methods for corner point identification, respectively. In fact, with the exception of the three additional incidents identified with the use of the regression models, these approaches identified the same set of 24 incidents as secondary incidents. The additional three incidents were found within the boundary of the impact area as delineated through the SBSIF method (Steps 1 and 2) with the use of the regression models. The static methods identified as many as twice the incidents as secondary as compared with those identified through visual inspection. That is, 70.8 and 95.8% error in terms of secondary incident identification occurred for the tested implementations of the static threshold filtering methods. By contrast, the error of the SBSIF method employing the regression models was only 12.5%.

Similar results from the Haghani et al. (2006) technique as compared to the proposed SBSIF method are expected if small increments of time are employed in searching for secondary incidents that fall within the impact area. However, such a technique will require excessive

computational effort as compared with the proposed SBSIF method. If larger time increments are employed, significant errors may occur. Whether or not the errors are of a negative or positive variety depends on the implementation.

To employ the progression curve method proposed by Chilukuri and Sun (2006), estimates of maximum queue lengths are required. Since no such data is available, this method could not be tested. It is worth noting, too, that in addition to the difficulties associated with implementing their approach due to such data requirements, this method employs a single curve for all incidents, regardless of the number of lanes that are blocked by the incident and prevailing traffic conditions. Thus, it is likely that such a method will result in significant positive and negative errors in secondary incident identification.

4.5 Summary

The proposed SBSIF methodology for efficiently delineating the boundaries of the incident impact area in a time-space contour map of traffic speeds and employing the outcome in identifying secondary incidents from archived incident databases overcomes the deficiencies of previously existing techniques. The method was evaluated on 693 primary incidents that arose along a 10-mile segment of I-287 in New York State and 24 and 27 secondary incidents of 630 potential secondary incidents were identified employing the visual and regression implementations for corner point identification with the proposed method. Results of the assessment indicated that a significantly greater rate of misclassification existed for the static methods as compared with the regression implementation of the proposed SBSIF method. In fact, while the SBSIF method erroneously identified three incidents as secondary, the more common static methods erroneously identified as many as 23 incidents as secondary incidents.

Comparable findings in terms of erroneous secondary incident identification rates by method were obtained in additional analysis conducted on a larger sample, i.e. involving approximately 300 additional incidents, from the I-287 data archives. The proposed methodology requires comparable computational effort to the static methods, outperforming existing dynamic methods in this regard.

The advantages of the SBSIF method and its regression implementation will be greatest when applied on large data sets. The regression models developed herein were calibrated on representative data simulated on a model of the 10-mile study segment of I-287. While these models may have direct applicability to other roadways with similar geometry and incident characteristics, additional regression models would need to be calibrated for use in impact area identification for roadways with different geometric design or significantly different incident properties. To further refine the regression models, additional factors, such as weather, might be considered. The greater the explanatory power of the set of chosen independent variables, the more accurate the models. However, the fewer the independent variables required to obtain reasonable estimates of the impact area corners points, the less data required and the more practical the models. Future extensions might also consider the incident impact on traffic traveling in the opposite direction due to rubbernecking.

Chapter 5: Time-Saving Technique for TIM Program Evaluation

5.1 Problem Statement and Background

Non-recurrent congestion induced by traffic incidents contributes significantly to service level deterioration of both freeways and arterials. A consequence of unstable traffic conditions that result from the primary incident is the occurrence of secondary incidents. Because the occurrence of traffic incidents on freeways and arterials is unavoidable, many traffic incident management (TIM) programs that seek to mitigate the impact of each incident have been widely employed throughout the world. Examples of TIM programs include: Freeway Service Patrol (FSP), automatic incident detection, ramp metering, incident site management, Variable/Dynamic Message Sign (VMS/DMS) advisory assistance, route diversion, and professional processing accident scene programs. Such programs aim to mitigate incident impact through quick response, thereby shortening incident duration, or control traffic demand around the incident scene. FSP programs, for example, dispatch patrol trucks along their designated beats to detect incidents and assist motorists. Move-It programs encourage or require drivers involved in a minor accident (i.e. with no injuries) to remove vehicles involved in a crash and associated debris out of the roadway (Dunn and Latoski, 2003). These programs can be integrated or stand alone.

As states grapple with significant budget deficits, TIM programs around the nation have been the target of cuts. Thus, it has become of increasing importance to show that the benefits of such existing or proposed programs to society significantly outweigh their costs, as such programs often require expensive equipment, personnel, overhead, maintenance and publicity. Benefit analyses are used to quantify the social benefits that are derived from improvements in

mobility, safety, energy consumption, and environmental impact that result from operating these programs. For example, the benefits of several FSP programs across the nation in terms of travel delay, fuel consumption, secondary incident and emission pollution were estimated (Chang and Shrestha, 2000; Chou et al., 2009; Latoski et al., 1999; and Yang et al., 2007). To demonstrate the benefits of controlling traffic demand around an incident by way of a VMS/DMS program in Minnesota, improvements in travel time, total delay and safety that resulted from the program were estimated (Huo and Levinson, 2006).

Many studies that seek to quantify the benefits of TIM programs rely on microscopic simulation techniques. Such simulation tools use car-following and lane-changing models to replicate the decisions and movement trajectories of individual vehicles and their response to other vehicles, incidents and geometric design (see May (1990) for addition detail). These techniques offer the ability to model variability in individual driver behavior, and thus, are more flexible than alternative analytical approaches. Moreover, the outcome is often easily understood by experts, as well as the layperson. These studies most often involve two sets of simulation-based experiments and can be categorized as "before and after" or "with and without" studies. "With and without studies" are employed where no "before" program data is available. Given an estimated (or assumed) savings in incident duration of x-minutes as a result of the TIM program implementation, benefits are estimated from two sets of simulation runs: one in which incidents with reported durations are simulated and the other in which the reported durations are extended by x-minutes, replicating the situation where the TIM program has not been implemented. The difference in performance measures between the two sets of runs provides an estimate of savings due to the program. There are shortcomings to either approach, e.g. confounding factors that are difficult to account for in "before and after" studies and a need to

surmise what might have been in "with and without" studies.

Although simulation is a popular approach for conducting such benefit studies, it can be quite time-consuming. Thus, several studies report findings based on simulation runs of only a small portion of recorded incidents. For example, Yoshii et al. replicated only a single incident in evaluating the benefits of a dynamic route guidance program (Yoshii et al., 1995). Similarly, only three incidents with different incident durations (22, 26, and 33 minutes) were considered in a series of ITS strategy evaluations involving local and coordinated ramp metering (Chu et al., 2004). In a study of the CHART FSP program in Maryland, 120 incidents out of 1,997 were simulated in estimating the program's benefits (Chang and Shrestha, 2000). Because the estimated benefits can vary greatly with the simulated incident properties, the findings may be misleading.

To overcome the shortcomings of simulating only a select portion of recorded incidents, some studies replicate very large numbers of incidents with a wide range of attributes. For example, in analyzing the FIRST program in Minnesota (MNDOT, 2004), hundreds of representative incidents were simulated in PARAMICS. The properties of the simulated incidents were carefully defined (with durations between 0 and 40 minutes and varying lane blockage characteristics). These runs resulted in more than 100,000 output files requiring analysis. In another study, 693 historical incidents with distinct incident duration and severity level (by lane blockage) arising along a freeway segment in New York State (all relevant incidents in the historical database) were simulated using CORSIM to evaluate the H.E.L.P. program (Chou et al., 2009). Proper simulation of hundreds of incidents often requires thousands of simulation runs. For example, replication of the 693 historical incidents in studying the benefits of the H.E.L.P. program required 6,930 runs under a single assumption associated with incident duration

reduction resulting from the program. While simulation of a large number of incidents with varying properties will produce more accurate benefit estimates, such studies can be quite computationally burdensome, particularly when the number of incidents is large as might be the case where a program covers a wide study area or an area that is densely populated.

The concept of employing randomly generated incidents for the purpose of investigating the benefits of a TIM program within a macroscopic simulation platform was first introduced by Latoski et al. (1999). Such random generation was required in their study to overcome deficiencies in the historical data set. This random generation approach was later expanded in Pal and Sinha (2002) for use in a slightly different context, where the goal was to evaluate various strategies for deploying FSP trucks along roadways in Indiana. The incidents once generated were fed into a mesoscopic simulation model that combines microscopic modeling of the FSP trucks with macroscopic models of general traffic. Macroscopic models capture the relationships between flow, speed and density characteristics of traffic flow, and (unlike microscopic models) do not characterize individual vehicle movements. Since the focus of their work was on the evaluation of proposed deployment strategies and a macroscopic approach was employed for traffic modeling, no experiments were conducted to assess whether or not the number of simulation runs could be reduced through the use of such random incident generation. Moreover, few details of the produced incident distributions were provided and only limited assessment of these distributions in terms of how well they represent historical data was completed.

In this chapter, the Property-Based Incident Generation (P-BIG) procedure is proposed for designing a set of incident scenarios, with incident properties, from historical incident data for use in conducting both "before and after" and "with and without" evaluation studies of existing and proposed TIM programs. This technique can be viewed as a variation on the random

incident generation approach conceived in Pal and Sinha (2002). The P-BIG procedure ensures that the carefully selected set of incident scenarios is representative of the historical incident data set and simultaneously not overly large in number so as to induce extensive computational burden. This technique overcomes the deficiencies of prior studies in which either too few, and not necessarily representative, incidents were replicated to ensure valid results or too many incidents were replicated, requiring enormous computational effort and time for output synthesis. Results of this work will benefit police and traffic agencies, especially those in less wealthy jurisdictions, charged with running incident management programs. Procedures developed in this work reduce the effort (and thus cost) for determining whether such a program is worth its cost, or alternatively, defending the program's benefits, potentially saving it from elimination.

5.2 Methodology

A Three-Stage Time-Saving Analysis Process with embedded P-BIG procedure for generating a set of incidents with representative incident properties is presented in this section. This technique involves multiple steps, including incident duration or traffic demand savings estimation, empirically or theoretically derived incident property probability distribution function fitting, scenario generation through randomly generating a small set of incidents from the distributions, simulation running, and results analysis.

In Stage 1 of the proposed Three-Stage Time-Saving Analysis Process for TIM program evaluation, incident and traffic data are collected and analyzed, critical incident property distributions and incident duration savings due to the TIM program are estimated.

In Stage 2, with input from the incident property distributions constructed in Stage 1, a pre-selected number of incidents are randomly generated. That is, for each generated incident, a

set of incident properties pertaining to incident severity, type, duration, time of occurrence, and location is generated from the incident property distributions developed in Stage 1. It is hypothesized that, if sufficient in number, these incidents will be representative of the historical incidents and their properties, and likewise, will reflect, in correct proportion, the properties of the historical data. The generated incidents are referred to as the *base set*, with durations consistent with already implemented TIM programs. A *comparison set* is generated by appropriately increasing incident duration for each incident by the estimated average savings in incident duration due to the TIM program as found in Stage 1. Note that if a "before and after" study is considered, rather than a "with and without" study, the base set would contain incidents with durations representative of those observed without (i.e. "before") the implementation of the TIM program and the durations associated with the incidents in the comparison set would be reduced appropriately to model the expected savings due to the program (i.e. "after" the program is implemented). In studying VMS/DMS programs, or other programs designed to control traffic demand around an incident, incident durations are constant between the base and comparison sets, and instead, properties associated with prevailing traffic conditions are varied.

In Stage 3, all random incidents within the base and comparison sets are simulated and performance measures are computed. Essential measurements for benefit evaluation are derived from the difference of the pair of measurements from the base and comparison runs.

A flow chart of this Three-Stage Time-Saving Analysis Process for benefit analyses of a TIM program is given in Figure 5-1. Details of the specific steps associated with this three-stage process are provided in following subsections.
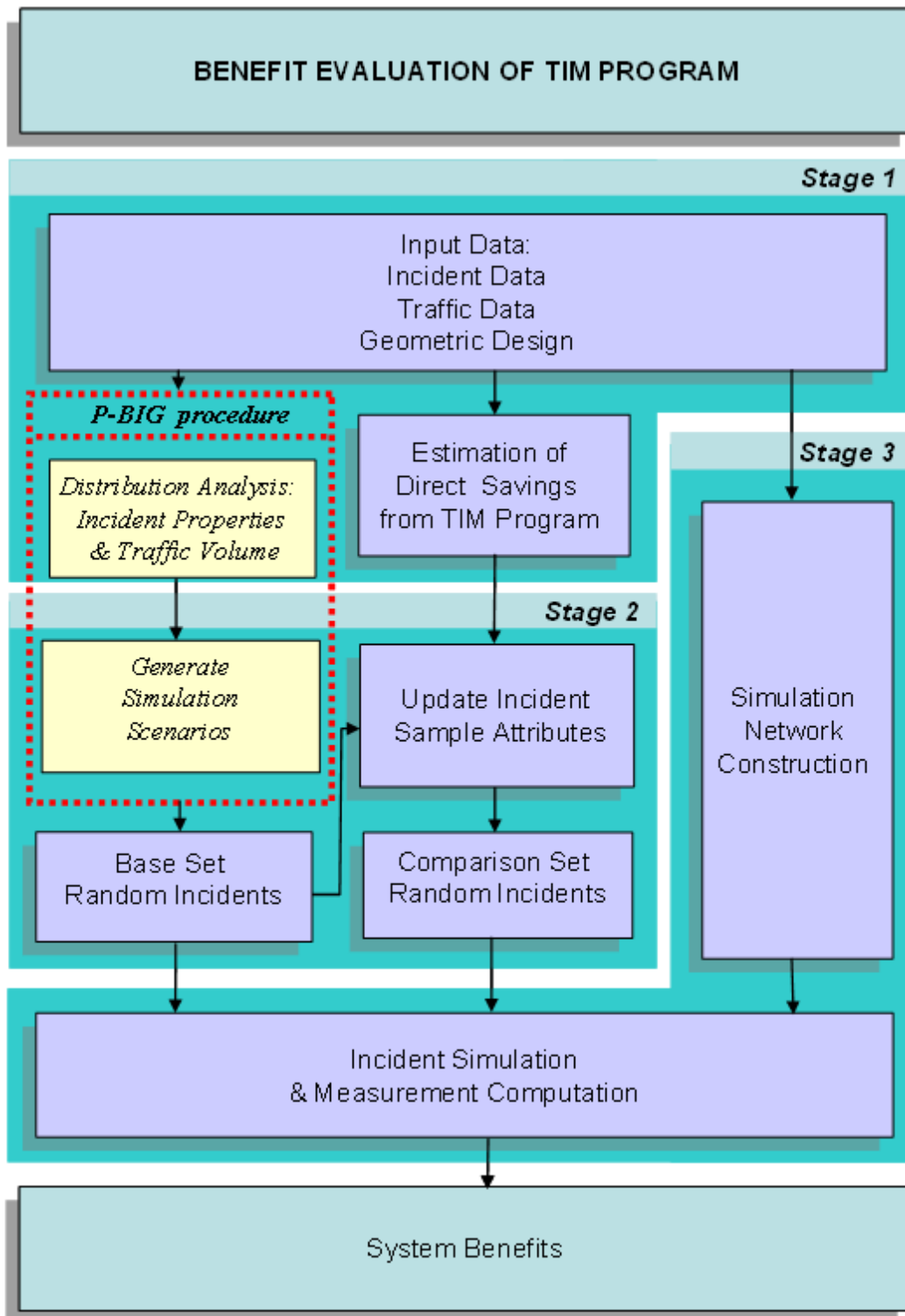
Figure 5-1: The three-stage time-saving analysis process for TIM program benefit evaluation

The contributions of this work are derived from the distribution analysis of Stage 1 and generation of simulation scenarios of Stage 2 that together comprise the P-BIG procedure.

5.2.1 Stage 1 - The Analysis Stage

To conduct a benefit study of a TIM program, incident data, traffic data, and geometric design associated with the study area must be collected. Once the data are obtained, two main tasks must be conducted in this first stage: 1) estimate direct savings, including reduction in incident duration and/or travel demand, that result from implementation of the TIM program and 2) fit incident property probability distributions. The direct savings in incident duration can be estimated by comparing two groups of incident data sets: "with and without" or "before and after". For example, many FSP program evaluations include "with and without" analyses to estimate average reduction in incident duration that results from implementation of the program. Chou et al. (2009) analyzed a total of 5,508 incidents to which either an FSP personnel or trooper responded. They found that the FSP program saved on average 19 and 20 minutes in incident duration for incidents involving disabled vehicles and collisions, respectively. In addition, reduction in travel demand can be derived from detector reports before and after the implementation of a TIM program aimed at reducing traffic demand around an incident. For instance, Huo and Levinson (2006) compared the detector output for a VMS study and found that approximately 13 to 15% of travel demand could be diverted.

The second task of the analysis stage is to fit a probability distribution function for each of the incident property characteristics. These functions are used in generating random incidents and provide an approximation to the historical data. There are several steps for fitting distributions of a sample of incidents with sufficient data points. First, the histogram of incident distributions must be drawn. Certain theoretical distribution functions can be used to fit the shape

of the histogram. Specifically, theoretical distributions of exponential, Weibull, log-logistic, gamma and lognormal can be used for fitting incident duration distributions (Nam and Mannering, 2000). Once the theoretical distribution is chosen, the parameters associated with the distributions must be estimated. The maximum likelihood estimation method is employed herein for this purpose. For example, the parameter, β, of an exponential distribution, $\exp(\beta)$, can be estimated from the sample mean. Finally, the goodness of fit for a chosen distribution can be tested by computing the chi-square statistic of theoretical and observed frequencies for chosen bins. When no theoretical distribution function is found to match the shape of the histogram, a continuous empirical distribution can be used as shown in Equation (5-1) (Law and Kelton, 2000).

$$F(x) = \begin{cases} 0, & \text{if } x < X_{(1)}; \\ \dfrac{i-1}{n-1} + \dfrac{x - X_{(i)}}{(n-1)(X_{(i+1)} - X_{(i)})}, & \text{if } X_{(i)} \le x < X_{(i+1)} \text{ for } i = 1,2,...,n-1; \\ 1, & \text{if } X_{(n)} < x, \end{cases}$$ (5-1),

where

$$x \quad : \quad x \in \{X_j\}, \quad j = 1,2,...n \quad \text{incident duration samples};$$

$$X_{(i)} \quad : \quad i\text{th smallest incident duration sample}, \quad i = 1,2,...n;$$

$$F(x) \quad : \quad \text{cumulative distribution function of variable } x.$$

5.2.2 Stage 2 - Incident Generation

A preselected number of incidents must be randomly generated. The P-BIG procedure proposed for this purpose is outlined in Figure 5-2. Incident occurrence is assumed to have a nonstationary Poisson distribution, where incident rates oscillate between high and low frequencies throughout the day. The process proposed herein generates incidents for 24 hours per day. A thinning algorithm that rejects or accepts generated random variates based on time-of-day is employed to produce incidents for select time periods as described in (Lewis and Shedler, 1979).

Procedure P-BIG

Step 0: i=1; $t_{i-1} = 0$.

Step 1: Create incident I_i with properties $t_i, l_i, m_i, d_i, y_i, s_i, r_i, e_i, v_i$; $t_i = t_{i-1}$.

Step 2: Generate U_1 and U_2 as independent identically distributed $U(0,1)$.

Step 3: Replace t_i by $t_i - (1/\lambda^* \times 24 \times P) \ln U_1$; T=$t_i / 60$.

Step 4: If $U_2 \leq \lambda(T)/\lambda^*$:

    Step 4-1: Return time property, t_i ;

    Step 4-2: Generate location property, l_i ;

    Step 4-3: Generate incident occurrence month property, m_i ;

    Step 4-4: Generate incident direction property, d_i ;

    Step 4-5: Generate incident type property, y_i ;

    Step 4-6: Generate severity property, s_i, conditioned on incident type;

    Step 4-7: Generate responding unit property, r_i, conditioned on incident type;

    Step 4-8: Generate incident duration properties, e_i, conditioned on incident type, lane
           blockage and responding unit;

    Step 4-9: Assign traffic volume, v_i, to incident based on incident properties and traffic
           data;

    else return to Step 1.

Step 5: If $t \leq 1440$, $i = i +1$, and return to Step 1; otherwise, stop. The procedure terminates.

Notation employed:

I_i	:	incident sample i ; $i \in Z^+$, an integer number for incident sample;
t	:	incident occurrence time (in minutes from midnight), $0 \leq t \leq 1440$;
l	:	mile marker, $0 \leq l \leq L$, where L is the highest mile marker value;
m	:	month, $m \in \{1,2,..,M\}$, where M is the number of months of data;
d	:	direction, $d \in \{E, W, S, N\}$;
y	:	incident type, $y \in \{1,2,...Y\}$, with Y classes of incident type (e.g. collision or disabled vehicle);
s	:	incident severity level, $s \in \{1,2,.. S\}$, with S classes of severity level;
r	:	responding unit, $r \in \{1,2,..R\}$, with R types of responding units (e.g. trooper);
e	:	incident duration, $e > 0$;
v		traffic volume; $v \in Z^+$;
P	:	adjustment factor for controlling number of incidents to be generated, $0 \leq P \leq 1$;
$\lambda(T)$	:	hourly incident rate at the Tth hour, T=(0,1,2...23);
λ^*	:	maximum hourly rate, $\lambda^* = \max\{\lambda(T)\}$.

Figure 5-2: Property-Based Incident Generation (P-BIG) procedure

To apply this procedure, hourly incident rates, $\lambda(T)$, $T = (0,1,2,\ldots 23)$, must be computed based on the incident samples. In Step 1, for i, a positive integer, a random incident (I_i) will be assigned with initial occurrence time (t_i), together with properties: location (l_i), month of occurrence (m_i), direction (d_i), incident type (y_i), severity level by lane blockage (s_i), type of responding unit (r_i), incident duration (e_i) and prevailing hourly traffic volume (v_i).

In Step 2, two uniformly distributed random variates are generated. In Step 3, the time of incident occurrence is updated by employing the first random variate (U_1) and the maximum hourly incident rate (λ^*) within the Poisson distribution. Note that P, $0 \le P \le 1$, is an adjustment factor to control the number of incidents to be generated. The smaller the value of P, the fewer incidents generated and the fewer the number of simulation runs required. By setting $P = 1$, the number of randomly generated incidents will be approximately equal to the number in the historical incident set. While the accuracy of estimates generated from results of the runs will be improved the greater the number of incidents considered, one must trade-off accuracy with computational effort.

Finally, in Step 4, the generated incident is accepted if the second random variate (U_2) is less than the ratio of its associated hourly incident rate to the maximum rate, $\lambda(T)/\lambda^*$. Once an incident is accepted, the incident duration is set (Step 4-1). Additional incident properties of incident location, month, direction, type, incident severity, responding unit and incident duration are generated in Steps 4-2 to 4-8. The procedure of creating incidents is repeated until a termination criterion based on a bound on t is met. As structured, incidents are generated over a 24 hour period, i.e. if t > 1440, the procedure terminates. If the incident is rejected, no incident properties are generated and the procedure starts over at Step 1.

Location, type, month and direction associated with each created incident can be directly generated from the appropriate distributions. Incident duration depends on incident type, severity and responding unit. Thus, a conditional distribution is used for generating incident duration once these properties are known (i.e. Steps 4-5 through 4-7). Likewise, severity and responding unit depend on incident type; thus, conditional distributions conditioned on lane type set in Step 4-5 are employed. This interdependence exists, for example, in the study of FSP programs, where FSP personnel respond to more disabled vehicle incidents than accidents. A final property, traffic volume, v, is assigned to each incident (Step 4-9). To make this assignment, incident properties of time, location and direction are used to determine the associated traffic volume based on historical traffic data. The user can filter any portion of the generated incidents, such as those occurring only during peak hours and/or only with program involvement.

Note that the procedure proposed herein considers the distributions of the most important properties for reporting incidents in most databases. Greater or fewer properties might be available for consideration, depending on the database used or data collected. The procedure for generating the attributes might be revised accordingly to fit the specific database.

5.2.3 Stage 3- Simulation and Standardization of Measurement of Effectiveness for Comparison

Once the incidents are generated, they can be employed in any simulation model for estimating performance measures. Many commercial microscopic simulation tools, including CORSIM, VISSIM, and PARAMICS, have the feature of modeling incidents. Several performance measures, such as travel delay, fuel consumption, and pollution, are computed from vehicle trajectories of the simulated vehicles recorded in each simulation run. The CORSIM microscopic

simulation platform is employed in this study. A benefit of the platform is that incident factors, including onset, clearance, duration, lane closure, capacity reduction caused by rubbernecking effect and warning sign/flair, are readily modeled for any prevailing traffic condition. With respect to modeling traffic incidents, this platform is considered to be more efficient than other microscopic simulation packages (Pulugurtha et al., 2002). Details of the processes required for replicating incidents within the CORSIM simulation platform, including the setting of key parameters, are provided in Chou et al. (2009).

To quantify the benefits of a TIM program, each incident must be replicated twice using different incident properties. The first run uses properties from the *base set*, while the second run uses properties from the comparison *set*. Suppose, for example, that a TIM program is estimated to save on average 10 minutes in incident duration, then the only difference between these two runs would be the length of incident duration. An incident in the base set with duration of 13 minutes would incur 23 minutes when considered as part of the comparison set. By evaluating the impact of the additional incident duration incurred as a result of an incident on average delay, fuel consumption and other measures of importance (in the comparison set) in comparison to the corresponding base set incident impact, one can estimate the benefit of the program savings for the given incident. By summing the benefits of all studied incident pairings (i.e. from base and comparison sets), the total benefits of a TIM program can be estimated. The average daily benefits in terms of savings achieved through incident duration reduction, $\overline{B}_d$, over a period, D, can be computed as in Equation (5-2).

$$\overline{B}_d = \sum_{d \in D} B_d / n = \left(\sum_{i \in I} \left| P_i^c - P_i^b \right| \right) / n \,, \tag{5-2}$$

where

D : set of days, d, for which incidents are simulated;

B_d : benefits achieved through incident duration reduction on day d;

n : number of days for running a program, $n=|D|$;

P_i^c : performance measure for incident i simulated from comparison set;

P_i^b : performance measure for incident i simulated from base set;

I : set of simulated incidents, i.

As designed, the proposed three-stage process for TIM program benefit evaluation uses a limited set of incidents whose properties approximate those of the entire historical data set. Savings in computational effort achieved through the proposed method for determining a reduced, but representative, set of incidents for simulation increases with increasing study period length.

5.3 Numerical Experiments and Case Study

To assess the proposed Three-Stage Time-Saving Analysis Process for TIM program evaluation, the methodology is tested using data collected over a six-month period (January to June of 2006) for the purpose of evaluating the Highway Emergency Local Patrol (H.E.L.P.) (i.e. a TIM) program in New York State. The H.E.L.P. program runs service patrol vehicles that provide free services, such as changing a tire, supplying a small amount of gasoline, jump starting a battery, pushing a vehicle out of the main lanes and off the freeway, or providing minor mechanical assistance for disabled vehicles. In the case of an accident requiring police or other emergency personnel presence, the H.E.L.P. vehicle driver can call for help and can assist in redirecting traffic around the incident. The H.E.L.P. program is operated along several freeway segments in New York State during the morning (6:00-10:00 a.m.) and evening (3:00-7:00 p.m.) peak hours.

To assess the proposed methodology in terms of its capability of estimating the program's benefits using only a reduced set of representative incidents, program benefits as estimated by the proposed procedure are compared with program benefits estimated by replicating all incidents occurring in the six month period. Two sets of runs of the proposed methodology were conducted, the first employing approximately 1/12 the number of historical incidents and the second employing 1/6 the number of historical incidents. These two sets of runs were designed to determine a lower bound on the number of incidents that must be replicated to create a representative set of incidents for procedural implementation. Accuracy of results was also examined with randomly chosen subsets of historical incidents.

5.3.1 Data Details and Distribution Estimation

Six-months of incident data along a 10-mile stretch of I-287, one of the roadways along which the H.E.L.P. program operates, were collected for this study. This roadway segment is located in Westchester County, New York, a New York City suburb. The archived incident data consists of 1,303 incidents, 968 of which occurred during the H.E.L.P. program operational hours. Incident logs describing various properties, including different stages of incident timestamps (start, end, dispatched and arrival times), incident type (disabled vehicle or collision), severity level (number of lanes blocked), direction (east or west), and responding unit (H.E.L.P., Trooper or both), are recorded in the database. H.E.L.P. truck drivers responded to 693 of the 1,303 incidents. The average reduction in incident duration due to the implementation of the H.E.L.P. program was estimated at 19 and 20 minutes for incidents involving disabled vehicles and collisions, respectively (Chou et al., 2009). A synopsis of empirical incidents and traffic data is given in this subsection. Properties of incident distributions and results of fitting distributions of incident

duration are also shown. Findings from statistical analysis of incident distribution functions were used as input for the P-BIG procedure.

5.3.1.1 Six-Month Incident Property Distributions

Time-of-day dynamics and the spatial distribution of the 1,303 incidents were analyzed. Higher incident frequencies were observed during the morning and evening peak hours as shown in Figure 5-3. Incidents occurring during the peak and non-peak hours represent 74% and 26% of all incidents, respectively. It was presumed that traffic flow patterns varied at different times of day, day of month, and location. While the traffic data were not available during the study period (the first half of 2006), average data from the first half of 2007 along the same study roadway segment were available. These data were collected from loop detectors (a traffic surveillance system which records vehicle speed, count and occupancy by measuring change of magnetic field of the detector when a vehicle passes through) at locations depicted in Figure 5-4. Traffic volume distributions at each of the detector locations for the 2007 traffic data are shown in Figure 5-5. It was assumed that traffic patterns had similar distributions in 2006 as observed in 2007.

Incident Distribution by Time-of-Day	Incident Distribution by Location
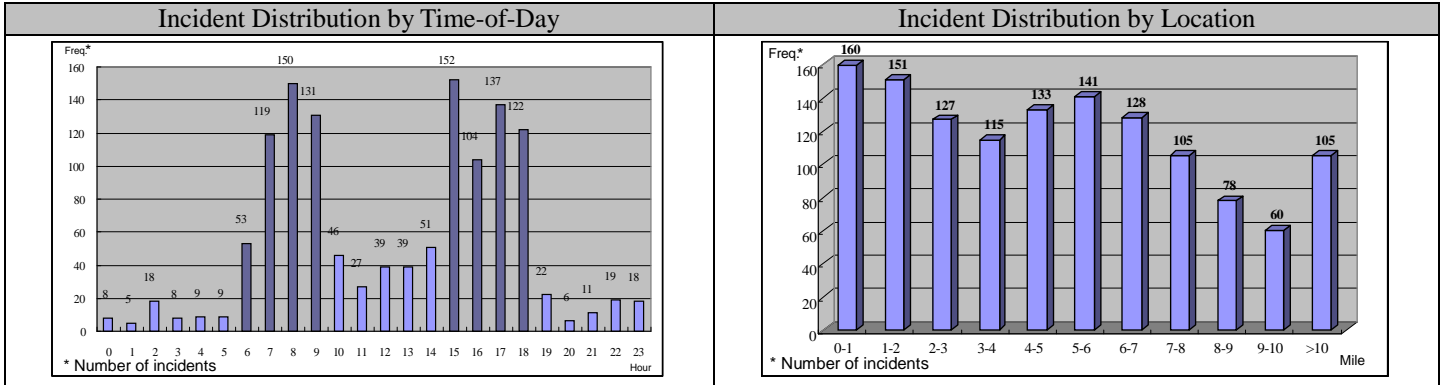
Figure 5-3: Incident distributions by time and space
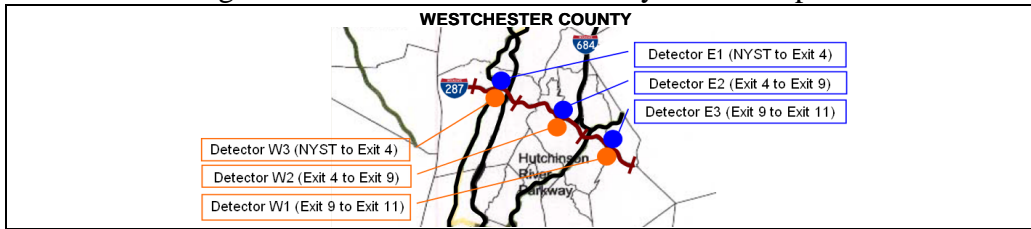
Figure 5-4: Detector locations

Westbound Weekday Traffic Volume	Eastbound Weekday Traffic Volume
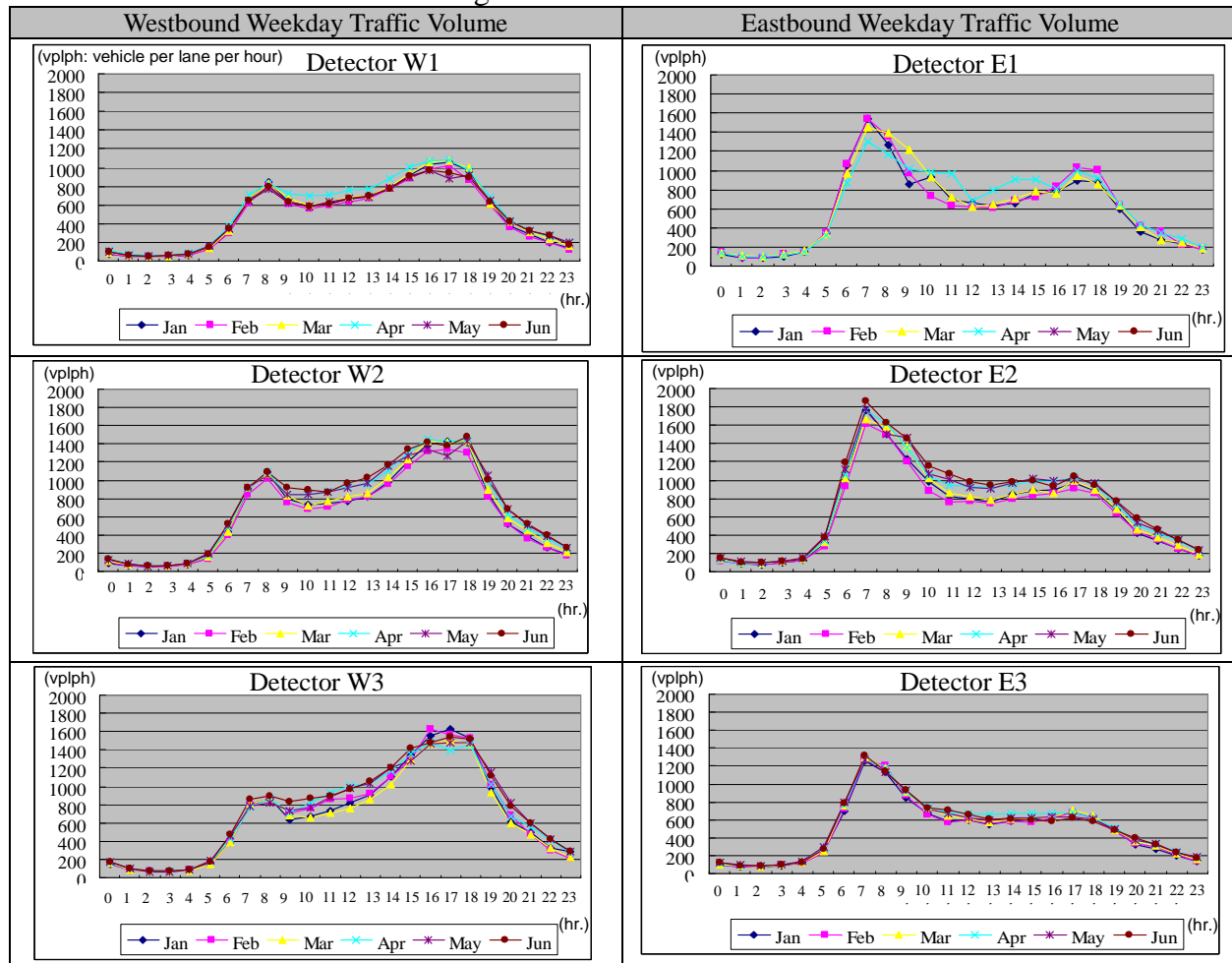
Figure 5-5: Time and space dynamics of traffic data distributions

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The studied incidents were classified into two categories: disabled vehicles and incidents involving collision (i.e. accidents). During the study period, there were 679 (52%) incidents involving disabled vehicles and 624 (48%) incidents involving collision reported. The number of lanes blocked by each incident was recorded. The greater the number of lanes blocked, the greater the impact on traffic conditions and the more severe the incident was assumed to be. For the disabled vehicle group of incidents, 91.4% blocked the shoulder. The remaining 8.6% blocked one main lane. For the incidents involving collision, the shoulder, one lane, two lanes and three lanes were blocked 72.7%, 23.5%, 3.4% and 0.1% of the time, respectively, as depicted in Figure 5-6.
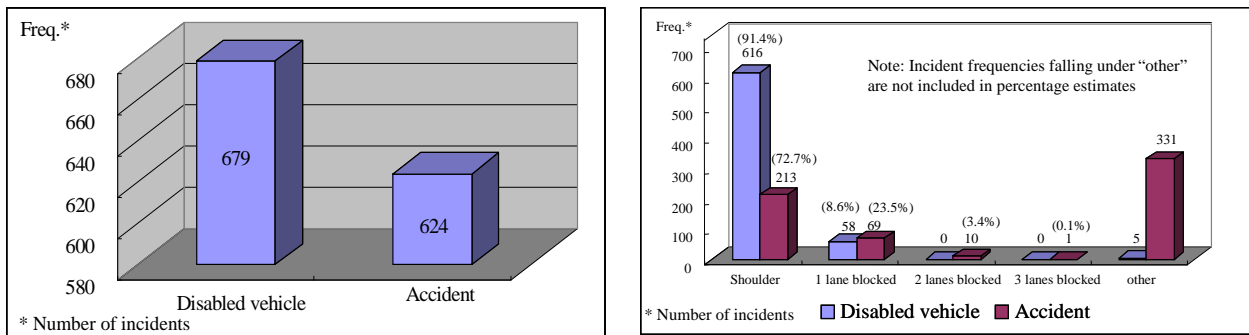
Figure 5-6: Incident distributions by type and lane blockage

5.3.1.2 Probability of Responding Unit Type

The H.E.L.P. program, like most FSP programs, is designed to assist motorists with disabled vehicles and in collisions involving property damage only. In events involving more severe collisions, i.e. involving injury or fatality, the H.E.L.P. program is designed to provide necessary assistance for the police or direct upstream (i.e. incoming) traffic safely around the incident scene. Thus, the incidents were classified into "H.E.L.P. only," "Trooper only" and "both H.E.L.P.

and Trooper" categories according to their responding unit properties. Only the 917 incidents arising during the H.E.L.P. program operational hours were considered in estimating the probability distribution function of the responding unit type. Incidents classified as "both H.E.L.P. and Trooper" (51 total) were excluded, because no information was available that indicated which responding unit detected the incident first. Table 5-1 shows the incident types and number of incidents to which either the H.E.L.P. truck drivers or the troopers responded. As indicated in the figure, the H.E.L.P. truck drivers assisted 89% of the disabled vehicles and 24% of the incidents involving collision during the peak hours. By contrast, the troopers handled 11% and 76% of the disabled vehicle incidents and incidents involving collision, respectively. This information is used in Step 4-7 of the P-BIG procedure provided in Figure 5-2 to compute the probability that the H.E.L.P. program was involved in a specific incident during peak hours.

Table 5-1: Incident response rates

	Collision	Disabled vehicle
H.E.L.P. only	78 (24%)	524 (89%)
Trooper only	248 (76%)	67 (11%)
Total	326	591

5.3.1.3 Incident Duration Distribution for "with H.E.L.P." Incidents

After an incident is generated with its properties and responding unit type in the P-BIG procedure, the incident duration must be specified. Because this duration depends on incident type, severity and responding unit class, conditional probability distributions of incident duration must be developed. For the purposes of the case study, incident durations are only required for those incidents in which the H.E.L.P. program was involved. Thus, all conditional distributions developed in this subsection are conditioned on H.E.L.P. program response.

In estimating these distributions, it was found that, for three of five severity and incident type classifications, the exponential distribution better fits the incident duration distribution than other theoretical distributions, including the lognormal and Weibull distributions, as determined using the Best-Fit software product (Palisade Corporation, 2002). The fact that the H.E.L.P. program reported to the database many incidents of short duration may explain why the exponential distribution provides a better fit. The results are shown in Figure 5-7. Two incident categories, collisions with one and two lanes blocked, are fitted with continuous empirical distributions because no theoretical distribution was found with good fit.
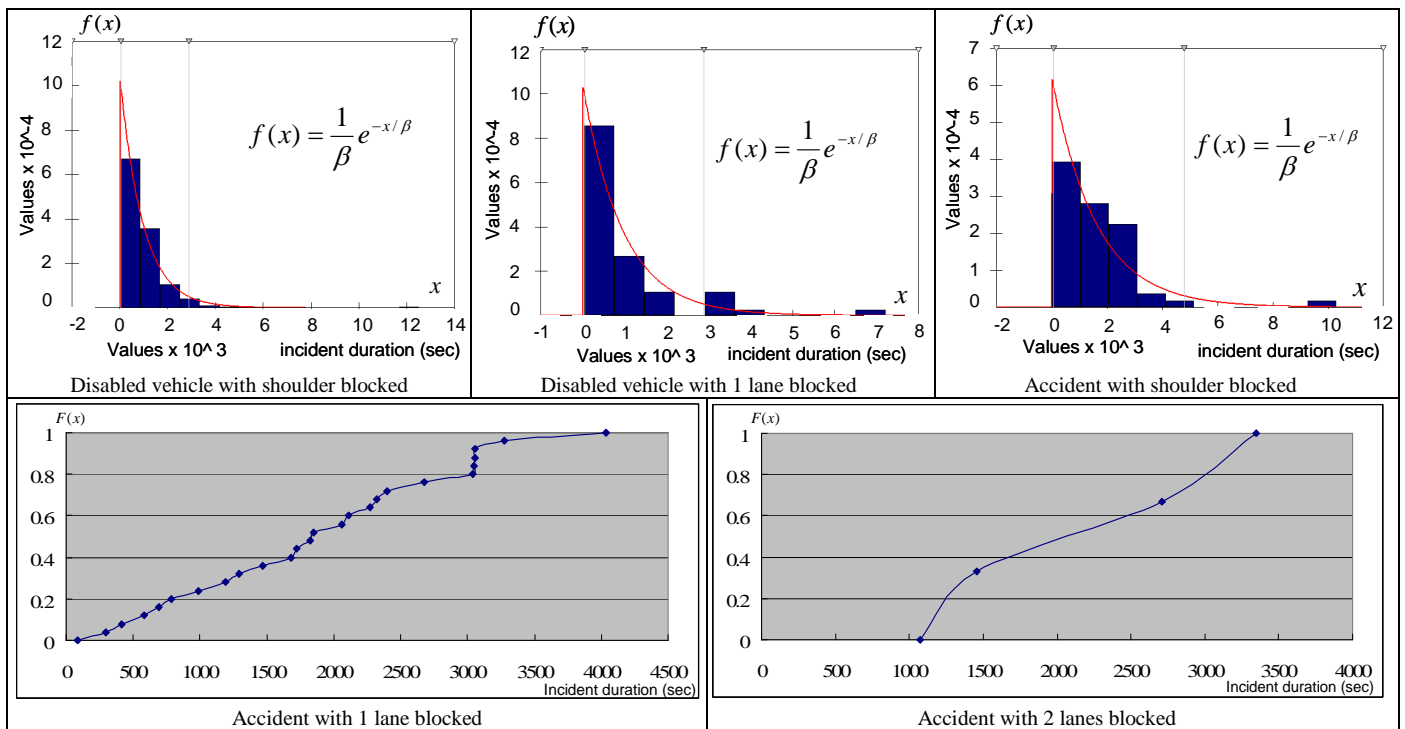
Figure 5-7: Fitting incident duration distributions using Best Fit

To estimate the parameters of the exponential distributions, the maximum likelihood estimation technique was applied, the results of which are shown in Table 5-2. The chi-square test was applied to test the goodness of fit of the resulting distributions. It is noted that of the

three classes with presumed exponential distribution, only the distribution associated with accidents blocking the shoulder pass this test assuming a 90% confidence level (i.e. with type I error probability $\alpha = 0.10$). While incident duration distributions for incidents involving disabled vehicles did not pass the chi-square test, the exponential distribution was deemed suitable based on results as displayed in Figure 5-7 and the fact that no more suitable theoretical distribution could be identified.

Table 5-2: Results of incident distribution fitting, parameter estimation, and goodness test

Incident Class	Sample size	Fitting Distribution	Estimated Parameter	Chi-square test result (χ^2 value, $\chi^2_{n,0.9}$, n)
Disabled vehicle with shoulder blocked	507	Exponential	961 (sec)	Fails (48.02, 29.62, n=22)
Disabled vehicle with one lane blocked	52	Exponential	962 (sec)	Fails (16.18, 13.36, n=9)
Accident with shoulder blocked	52	Exponential	1603 (sec)	Passes (11.342,13.36, n=9)
Accident with one lane blocked	26	Empirical	N/A	N/A
Accident with two lanes blocked	4	Empirical	N/A	N/A

Note: "n" is the bin number used for fitting the distributions and chi-square test

5.3.2 Evaluating the P-BIG Procedure

Resulting incident properties from exercising the P-BIG procedure are compared with those of the historical incidents. The following settings were employed within runs of the P-BIG procedure. $Y=2$ (i.e. $y \in \{1(\text{disabled vehicle}), 2(\text{collision})\}$), $M=6$, $d \in \{E,W\}$, $S=3$ (i.e. $s \in \{1(\text{shoulder blocked}), 2(1 \text{ lane blocked}), 3(2 \text{ lanes blocked})\}$), $R=2$ (i.e. $r \in \{1(\text{by H.E.L.P.}$ personnel), 2(\text{by trooper})\}$) and $P=1$.

Properties of historical incidents were compared with those of a comparable number of incidents generated by the P-BIG procedure for the purpose of evaluating how representative the generated incidents are of the historical incidents. The proposed procedure was applied using a

set of randomly chosen seeds (fixing the starting points for the sequence of random numbers used in generating random events), fitted distributions with parameters, and adjustment factor, *P*, equal to one. Hourly incident rates across different hours of a day were computed. A maximum hourly incident rate of 0.126 was noted to arise during the 8:00 to 9:00 a.m. hour. The comparison between the sample (i.e. incidents generated by the proposed technique) and historical data of incident rates is depicted in Figure 5-8. As shown in Figure 5-8, the resulting incident set maintains an incident occurrence rate and distribution over the day that well matches that of the historical data set.
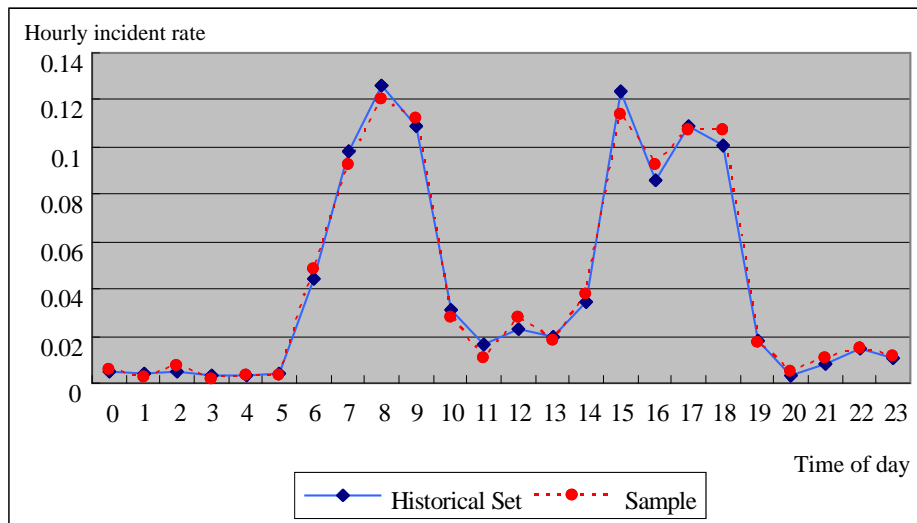
Figure 5-8: Historical and random incident rates by time of day

The percentage of incidents to which different units responded in both historical and random incident sets is given in Table 5-3. It can be seen that the percentage of incidents to which the H.E.L.P. truck drivers and troopers responded are nearly identical for both the historical and sample data sets for both accident and disabled vehicle classes.

Table 5-3: Comparison of incident frequency percentages by responding unit

	Accident		Disabled vehicle	
	Historical	Sample	Historical	Sample
H.E.L.P only	24%	27%	89%	89%
Trooper only	76%	73%	11%	11%

By inspecting the responding unit property of the sample incident set, 688 random incidents (and 693 historical incidents) were identified as having program involvement. Incident duration distributions at 10-minute intervals for these two groups were investigated as depicted in Figure 5-9. A similar pattern for incident duration is depicted between these two data sets. Likewise, a good match between data sets is noted after conditioning on incident type and severity level (i.e. number of lanes blocked) as shown in Tables 5-4 and 5-5 for one of the test sets completed for a given seed.
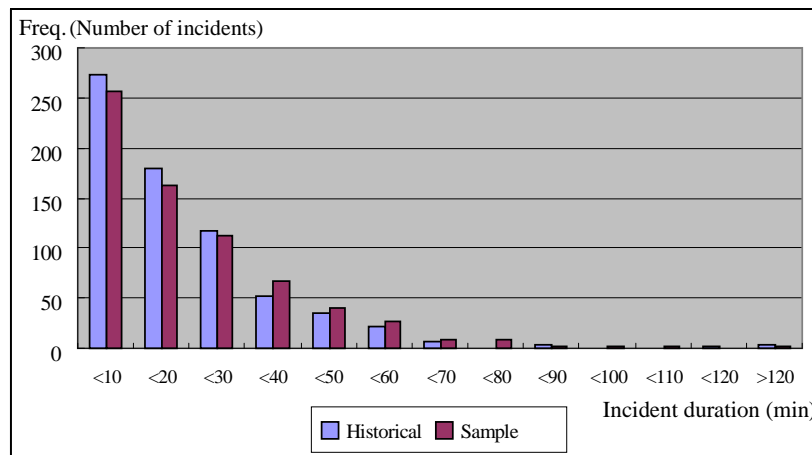
Figure 5-9: Comparison of incident duration distribution at 10-minute intervals

In Table 5-4, the incident durations are compared by incident type. The average durations for incidents involving disabled vehicles are approximately 16 and 18 minutes for the historical and sample data sets, respectively. For incidents involving accidents, the durations are approximately 29 and 27 minutes, respectively. Not only the values of average incident duration,

but also the reported frequencies and standard deviations of the historical and random incident sets, are similar. Resulting severity levels are compared in Table 5-5. The average duration for incidents with shoulder, one-lane and two-lane blockage ranges from nearly 18 to 36 minutes and 20 to 36 minutes for the historical and sample incident sets, respectively. The frequencies and standard deviations in this table are also similar.

Table 5-4: Comparison of incident duration by incident type (minutes)

	Historical			Sample		
	Freq.	Avg.	Stdev.	Freq.	Avg.	Stdev.
Disabled Vehicle	561	16.1	18.8	533	18.1	15.6
Accident	133	28.7	21.7	155	26.8	22.7
Total	693	18.5	20.0	688	20.0	17.8

Table 5-5: Comparison of incident duration by severity level (minutes)

Lane closed	Historical			Sample		
	Freq.	Avg.	Stdev.	Freq.	Avg.	Stdev.
Shoulder	601	17.8	19.8	600	19.6	18.0
1 lane blocked	86	22.1	21.0	84	22.0	16.6
2 lanes blocked	6	36.1	13.8	4	35.9	13.4
Total	693	18.5	20.0	688	20.0	17.8

Results of this comparison, thus, indicate that the proposed methodology generates random incidents with historical incident property distributions comparable to that of the original historical data.

In the next subsection, simulation results for varying incident sample sizes are compared with results from runs involving all historical incidents to show that a significant reduction in sample size can produce comparable results to runs on all historical incidents when the proposed P-BIG procedure is employed to generate the set of incidents for sample runs.

5.3.3 Comparison of Simulation Results

The Three-Stage Time-Saving Analysis Process was applied to study the impact on travel delay

of the 693 incidents arising over the six-month study period along the 10-mile stretch of I-287. Simulation runs to estimate impact on travel delay were conducted. Specifically, a CORSIM simulation model of the freeway segment with three lanes and one shoulder developed in Chou et al. (2009) was employed. In the previous subsection, it was shown that for P=1, the P-BIG procedure produces incidents with similar characteristics to the historical data; hence, one can expect comparable findings in terms of program savings in travel delay if one simulates the random incidents in place of the historical incidents. Computational effort, however, will not be reduced. In this subsection, the impact of testing a smaller number of incidents (generated by the proposed P-BIG procedure) as compared with the number of historical incidents is assessed.

This study first simulated all 693 historical incidents to which the H.E.L.P. program responded (i.e. the *base set*) in the CORSIM model. Given an estimation of 20-minute savings in incident duration due to the program, all incidents were simulated a second time with durations lengthened by 20 minutes (i.e. the *comparison set*). All other factors were assumed to remain constant. Thus, any change in performance is due to the additional delay that results as a consequence of TIM program absence. Five simulation runs for each incident, each with a different seed value, as suggested by Yang et al. (2007) in considering simulation output variability, were conducted. A total of 6,930 replications were, thus, completed. Results of these runs show that an average of 96.4 (or 385.1-288.7) vehicle-hours of travel delay per day were saved due to the H.E.L.P. program. This value is considered to be "true" and is compared with the results from simulating smaller incident data sets generated by the P-BIG procedure.

Two incident data sets were generated using the P-BIG technique, the first with approximately $1/6^{th}$ (P=1/6) and the second with $1/12^{th}$ (P=1/12) the number of incidents as compared with the historical data set. Note that for P=1/6 the number of incidents generated for the

simulation is commensurate with the number of weekdays in a month. Simulation runs of both data sets were conducted, requiring approximately 1/6 and $1/12^{th}$ the computational effort, respectively.

For $P=1/6$, approximately 120 random incidents were generated and replicated. 120 replications were completed and savings in average daily travel delay were estimated. To ensure that the results were not specific to any randomly generated set of 120 incidents, the same procedure was repeated 10 times with 10 randomly chosen sample sets and the average daily travel delay savings of the H.E.L.P. program were estimated for each of the 10 sets of runs. A confidence interval was constructed using the Student's t-distribution. The performance among these 10 samples shows a 95% confidence interval between 79.9 and 121.3 vehicle-hours of average daily travel delay savings, with an average daily travel delay savings of 100.6 vehicle-hours due to the H.E.L.P. program. Note that the "true" value of 96.4 vehicle-hours falls within the confidence interval. Additionally, the estimated average daily travel delay savings (of 100.6 vehicle-hours) is less than 5% higher than the "true" average daily travel delay savings (of 96.4 vehicle-hours).

This experiment was repeated with $P=1/12$. The 95% confidence interval was constructed, resulting in an interval between 45.4 and 110.6 vehicle-hours, with 78.0 vehicle-hours of average daily travel delay savings. Although the "true" value of 96.4 is also covered within the 95% confidence interval, the average daily travel delay savings (of 78.0 vehicle-hours) is 19% lower than the "true" value (of 96.4 vehicle-hours). The results are displayed in Figure 5-10. These results indicate that $P=1/6$ provides representative incidents and comparable results, while this is not the case for $P=1/12$.
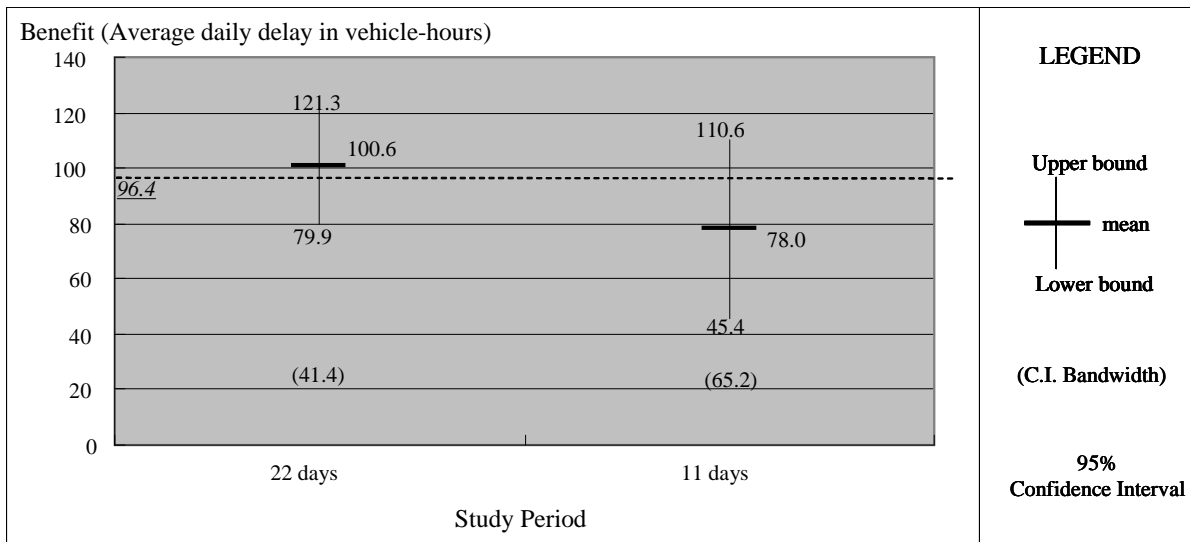
Figure 5-10: Confidence intervals of simulation results

To further assess the P-BIG procedure, results employing the procedure are compared with results gained from simulation of a randomly chosen subset of historical incidents. Specifically, 120 incidents were randomly selected from the 693 historical incident data set and simulation runs of each incident were conducted (and repeated five times for five seed values) for both base and comparison sets. Again, a 20 minute average savings in incident duration due to the H.E.L.P. program was assumed. This process was repeated 10 times and average daily travel delay savings were estimated. The performance among these 10 samples show a 95% confidence interval between 58.9 and 107.7 vehicle-hours of average daily travel delay savings, with mean 83.3 vehicle-hours, due to the H.E.L.P. program. Note that the "true" value of 96.4 vehicle-hours still falls within the confidence interval. However, the estimated average daily travel delay savings (of 83.3 vehicle-hours) is approximately 14% lower than the "true" average daily travel delay savings (of 96.4 vehicle-hours). Additionally, the confidence interval is significantly wider than the results from the P-BIG procedure as depicted in Figure 5-11, indicating greater likelihood that the random procedure will provide an erroneous estimate as compared with the P-BIG procedure. In fact, the random procedure results (for 120 incidents) are

similar to those of the P-BIG procedure when only approximately 60 incidents are considered. To obtain estimates with a confidence interval of width comparable to that of the P-BIG procedure, nearly 300 incidents would need to be randomly selected as determined in additional experiments. Thus, one can conclude that the P-BIG procedure is beneficial and outperforms simple random incident selection approaches. The P-BIG procedure is estimated to save over 100%, perhaps as great as 150%, in terms of the number of runs that would be required to obtain equally good estimates if incidents are simply chosen for replication at random.
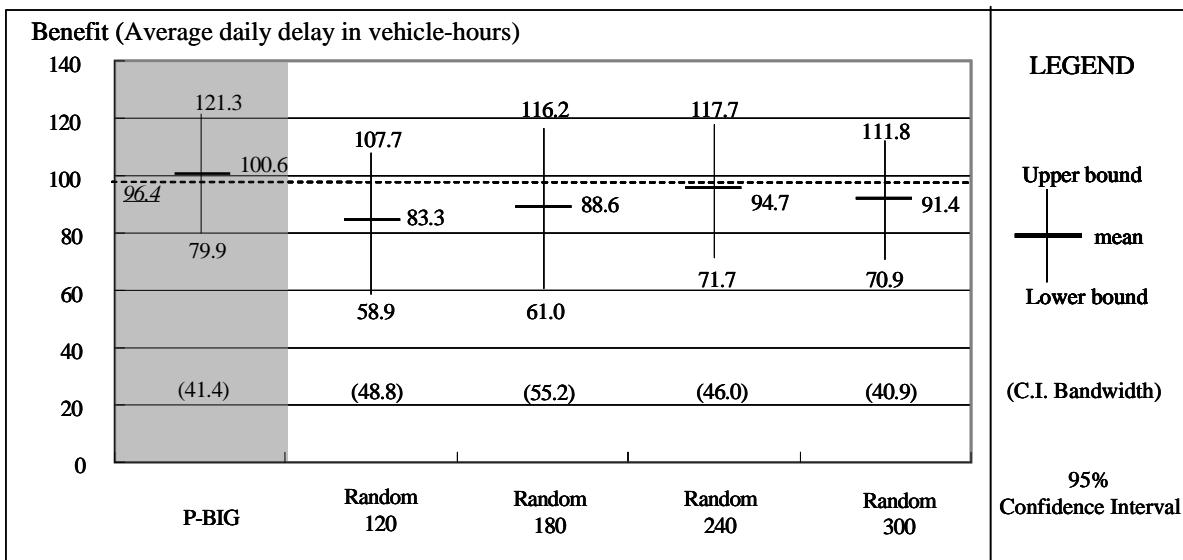
Figure 5-11: Comparison of confidence interval results with and without the P-BIG procedure

5.4 Temporal Variability and Implications for Reducing Data Requirements

Data collection and preparation for studies of a TIM program can be quite onerous, regardless of the evaluation methodology used. It was conceived that it might be possible to reduce, not only computational effort required for replication, but also data collection and statistical analyses

efforts required for incident property probability distribution fitting and program savings estimation. In fact, a range of time periods (from one month (Yang et al., 2007) to 19 months (Latoski et al., 1999)) for data collection were noted in relevant studies. Thus, it was hoped that one could employ data from only a short time period to fit the incident occurrence and property distribution functions required in the P-BIG procedure. For example, if the incident data show no statistical difference from month to month, then an arbitrary one-month period can be picked to represent important properties of the entire incident data set. Additional experiments using the data collected for evaluation of the H.E.L.P. program as discussed previously were run to assess the viability of employing a reduced data set in generating the distributions employed by the P-BIG procedure. In this section, incident duration distributions across different months are presented and statistically analyzed to determine whether or not one month of data collection effort could suffice in developing the distribution functions required by the P-BIG procedure.

Incident properties across the six month study period were considered. Table 5-6 provides a summary of incident duration by incident severity and type for each month in the study period. It can be seen from this table that incident duration varied significantly across different months for some incident categories. For example, the average duration of incidents involving an accident with two lanes blocked ranged from nearly 18 minutes in April to 56 minutes in June. In addition, there were no such incidents observed in January. Thus, incident data from one month may not adequately represent incident properties for other months of the year. Additional study is required to confirm that the variability is seasonal in nature and not random.

Table 5-6: Performance of incident duration for different classes

Incident Class		Month						Total/ Average
		Jan.	Feb.	Mar.	Apr.	May	Jun.	
Disabled vehicle with shoulder blocked	Freq:	95	65	77	49	101	126	513
	Mean (min):	13.0	16.5	14.2	13.8	20.4	17.2	16.2
	Stdev (min):	11.8	26.9	14.9	10.6	23.3	17.3	18.6
Disabled vehicle with 1 lane blocked	Freq:	0	27	8	6	3	4	48
	Mean (min):	-	12.5	18.2	13.1	13.5	25.2	16.0
	Stdev (min):	-	24.3	20.6	11.8	11.7	20.2	15.6
Accident with shoulder blocked	Freq:	17	12	8	6	23	21	87
	Mean (min):	27.0	30.9	20.4	32.2	23.5	30.8	27.3
	Stdev (min):	18.9	46.6	18.8	15.3	15.7	21.9	24.0
Accident with 1 lane blocked	Freq:	2	11	12	4	5	5	39
	Mean (min):	56.0	23.6	33.2	28.5	22.1	44.5	31.2
	Stdev (min):	15.8	11.6	17.6	20.9	11.9	11.9	16.8
Accident with 2 lanes blocked	Freq:	0	1	2	1	1	1	6
	Mean (min):	-	34.7	34.7	17.9	38.7	55.7	36.1
	Stdev (min):	-	0	14.8	0	0	0	13.8

A series of Kruskal-Wallis (K-W) statistical tests were applied to test the null hypothesis that each month of incidents comes from the same population (i.e. they have equal populations). The hypothesis is rejected if the K-W H statistic is significant at a test level of 0.05, where the K-W H statistic is computed through Equation (5-3), assuming that the H statistic follows a chi-square distribution (Kruskal and Wallis, 1952). The SPSS statistical software package (Huizingh, 2007) was employed to conduct the K-W statistical tests, using $k = 6$, results from which are summarized in Table 5-7. The hypothesis of equal population was rejected when disabled vehicles blocking the shoulder are considered. This class of incidents is the largest class, involving 74% of all incidents reported in the data collected to study the benefits of the H.E.L.P. program. Thus, using only one month of incident data may not adequately represent conditions over a longer period. Note that the sample size under other incident categories may not be large enough to make a solid conclusion about the sufficiency of employing only one month of data.

$$H = \frac{12}{n(n+1)} \sum_{i=1}^{k} \frac{W_i^2}{n_i} - 3(n+1),$$ (5-3),

where

H : statistic with chi-square distribution with $k-1$ degrees of freedom;

n_i : number of incidents in month i, $i = (1,2,..k)$; $n = n_1 + n_2 + ... + n_k$;

k : number of months considered;

W_i : sum of *ranked values* for each incident sample in month i.

Table 5-7: K-W test results of incident duration distributions for different classes

Incident Class	K-W statistics (chi-square value, P value)	Test result (90%)
Disabled vehicle with shoulder blocked	(16.365, 0.006)	Reject
Disabled vehicle with 1 lane blocked	(5.615, 0.23)	Cannot reject
Accident with shoulder blocked	(4.059, 0.541)	Cannot reject
Accident with 1 lane blocked	(10.481, 0.063)	Cannot reject

Additional experiments were run to assess average daily travel delay savings when replicating all historical data for each month separately. The results for each month are compared with the "true" value of 96.4 vehicle-hours of average daily travel delay estimated from runs replicating all six months of historical incidents. Results of these experiments are given in Table 5-8.

Table 5-8: Simulation results by simulating monthly incident data separately

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Total
Number of incidents	115	116	107	67	133	156	693
Number of weekdays	20	19	23	20	22	22	126
Total travel delay (vehicle-hours)	336.0	2,196.6	4,460.7	1,896.3	1,011.2	2,245.3	12,146.0
Average daily travel delay (vehicle-hours)	16.8	115.6	193.9	94.8	46.0	102.1	96.4

The results indicate that there is great variability in travel delay savings, ranging from nearly 17 to 194 vehicle-hours saved per day when considering each month separately. Thus, there is a high risk of over- or under-estimating the program's performance with only one month

of data. A longer study period is suggested to compensate for short-term variation in incident properties. Such variability may be of more or less significance in other parts of the country. This issue of seasonal variation must be considered when applying any TIM program evaluation methodology on a limited data set.

5.5 Summary

The Three-Stage Time-Saving Analysis Process with embedded Property-Based Incident Generation (P-BIG) procedure was developed for use in TIM program evaluation in which simulation is applied to assess travel delay savings. The procedure overcomes the drawbacks of approaches applied in existing studies of such programs. For example, some studies experiment with all historical incidents in a study period and, thus, require enormous computational effort, while other studies experiment with only a small subset of randomly chosen incidents from the historical incident dataset. The use of a sample of historical incidents results in significant reduction in computational effort; however, if not chosen carefully, the results of such experiments may over or underestimate program benefits. This study provides a methodology, the P-BIG procedure, for the careful selection of a set of incidents for use in such experiments. The procedure estimates incident property distribution functions based on historical data. These distributions are integrated within a non-stationary Poisson random variate generation process to produce a relatively small set of representative incidents for simulation and derivation of benefit estimates.

To assess the proposed methodology, the Three-Stage Time-Saving Analysis Process was applied on a case study involving a freeway service patrol program in New York State. Six months of empirical data pertaining to the program were examined. Experiments were conducted

in a simulation platform in which all historical incidents were replicated, requiring 6,930 simulation runs. Results from these initial experiments showed that an average of 96.4 vehicle-hours of daily travel delay was saved due to the H.E.L.P. program. Additional experiments were conducted on a set of incidents generated by the P-BIG procedure. A savings of 82% in simulation run time and an average error of only 5% were noted as compared with runs involving all historical incidents. When 120 incidents were randomly selected without the assistance of the P-BIG procedure, the average error was over 14%. To achieve a similar 5% error, nearly 300 randomly chosen historical incidents would need to be considered in the experiments. Thus, careful selection of a set of incidents using the proposed P-BIG procedure results in estimated benefits that nearly perfectly match estimated benefits from runs of all historical incidents with only 18% of the computational effort.

In the case study, monthly variation in incident properties was found to be significant for the six-month study period, suggesting that such variation should be considered in TIM program evaluation studies, as replication of incidents based on properties from only one month could lead to over or underestimation of program benefits. This finding applies not only to the methodology developed herein, but to more traditional simulation-based approaches for studying TIM program benefits. Future study could investigate additional characterization of incident property distributions and could test the Poisson arrival assumption related to incident occurrence.

Additional benefits of the proposed methodology may be derived in benefit studies, where efforts required for data collection are prohibitive. In such circumstances, it may be reasonable to employ the incident property distributions determined in this study, possibly with changes in only the parameters. While imperfect, for many locations and many studies, such input may be sufficient.

Chapter 6: The Impact of Violations in Computational Assessment of Non-barrier Separated Managed Lanes

6.1 Introduction and Motivation

State agencies have become increasingly interested in the construction of managed lane facilities operating concurrently with general purpose (GP) lanes along existing roadways as a means of addressing the continued growth of traffic congestion on the United States' (U.S.) freeways. High-Occupancy Vehicle (HOV) lanes, for example, have been widely implemented and the benefits of such lanes have been espoused. Along many roadways, it has been noted that such HOV lanes are underutilized. That is, these lanes can carry additional traffic without significant performance degradation. Thus, conversion of HOV lanes to HOT lanes, lanes that can be used by vehicles with 2, 3 or more riders for free or at a reduced cost and by vehicles with single occupants for a fee, is beginning to gain traction around the country. It is believed that such conversion can facilitate effective use of existing roadway capacity, lead to improved travel times for all vehicles, and produce additional revenue to support much needed transportation improvements. California, Colorado, Florida, Georgia, Minnesota, New York, Utah, Texas, Virginia and Washington, for example, have recently constructed new HOT lane facilities, converted HOV lanes to HOT lanes, or are in the process of studying the benefits and requirements of constructing (or converting HOV lanes to) HOT lanes. See Miller-Hooks et al. (2007) for additional details.

Continuous access to HOV lanes is a commonly used practice; however, given existing toll collection technologies, access to HOT lanes must be more limited. Physical barriers in the form of concrete barricades or plastic pylons, for example, are often constructed to ensure

compliance with rules for accessing HOT lanes. Increasingly, however, non-barrier separation techniques are employed for this purpose. Such techniques may be used where the necessary space required for physical barrier separation and police activities required for enforcement is limited or construction and maintenance costs of such barriers is prohibitive. Non-barrier separation methods (buffer separation delineated by white or yellow lines), as a result, have become more common. Non-barrier separation methods, however, permit nearly unlimited improper ingress/egress to/from the managed lanes. These violations impact free-flow speeds of both managed and GP lanes. Additionally, violations have a negative impact on revenue. While vehicle occupancy violations are the primary violation-related concern associated with HOV lane use, violations of a variety of types exist with respect to the use of non-barrier separated HOT lane facilities. Specifically, these violations include: (1) carrying fewer people than the minimum occupancy required (i.e. vehicle occupancy violations); (2) failure to pay electronic tolls (e.g. may have proper transponder, but the account may not be in good standing); and (3) access to or from the HOT lanes at points where such access is denied (i.e. access violations).

To predict improvements in travel speeds and other traffic performance metrics and the potential revenue that can be raised through the introduction of a new HOT lane facility within an existing roadway, and to assess potential practicable operational strategies and facility designs, computer simulation is often employed. For example, simulation-based studies have been conducted on proposed and existing non-barrier separated HOT lane facilities of I-394 in Minnesota (Buckeye, 2009; Lari and Buckeye, 1998; Halvorson et al., 2006; Munnich and Buckeye, 2007), SR-167 and I-405 in Washington State (WDOT, 2003; Westby, 2005), I-15 in Utah (Miller-Hooks et al., 2007), and I-580, I-680, I-880 and SR-85/US-101 in California (PB Americas, 2006; Caltrans, 2007; Orange County Transportation Authority, 2002; Santa Clara

Valley Transportation Authority, 2005). While numerous studies have indicated that violations are of significant concern for HOT lane facilities, in fact the national average annual violation rate associated with HOV and HOT lanes in the U.S. was estimated in 2005 to involve between 10 and 15 percent of all vehicles using managed lanes (Martin et al., 2005), to the best of the authors' knowledge, only one previous simulation-based study has replicated violators; Chen et al. modeled occupancy violators (Miller-Hooks et al., 2009). They did not, however, consider the impact of the violations on roadway performance.

In this chapter, the potential impact of violations related to HOT lane access and vehicle occupancy on traffic performance in managed and GP lanes is quantified for an existing roadway segment with single HOV lane and proposed HOT lane facility conversion. Techniques are developed for modeling violation behavior in concurrent flow lane operations within a widely used microscopic traffic simulation tool. The significance of the violation impact on traffic performance for future managed flow lane facility performance and benefit analyses is assessed in extensive and systematically designed experiments. Based on results of the assessment, recommendations are made as to the criticality of modeling violations in simulation analyses, including violation rates, which if exceeded given that violations are unmodeled, would significantly impact performance measurements. Implications for enforcement are also considered.

6.2 Review of Managed Lane Facility Violation Rates in the U.S.

Originally continuous access HOV lanes, the I-394 MnPASS Express Lanes, re-opened in May 2005 as Minnesota's first HOT lane facility (a 5-mile portion of which is non-barrier separated). Munnich and Buckeye (2006) estimated that the violation rate associated with the original HOV

lane facility was on the order of 20 percent in terms of the number of vehicles employing the lane for some portion of their trip. After conversion to HOT lanes, additional law enforcement and technologies were employed to catch violators. Even with significant enforcement, violation rates associated with the MnPASS lanes are estimated to be approximately 9 percent. In fact, of all citations written along the HOT lane portion of I-394, 46.8% were related to occupancy violations and 12.4% were for violations involving the crossing of the buffer (Buckeye, 2009).

Efforts to reduce violations related to HOV lanes continue along SR-167 in Washington State. This 9-mile stretch of HOV lane is slated for conversion to a buffer-separated HOT lane facility currently uses the HERO program to encourage drivers to self enforce HOV lane rules. The HERO program enables drivers to report an HOV lane violator by e-mail or phone. When a large number of violators are reported at a specific location, the Washington State Patrol is informed and will target their enforcement to that location. The violation rate estimated for the entire HOV lane network in Washington State ranges between 1 and 7 percent (Munnich and Buckeye, 2007).

Utah's buffer separated HOT lane facility is located along 38 miles of I-15 emanating from Salt Lake City. During a travel time study along this facility that involved probe vehicles, violations were noted and observations were made. The most noteworthy of the observations are that when GP lane speeds decrease, the number of vehicles improperly crossing solid markings (violation type (3)) to use the express lanes for the purpose of passing slower moving vehicles increase and as HOT lane speeds decrease, violations involving the crossing of solid markings from the HOT lane into the GP lanes increase (Martin et al., 2005).

Additional experience with enforcement related to violations associated with managed lanes is reported by the California Department of Transportation (CalTrans) (Miller-Hooks et al.,

2007). While significant funds (nearly all of the toll revenue) are expended on enforcement, high violation rates remain. In California, it is currently recommended that routine enforcement be used to keep HOV violation rates to less than 10 percent. Experience has shown that complaints increase as violation rates approach and exceed 10 percent. Once violation rates of 10 percent or higher are detected, the local area California Highway Patrol is notified of the need for greater enforcement in a particular location. CalTrans reported that the highest violation rate arising within the San Francisco Bay Area occurs in Alameda County along the westbound lanes of I-80. For 2005, this rate was estimated to be 20.6% during the p.m. peak (Cabanatuan, 2007).

Fitzpatrick et al. (Fitzpatrick et al., 2008) studied violation rates associated with access to or from a non-barrier separated HOV lane at points where access is denied. They found that the percent of maneuvers in compliance with the pavement markings varied with the length of the intermediate access opening and driving speed. Non-compliance rates (with respect to pavement markings) were approximately 15 percent during those periods with speeds less than 40 miles per hour in GP lanes or speeds greater than 60 miles per hour in the managed lane.

Estimates of violation rates pertaining to managed lane facilities obtained from the literature are summarized in Table 6-1.

Table 6-1: Violation rates of concurrent flow lanes

Managed Lanes	Average Violation Rates	Year	Reference
Alameda County, CA	20.6% p.m. peak	2005	(Cabanatuan, 2007)
Boston, MA	Under 5%	2003	(Cothron et al., 2003)
Dallas area, TX	1-6%	2003	(Cothron et al., 2003)
Ft. Lauderdale, FL	20%	2003	(Cothron et al., 2003)
Hartford, CT	5%	2003	(Cothron et al., 2003)
Honolulu, HI	20%	2003	(Cothron et al., 2003)
Minnesota (I-394), MN	9%	2007	(Munnich and Buckeye, 2007)
Montgomery, MD	7-33% NB, 6-16% SB	2003	(Cothron et al., 2003)
Nashville, TN	33-40%	2003	(Cothron et al., 2003)
Northern Virginia, VA	12-13%	2003	(Cothron et al., 2003)
Orlando, FL	90%	2003	(Cothron et al., 2003)
Salt Lake City, UT	2.59% a.m. peak	2005	(Martin et al., 2005)
Suffolk County, NY	5-10%	2003	(Cothron et al., 2003)
Washington State, WA	1-7%	2006	(WDOT, 2003)

Even with significant enforcement, violation rates related to non-barrier separated managed lanes in the U.S. are considerable. Such violations can dramatically impact traffic performance in both the managed and GP lanes. Despite this, with the exception of the earlier mentioned work by the authors (Miller-Hooks et al., 2009), no prior model developed for the purpose of predicting improvements in travel speeds and other traffic performance metrics and the potential revenue that can be raised through the introduction of a new HOT lane facility within an existing roadway, or assessing potential practicable operational strategies and facility designs, has incorporated this violation behavior. This chapter assesses the importance of this omission.

6.3 Violation Modeling Techniques for Use in VISSIM

The VISSIM simulation software package was employed within this study. This traffic simulation software, a microscopic simulation methodology, is widely used in the U.S. as a tool for assessing the operational impacts of the introduction of HOT lanes and the selection of

particular toll collection and access point locations or designs to existing roadway facilities. It has also been used to provide necessary input in terms of travel times for revenue forecasting. While VISSIM has been employed to model HOT lane facilities in numerous simulation-based studies of facilities in a variety of states, and in two locations in the U.S. of which the authors are aware such HOT lanes have been treated as a separate lane rather than as a separate facility (Westby, 2003; Miller-Hooks et al., 2009), no such prior work has studied the impact of violations. In this section, modeling techniques created to allow treatment of the HOV or HOT lanes as non-barrier separated lanes (as opposed to separate facilities), facilitating the modeling of violations involving access to and from the HOT lanes at undesignated locations, are presented.

6.3.1 General Freeway Operations Modeling using VISSIM

The VISSIM software package, like many others, implements accepted car-following and lane-changing models to capture the detailed interaction between vehicles. Miller-Hooks et al. (2009) provide details associated with modeling concurrent flow lanes in VISSIM. In this previous work, techniques for ensuring smooth transitioning between collector-distributor (CD), GP and HOV or HOT lanes with continuous or limited at-grade access, providing access as required to managed lanes for only a subset of vehicle classes, and ensuring consistency in acceleration and deceleration lanes, as well as meeting other model requirements, are described. These techniques were adopted in this study. Additional modeling efforts involving the inclusion of Route Decisions and changes to the Lane Change parameter of associated connectors were expended to further reduce bottlenecks that were noted to incorrectly arise at merging and weaving portions of the on-ramps and occurrence of missing vehicles.

Once the simulation model is constructed, parameters associated with car-following and lane-changing behavior must be tuned (calibrated) such that traffic measures from the simulation best match actual measurements taken from the field. Five critical parameters in the "Wiedemann 99" model, the chosen modeling option, were identified in Miller-Hooks et al. (2009) through extensive computational testing and advice from the literature and modeling experts.   This study benefits from this prior calibration effort.

6.3.2 Modeling Violations along Managed Lanes on Freeways

Vehicle occupancy and access type violations (violations types (1) and (3)) are studied herein. Such violations are depicted in Figure 6-1 for a hypothetical freeway segment (single direction) with three GP lanes and a single non-barrier separated, at-grade, limited access, HOT lane and a single gantry for tolling. Four vehicle classes are considered: (1) single occupancy vehicles (SOVs) without the necessary equipment to use the HOT lane; (2) vehicles with the necessary number of occupants for HOV/HOT lane use; (3) single occupancy vehicles with the necessary equipment to use the HOT lane; and (4) trucks, which are not permitted to use the HOT lanes.
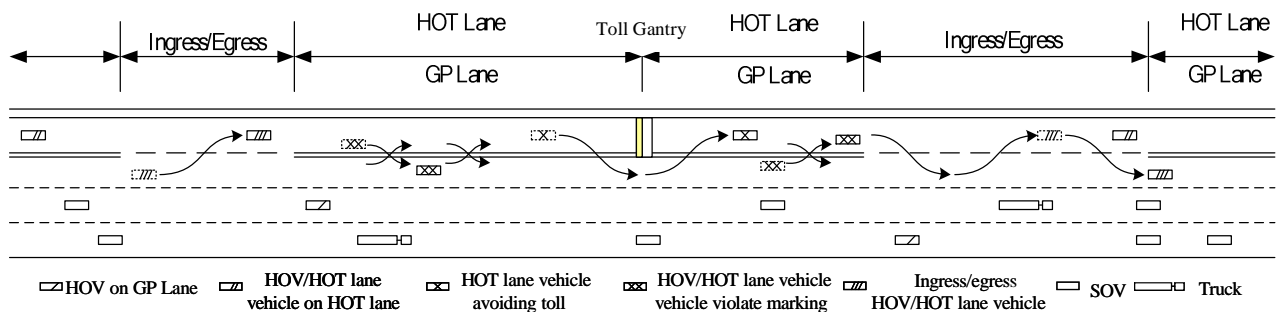
Figure 6-1: Example of driving violation maneuver

The figure illustrates a number of different maneuvers, including the movement of vehicles into and out of the HOT lane at permissible access points, shown by a dashed line, a vehicle whose driver avoids toll payment by switching between the HOT lane and the adjacent GP lane immediately prior to the tolling location (rectangle with single cross), and vehicles whose drivers violate the law by crossing the buffer either from the GP lanes into the HOT lane or from the HOT lane into the GP lanes (rectangle with double crosses). Although not depicted in the figure, one might also illustrate similar access violation behavior by SOVs and trucks.

In succeeding subsections, the methodology employed within VISSIM to model and control such violation behavior is described. The rate of violation is set in setting the percentage of vehicles that fall under each vehicle type, creating the vehicle composition. Violators are created as a vehicle type and more than one vehicle type associated with violation behavior can be created.

6.3.2.1 Occupancy Violation

To model occupancy violations, two Vehicle Classes associated with different Vehicle Types are created with the same driving behavior (e.g. speed function) but different occupancy values: one with a single occupant (the violator) and the other with multiple occupants (legitimate HOT lane user). The Lane Closure property of each lane of each link in the VISSIM model can be set to one of two states for each Vehicle Class: "open" or "closed." This setting permits control of the movements of vehicles across lanes within a given vehicle class. Thus, by setting the GP lanes to "closed" at locations parallel to HOT lane buffers and "open" at the access points, and similarly setting the HOT lane to "open" throughout, the valid HOT lane users will use the HOT lane as needed and the GP lanes only for ingress and egress to and from the facility. This is depicted in

Figure 6-2a. Note that occupancy violators are similarly modeled, effectively increasing the rate of HOT lane use and decreasing the rate of GP lane use.

6-2a: Normal HOV/HOT lane users and occupancy violators

6-2b: Access violation type 1 (without lane closure setting)

6-2c: Access violation type 1 (with lane closure setting)

6-2d: Access violation type 2
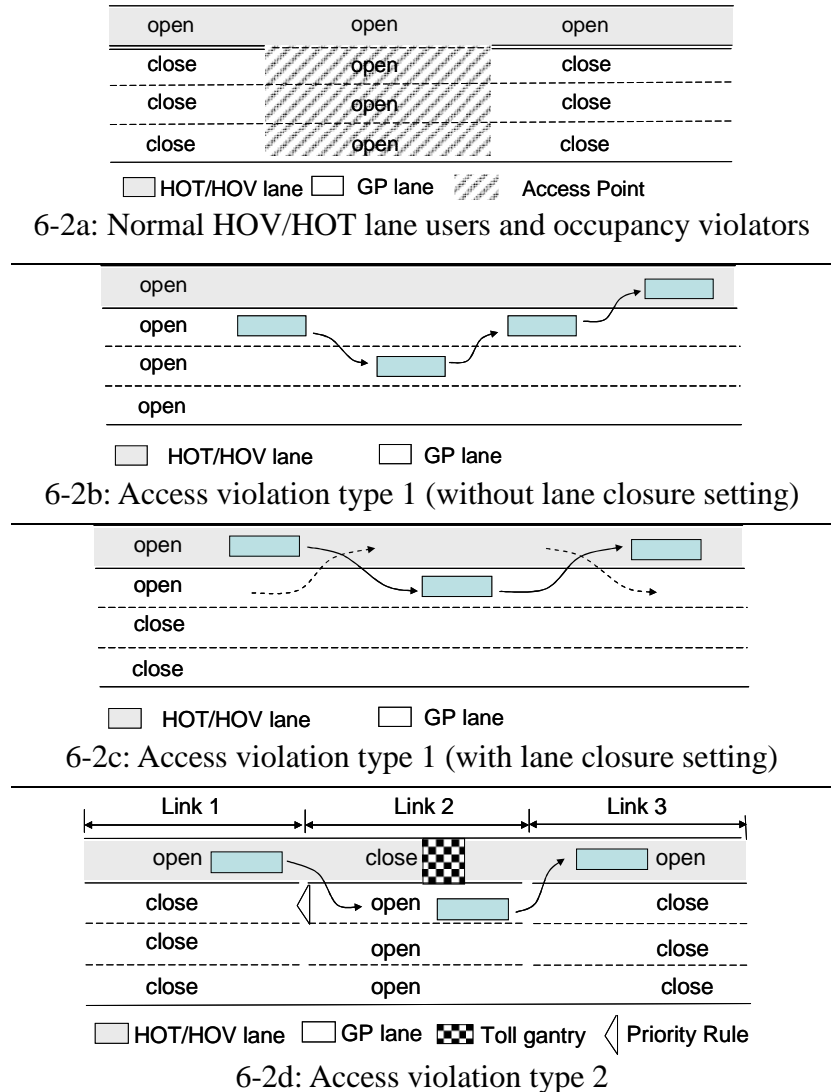
Figure 6-2: Lane and link property settings for modeling violators

6.3.2.2 Access Violation

No prior relevant study considered the possibility of vehicles crossing into or out of the HOT lane facility to or from the GP lanes at locations other than designated access points. To model access violations, where vehicles maneuver between the HOT lane facility and the GP lanes at

locations other than these permitted access points, the HOT lane and GP lanes must be treated within a single link (as opposed to separate links or facilities). By doing so, a new vehicle class can be introduced for which the Lane Closure properties can be set so as to permit the vehicle to move between the HOT lane facility and adjacent GP lane at any location or even prespecified locations where violations are most like to arise (e.g. immediately before or after a tolling facility).

In this work, two types of "Access Violations" are considered: (1) Access Violation Type 1 (AV-1) by which vehicles committing this violation freely move between the HOT and GP lanes, disregarding the buffers and (2) Access Violation Type 2 (AV-2) by which vehicles cross the buffer just prior to and after a tolling facility in order to avoid toll payment while maintaining nearly continuous use of the HOT lane.

To model violations of type AV-1, the Lane Closure property associated with the violation vehicle class for all lanes are set to "open." This is depicted in Figure 6-2b. One could similarly set only the HOT lane(s) and single adjacent GP lane to "open," while simultaneously setting the remaining GP lanes to "closed" for more limited maneuvering between GP and HOT lane facilities (Figure 6-2c).

To model violations of the AV-2 type, the link in which the tolling facility is present is split into three connected links, the middle including the tolling facility. To force the violation behavior at the tolling location, the Lane Property of the HOT lane for the violators is set to "closed" while the remaining lanes are set to "open." Assuming that the vehicles involved in this violation behavior are HOT lane users, the Lane Property for the HOT lane on the upstream and downstream links is set to "open" for the violators, while the remaining lanes are set to "closed." With no further modeling effort, it was found that under congested conditions, this approach

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resulted in only a portion of vehicles committing the AV-2 type violation of those that were intended to commit such violations. Despite that the HOT lane was in the "closed" state for these vehicles, if the vehicle was unable to merge easily into the GP lane (i.e. a gap did not arise quickly permitting the maneuver), then the vehicle continued through the toll on the HOT lane. To ensure that the majority of violators commit the violation as intended, despite that their behavior may affect traffic in the GP lanes, thus replicating more aggressive behavior, a Priority Rule is set. This rule gives priority to the vehicle in the HOT lane seeking to merge into the GP lanes. It is assumed, thus, that any vehicle willing to merge out of the HOT lane just prior to paying a toll, despite the possibility of receiving a moving violation, will be aggressive enough to take advantage of relatively small gaps between vehicles in the GP lane in merging into that lane. The vehicles in the GP lane respond by slowing down to avoid collision, but effectively permitting the illegal maneuver. This modeling approach is depicted in Figure 6-2d.

To illustrate the capabilities enabled by the proposed modeling methodologies described here, vehicle trajectories of four vehicles (Vehicles 109, 135, 130 and 237) were extracted from the simulation output of runs of a VISSIM model of a short, 3-GP lane, 1-HOT lane freeway segment. The trajectories are depicted in Figure 6-3. In the figure, Vehicle 109 can be seen merging back and forth between the HOT lane and adjacent GP lane, including stretches in which access is prohibited. Vehicle 135 can be seen merging out the HOT lane just prior to the toll gantry, avoiding toll payment, and merging back into the HOT lane immediately after passing the toll gantry.   Trajectories of two exemplar, non-violation type vehicles (Vehicles 130 and 237) that use the designated access points to enter or exit the HOT lane are also depicted.
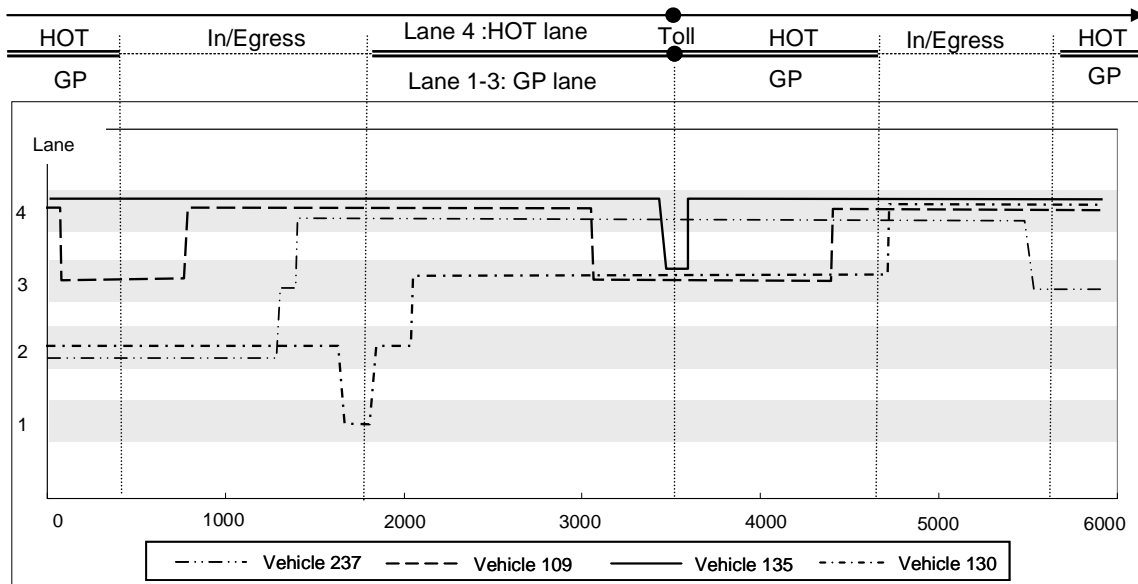
Figure 6-3: Vehicle trajectories developed from simulation results in which AV-1 and AV-2 type violations are modeled

6.4 Case Study

To assess the impact of violation maneuvers on performance of existing and proposed concurrent flow lane operations with continuous or limited at-grade, buffer separated HOV or HOT lane facilities, two VISSIM models (version 5.1) were created. These models contain a single continuous access HOV lane (Existing) and one limited access, at-grade HOT lane (Alternative). The HOT lane alternative assumes conversion of the existing continuous access HOV lane to a single limited access HOT lane. The models replicate a seven-mile stretch of I-270 in Maryland for a study period consisting of morning peak hours (6:00 a.m. through 9:00 a.m.) during which existing HOV (or designed HOT) lane restrictions apply and build on a previously developed and calibrated model (based on segment travel times) of this roadway segment (Miller-Hooks et al., 2009). Figure 6-4a shows the study area, including three potential access points anticipated for the Alternative network. The study roadway segment consists of six interchanges connecting I-270 with local roads, including the I-370 freeway, Shady Grove Road, Montgomery Avenue

(MD 28), Falls Road (MD 189), Montrose Road, and the Spur connection to I-495. The interchanges involve eight on-ramps from local roads to CD lanes, five off-ramps from the CD lanes to the local roads, four slip ramps from CD lanes to GP lanes, and two slip ramps from GP lanes to CD lanes as shown in Figure 6-4b. While access to/from the 1,000 foot section of the existing HOV lane that is closest to the Spur is restricted, for simplicity, continuous access is assumed under the Existing scenario. Traffic demand data was provided by Maryland State Highway Administration (SHA) based on 2006 survey data. Other required input data, including, for example, vehicle occupancy and composition are given in (Miller-Hooks et al., 2009).

Link	Volume (PLPH)	Link	Volume (PLPH)	Link	Volume (PLPH)
1	1881	305	600	311	825
301	1163	307	300	313	475
303	525	309	1250	315	650

6-4a: Study area	6-4b: Simulation network and 2006 traffic data
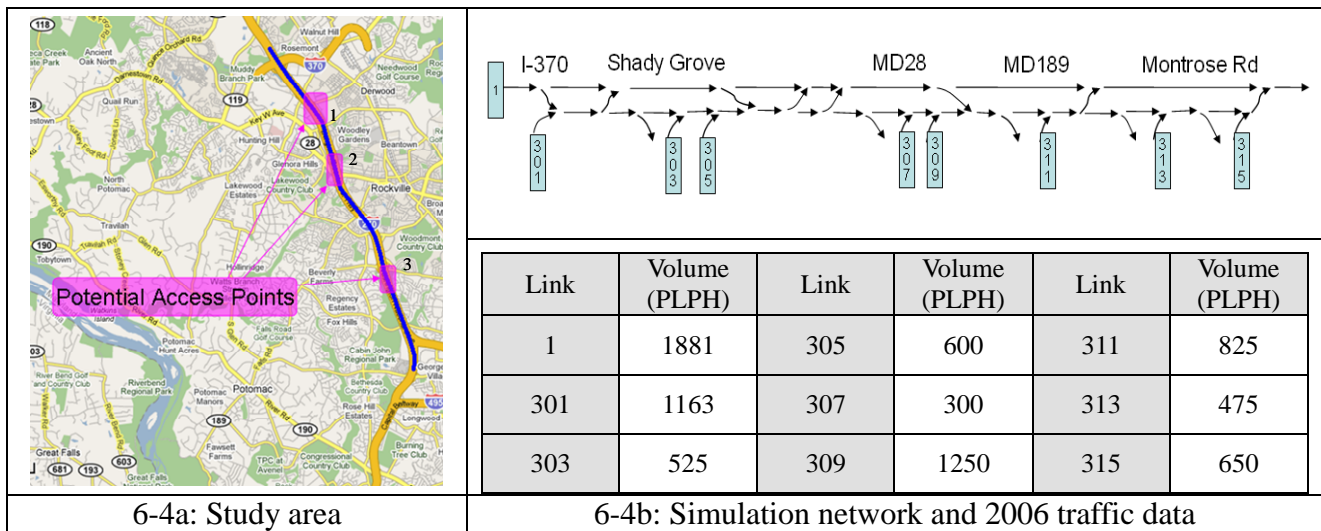
Figure 6-4: 2006 traffic demand survey data and other case study details

6.4.1 Experimental Design

Numerical experiments were conducted to assess the impact of occupancy and access violations on performance of HOV/HOT and GP lanes in the studied freeway segment involving concurrent flow lane operations. Modeling techniques described in Section 3 for replicating violation behavior were used. Both Existing (with single HOV lane) and Alternative (with single HOT lane) scenarios are considered. In both the Existing and Alternative model runs, demand is set to

one of three levels: demand equivalent to 2006 surveyed numbers (2006 demand), 2006 demand with an additional 200 vehicles per lane per hour (vplph) (2006+200 demand), and 2006 demand with an additional 400 vplph. Five categories of violations are considered in the experiments: occupancy; AV-1; AV-2; combined AV-1 and 2; and combined occupancy, AV-1 and AV-2. Five violation rates are employed: 0, 5, 10, 15 and 20% of total demand.

To implement the violation rates, demand is adjusted within the eight vehicle classes that are modeled, details of which are given in Table 6-2. The experiments control the composition percentage between Classes 5 and 6. One might consider similar alternative experiments where demand is moved from Class 7 to 5 instead of Class 6 to 5.

It is expected that electronic, nonintrusive toll collection gantries will be employed to collect toll payments from SOVs employing the HOT lane. In this study, it is presumed that these tolling facilities will be located immediately after the end of each access point, allowing tolls to be collected once vehicles enter the HOT lane facility. Tolls could similarly be placed prior to the access points, allowing collection as vehicles merge out of the HOT lane facility. The latter scenario is not tested in this study.

Table 6-2: Traffic composition and employed violation rates

Vehicle Class	Vehicle Type	Occupancy	Using HOV?	Composition (%)				
Class 1	truck	1	no	0.053	0.053	0.053	0.053	0.053
Class 2	truck	1	yes	0.000	0.001	0.001	0.001	0.001
Class 3	bus	2+	no	0.003	0.003	0.003	0.003	0.003
Class 4	bus	2+	yes	0.001	0.001	0.001	0.001	0.001
Class 5	passenger car	1	yes	0.000	0.05	0.10	0.15	0.20
Class 6	passenger car	1	no	0.703	0.657	0.607	0.557	0.507
Class 7	passenger car	2+	yes	0.188	0.188	0.188	0.188	0.188
Class 8	passenger car	2+	no	0.047	0.047	0.047	0.047	0.047

Each VISSIM model run with select scenario, demand level, violation type and violation rate entailed 5,400 seconds of simulation time, the first 1,800 seconds of which was considered as the warm-up period. For each such combination, five simulation runs were made. Average results when provided, unless otherwise specified, are hourly averages based on the 3,600 seconds of simulation run time from each of the five runs. A total of 525 simulation runs were conducted. Each run required approximately 40 to 60 minutes on a Dell Optiplex GX520 Pentium 4 personal computer with a dual core processor, 3.20 gigahertz, and two gigabyte ram, running the Windows XP operating system. Results of these runs are given next.

6.4.2 Experimental Results and Analysis

To assess the impact of violations on traffic performance in the HOV/HOT (or GP) lane, the average travel time incurred by those vehicles traversing the entire length of the HOV/HOT lane (or GP lane) in the study area is collected. Average travel times estimated from the runs are reported in Figures 6-5 ~ 6-8.

Impact of occupancy violations on average travel time (Existing)	
Segment Travel Time on HOV Lane (sec)	**Segment Travel Time on GP Lane** (sec)
6-5a: HOV Lane	6-5b:GP Lane
Impact of occupancy violations on average travel time (Alternative)	
Segment Travel Time on HOT Lane (sec)	**Segment Travel Time on GP Lane** (sec)
6-5c: HOT Lane	6-5d: GP Lane
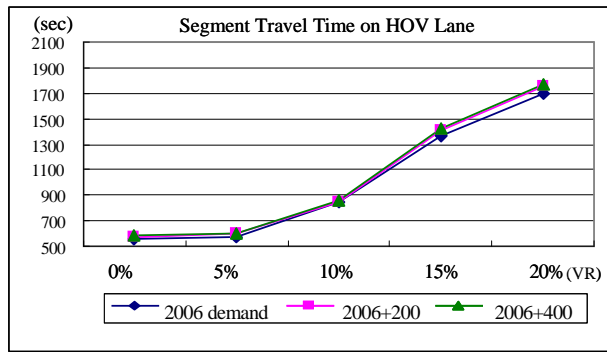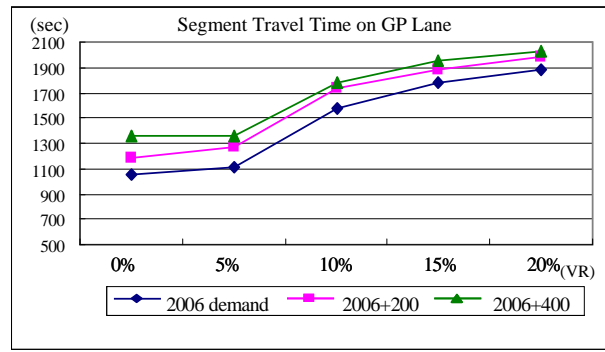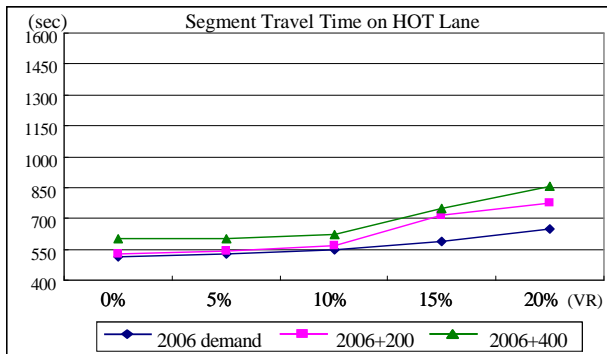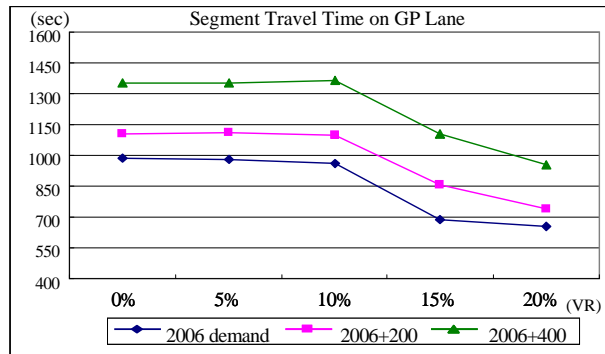
Figure 6-5: Impact of occupancy violations on average travel time

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6-6a: HOT Lane	6-6b: GP Lane
6-6c: HOT Lane	6-6d: GP Lane
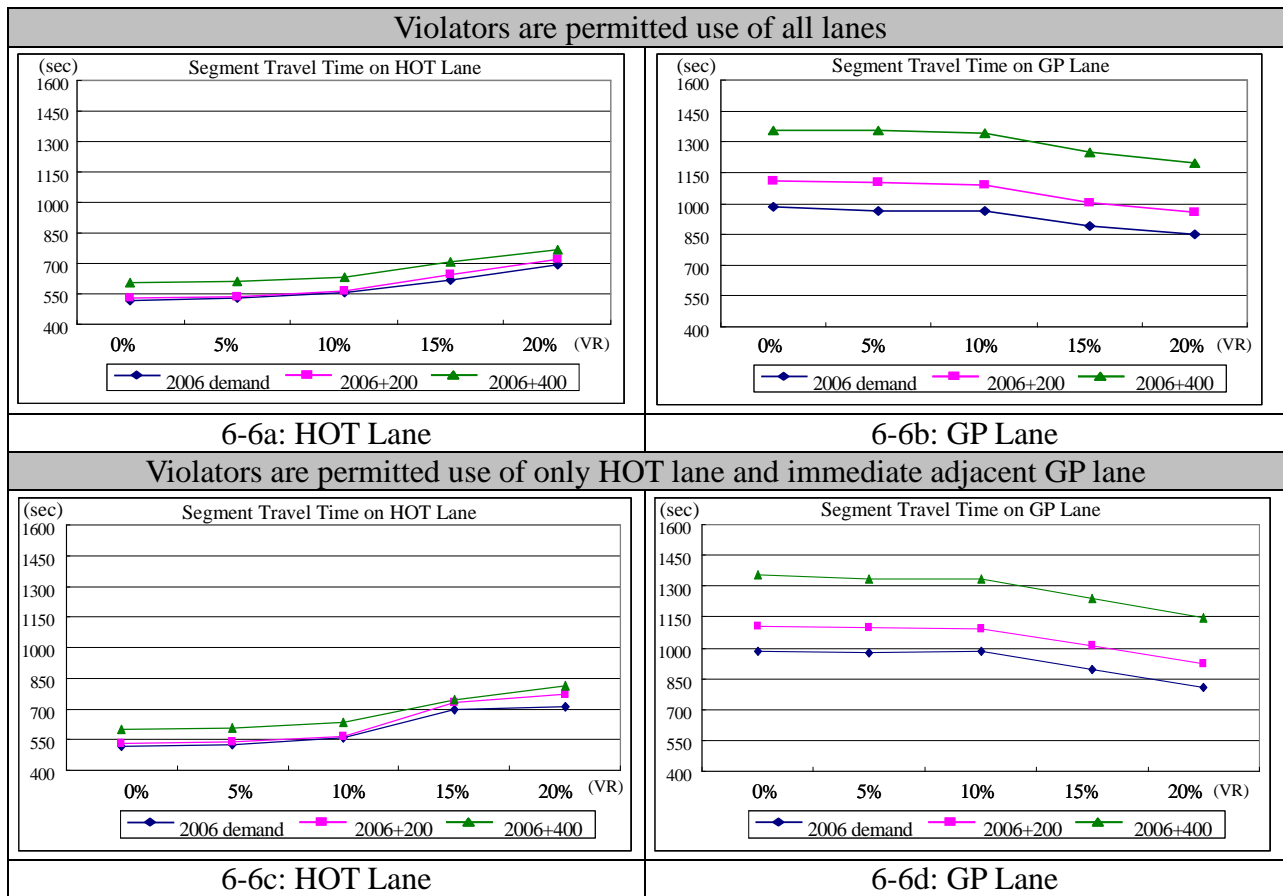
Figure 6-6: Impact of AV-1 violations on average travel time (Alternative)

6-7a: HOT Lane	6-7b: GP Lane
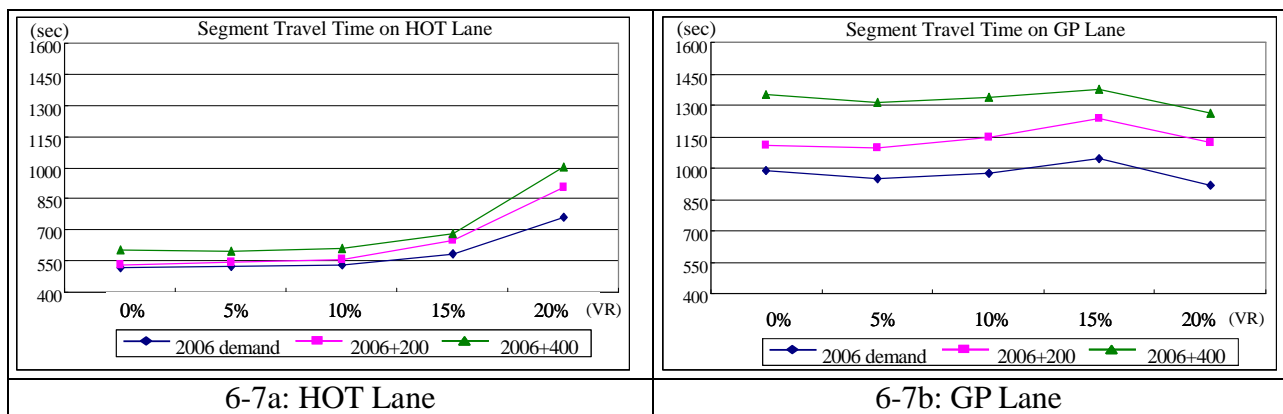
Figure 6-7: Impact of AV-2 violations on average travel time (Alternative)
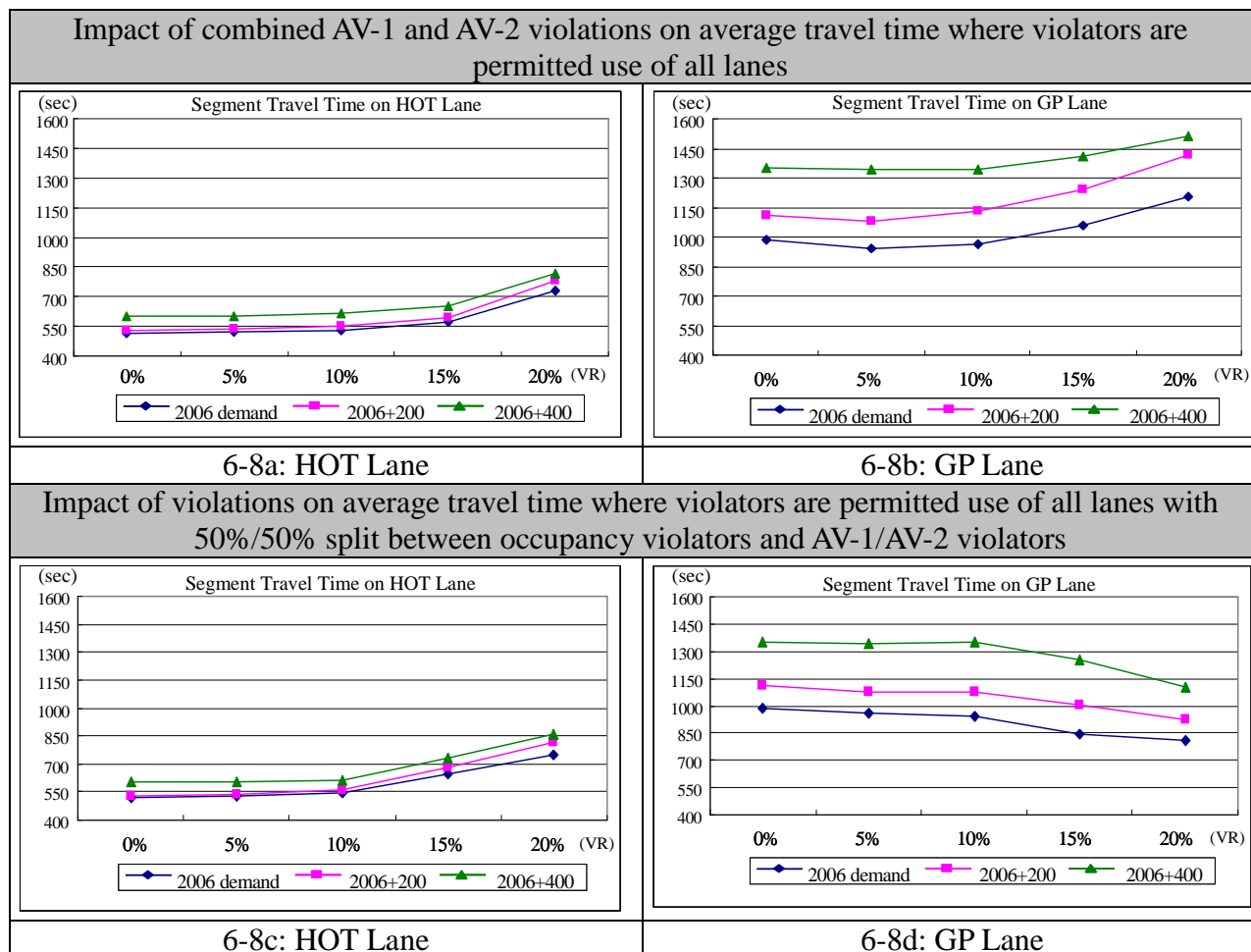
Figure 6-8: Impact of violation combinations on average travel time (Alternative)

As is shown in Figure 6-5a and b, an occupancy violation rate of 10% or more results in significant increase in travel time in both HOV and GP lanes under existing conditions. Similarly, at an occupancy violation rate of 10% and higher, travel times increase substantially in the HOT lanes, while simultaneously decreasing in the GP lanes (Figure 6-5c and d). In a comparison of Figures 6-5a and c, one will note that the degradation in the performance of the managed lanes is less significant for the limited access HOT lane than it is shown to be for the continuous access HOV lane. It is hypothesized that this is due to a reduction in weaving between the managed lane and adjacent GP lane under the HOT lane design. Improvements noted for the GP lane

performance with increasing violation rates are due to the associated reduction in GP lane use, since HOT lane violators are assumed to be generated from the class of SOVs without suitable toll payment equipment. This same improvement is not noted under existing conditions, where continuous access between HOV and GP lanes is permitted, allowing unlimited opportunity for weaving. Thus, it is concluded that the additional delay due to weaving between GP and managed lanes with continuous access outweighs the benefits of a reduction in the number of GP-only lane users as occurs in creating the violation class. It appears that the increased opportunity for weaving under existing conditions as compared with the alternative HOT lane design also leads to greater percentage degradation in performance with increased violation rate, and hence, increased managed lane use.

As depicted in Figure 6-6, at rates of 10% and higher, the AV-1 type violations are shown to significantly impact the performance of both HOT and GP lanes. Specifically, as violation rates increase, average travel time in the HOT lane increases, while decreasing in the GP lanes. The same general trend in terms of worsening performance of the HOT lane and improving performance of the GP lanes with increasing numbers of violators is seen in Figures 6-5c and d as was noted for occupancy violation under the alternative HOT lane design. This can be similarly explained by the reduction in use of the GP lanes and increase in use of the HOT lane with shifting demand between the user classes. By comparing Figures 6-6a and b with c and d, one will note that if the HOT lane access violators limit their maneuvers to only the HOT lane and its adjacent GP lane, the violations are expected to have greater negative impact on the performance of the HOT lane than if these maneuvers are not limited to only these lanes.

Figure 6-7 shows similar degradation in the performance of the HOT lane at 10% and higher violation rates for AV-2 type violations, as for other violation types under the alternative

design. Despite the reduction in demand for the GP lane that results from the conversion of SOV to HOT lane users, performance of the GP lane does not necessarily improve with increasing violation rate (and decreasing GP lane use). It is hypothesized that the lack of improvement in the GP lane average travel times is due to short-term queuing that results from a vehicle aggressively entering the adjacent GP lane from the HOT lane at the toll gantry location. Such behavior is not replicated under AV-1 type violations, because it is assumed that drivers of vehicles falling under this class will only switch into the GP lanes when traffic conditions are better in the GP lanes than in the HOT lane. Thus, these vehicles only enter the GP lane when a suitable gap is present.

When the combination of AV-1 and 2 violations are considered together, that is when violators will commit both types of access violations, the performance of both HOT and GP lanes degrade. The relative degradation in performance increases with increasing violation rate, particularly at rates of 10% and higher, as shown in Figure 6-8a and b. When half of the access violators (combined AV-1 and 2) are reset as occupancy violators (i.e. representing drivers who do not cross barriers despite that they use the HOT lane illegally), the impact of the occupancy violations is significant as noted by comparing results given in Figures 6-8c and d with those of the other figures.

In an overall assessment of the impact of violations on average travel times (Table 6-3), it is noted that access violations of type AV-1 have the greatest impact on HOT lane performance (7% and 32% increase in average travel time) at violation rates of 10 and 15% and of type AV-2 (62% increase in average travel time) at a violation rate of 20%. The significance of performance degradation in the HOT lane due to violation type AV-2 can be expected as drivers of vehicles falling under this violation type are expected to reduce their speeds to undertake the maneuver

required to avoid the toll gantry. Likewise, they impact speeds in the HOT lane upon reentry just past the toll gantry. That the degradation in performance of the HOT lane increases nonlinearly with increasing violation rate under any violation type and combination can be noted from Figures 6-5 ~ 6-8 and Table 6-3. As it relates to the GP lanes, only when violation types AV-1 and 2 are combined does the average travel time increase with increasing violation rate. In all experiments, the general trends in change in performance resulting from increased violation rates were unaffected by increased traffic volume (i.e. 2006+200 and 2006+400).

Table 6-3: Percent variation in average travel time as a function of violation rate (Alternative)

Violation rate / Violation type	HOT lane				GP lane			
	5%	10%	15%	20%	5%	10%	15%	20%
Occupancy	2%	5%	24%	38%	0%	-1%	-24%	-32%
AV-1	1%	7%	32%	40%	-1%	-1%	-9%	-17%
AV-2	1%	3%	16%	62%	-3%	1%	7%	-4%
(AV-1)+(AV-2)	1%	3%	11%	42%	-2%	0%	8%	21%
Occupancy+(AV-1)+(AV-2)	1%	5%	25%	48%	-2%	-2%	-10%	-18%

6.5 Summary

Results of this study indicate that vehicles choosing to violate restrictions placed on the studied non-barrier separated, limited access HOT lane facility significantly impact roadway facility performance estimates in simulation-based concurrent flow lane studies when occurring at high violation rates. Moreover, this impact grows nonlinearly with increasing rate of violation. The impact of occupancy violations on the performance of a continuous access HOV lane was shown to be similarly significant. The effects of violation behavior become noteworthy at a violation rate of 10% (of roadway users). The performance of the GP lane is similarly impacted; however, the direction of impact differs for the two managed lane types studied. The average travel time

on the GP lanes increases substantially with increasing occupancy violation rate under a continuous access HOV lane design, while a decrease in average travel time (i.e. performance improvement) is noted for similar occupancy violations under the limited access HOT lane facility design. Where violations involving toll avoidance arise, no such improvement occurs.

The observations from this study imply that it is critical to model violation behavior in simulation-based performance analysis of proposed HOT lane facilities should violation rates on the order of 10% or higher be anticipated. Given experienced violation rates for non-barrier separated HOV and HOT lane facilities around the U.S. and the potential contribution to system performance that these violations play as noted in the simulation study conducted herein, simply ignoring the potential impact of violators may result in a misrepresentation of the benefits of a proposed managed lane facility, particularly at violation rates of 10% and higher.

This study has additional implications for enforcement planning for such managed lane facilities. Results of this study indicate that, safety and revenue aside, low violation rates may have little impact on mobility. Of course, without enforcement, violation rates will grow, as drivers observe acts of violation that go unpunished. An enforcement plan is warranted to reduce violation rates to levels at which degradation in performance of the managed lane due to violations does not outweigh the benefits of construction of such a facility. Additionally, one can replicate conditions under an overall reduction in violation rate or changes due to selective enforcement plans using the modeling techniques described herein. In addition to modeling enforcement plans that target specific violation types, location-based reductions consistent with fixed enforcement locations as might arise when technology-based enforcement is employed can be replicated. Thus, modeling results can be applied in benefit/cost studies of enforcement strategies.

In this study, the impact of violations is evaluated based on only a segment of 7-mile stretch of one roadway. It would be beneficial to test whether or not the findings of this study can be duplicated for an alternative roadway segment with different geometry and for a wider study area. Moreover, one setting of car-following and lane-changing parameters was used for the entire study. However, vehicles that violate roadway markings are likely to behave differently from other vehicles, particularly as it relates to lane-changing decisions. To set parameters by vehicle in this way within the VISSIM simulation platform, the "external driving model" can be applied through which lane-changing and car-following parameters associated with violation maneuvers can be set. Appropriate settings should be chosen based on real-world measurements. Through this approach, however, parameters would be fixed and could not vary by maneuver type.

Chapter 7: Safety Implications of Violations in Concurrent Flow Lane Operations

7.1 Introduction and Background

To mitigate congestion along freeways, managed lanes, e.g. high occupancy vehicle (HOV) or high occupancy toll (HOT) lanes, operating concurrently with general purpose (GP) lanes have gained popularity across the nation. Among the construction options to separate managed and GP lanes, non-barrier separation techniques, which use only solid pavement markings, are increasingly employed. These techniques inform drivers that crossing between GP and managed lanes is prohibited; however, they cannot prevent vehicles from violating such regulations. In fact, the national average annual managed lane violation rate, which includes both occupancy- and access-type violations, was estimated in 2005 to involve between 10 and 15 percent of all vehicles using managed lanes (Martin et al., 2005). Such violations have a negative impact on both mobility and safety for the freeway operation. Chou et al. (2009) quantify the impact of these violations on mobility for an existing roadway segment. Others have commented on safety implications of these maneuvers. Billheimer et al. (1990) pointed out that weaving illegally in and out of a managed lane creates a direct safety hazard, but was unable to directly correlate the violation rate to accident occurrence. Parker et al. (1995) employed a survey instrument which showed a connection between self-reported tendency to commit driving violations and increased accident involvement. It appears that no prior study has quantified the impact of violations on safety. This study seeks to help fill this gap.

In this chapter, it is hypothesized that violations, particularly those pertaining to managed

lane egress and ingress, lead to sudden changes in speed of approaching vehicles. These sudden changes in speed can propagate upstream, further resulting in congestion and increased speed variance (or traffic instability) over the affected portion of the roadway.

Numerous studies have investigated the relationship between speed variance and accident rates. Park and Ritchie (2004) show that excessive maneuvering between lanes results in a significant increase in speed variability, as noted from analysis of detector data. Zheng (2009) compared 82 crash events and found that the standard deviation of speed within the roadway segment in which the event took place positively correlates with the occurrence of crashes. In a study of crash data using detector output along I-880 in California, Oh et al. (2005) found that under low levels of speed variation, accident likelihood is reduced.

The safety impact of congestion has been widely studied (e.g. Ivan et al., 2000; Martin, 2002). These works consider negative or possible positive relationships between congestion and traffic accidents. That is, it is generally accepted that serious multi-vehicle incidents more frequently arise under moderate congestion levels than at very low or very high congestion levels. Shefer and Rietveld (1997) theorized a parabolic relationship between traffic flow density and fatal accidents, wherein fatal accidents would be lowest both at the highest and lowest levels of congestion. Noland and Quddus (2005) attempted unsuccessfully to show that this parabolic relationship exists through the study of casualty data in congested and uncongested periods in London. While such specific conceptual and overarching relationships have not necessarily been proven, it is generally accepted that there is a relationship between congestion levels and incident rates. As it relates specifically to managed lane operations, Golob et al. (1989) noted that changes in collision characteristics along managed lanes were due to the changes in spatial and temporal attributes of surrounding traffic congestion. The authors are not aware of other works that have

studied congestion and safety relationships in the context of managed lane operations. Since movement violations impact mobility, and thus, affect congestion, violations of the type studied herein will also impact safety.

This chapter seeks to quantify the safety impact of access-type violations, as a consequence of increased speed variation and changes in congestion, in the context of concurrent flow lane operations with a nonbarrier separated managed lane facility. A three-step simulation-based methodology to analyze the impact of violations on safety is proposed. The methodology is applied to a case study, constructed on a calibrated simulation network of an existing roadway segment of I-270 in Maryland.

7.2 Methodology

A simulation-based methodology is employed to assess the potential impact of access-type violations in the context of concurrent flow lane operations on safety. In the methodology, safety is measured by the length of discontinuities in traffic speed resulting directly from violation incidents as determined through inspection of traffic speed contour maps. The larger the total length of discontinuities in the traffic speed contour map, the greater the speed variability and the less safe the situation is presumed to be. In addition to safety implications of increased speed variability, increased congestion may result as a consequence of a sudden decrease in vehicular speeds. Under certain levels of traffic flow, as congestion increases, interactions among vehicles increase, and there may be secondary safety effects.

Step 1 of the proposed methodology simulates traffic operations and a set of randomly arising access-type violations, rates for which are predetermined. Detectors are set up in the simulation at short intervals within each modeled lane. A traffic speed contour map is developed

in Step 2 from the output of the simulation run. This map is created by plotting the detector surveillance data in a time-space surface diagram. The axes of the plot are developed over constant increments of time (generally shown on the x-axis) and space (generally shown on the y-axis). Such maps have been used for many traffic analysis applications, including, for example, the identification of bottlenecks (Chen et al., 2004; Bertini et al., 2008). Finally, in Step 3, the total number of time-space increments along which significant speed discontinuities are noted are counted. These identified increments are referred to herein as Hazardous Time-Space Spots (HaTSSs). A count of those HaTSSs arising along the lagging edge of an identified region of speed discontinuity provides a safety index, i.e. the HaTSS safety index. This index can be separated by lane type, resulting in HaTSS GP and HOT lane safety indices. All three steps are repeated for each random seed and the average total is produced over all seed values. Additional description associated with each of the methodological steps is given next. Despite its more general applicability for traffic safety analysis, this description focuses on the application to concurrent flow lane operations and access-violators. It is presumed that all associated traffic, geometry and other input data required for the simulation are given and a violation rate is chosen.

7.2.1 Step 1: Simulation Runs with Violation Maneuvers

The chosen simulation platform must permit the modeling of concurrent flow lane operations and associated access-type violation behavior. It is anticipated that microscopic simulation would ordinarily be warranted.

7.2.2 Step 2: Traffic Speed Contour Map Creation

To capture the impact of a violation maneuver, very short observation time increments must be

employed in recording traffic speeds. In freeway bottleneck and incident management studies, 20 or 30 second time-increments for reporting traffic characteristics from simulated detectors are often employed (e.g. Zheng et al., 2009; Bertini et al., 2008; Ouiroga et al., 2005). The average speed of vehicles traveling over the space between two detectors within the time interval must be computed for every time step and roadway segment (i.e. between detectors). This data is employed in developing the traffic speed contour map for the given simulation run (i.e. for a given seed value).

7.2.3 Step 3: Identification of HaTSS of Traffic Flow Discontinuity

Figure 7-1 illustrates, by example, the potential impact of a hypothetical violation instance in a traffic speed contour map. The cells of the contour map are classified as falling under low-speed or normal-speed types. If the speed differential of a cell from a target norm is significant enough, the cell is categorized as being of the low-speed type. At the leading edge of the region of discontinuity is a congestion discharge region, i.e. a region in which traffic has begun to recover and speeds are increasing toward the norm. The lagging edge of the discontinuity region develops as a result of backward forming shockwaves. Beyond this edge, speeds are yet to be affected by the violation. Since collisions are most likely to occur along this lagging edge, the cells (i.e. the HaTSSs) that form this edge are the "spots" that are counted in producing the HaTSS safety index.
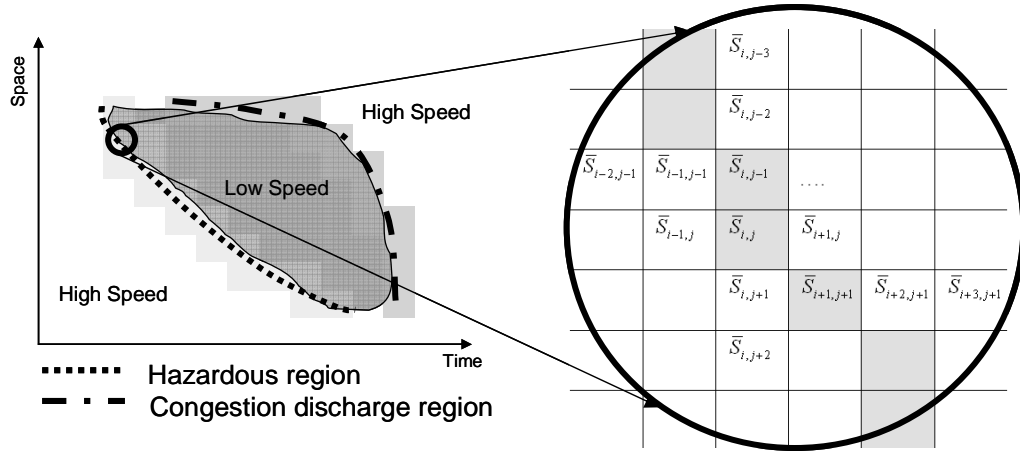
Figure 7-1: Violation impact and HaTSS identification

To compute the HaTSS safety index, the average speed, $\bar{S}_{i,j}$, within each cell of the traffic speed contour map is compared with the related cell that represents the same location at the previous time step, $\bar{S}_{i-1,j}$. If the average speed has dropped by a chosen speed difference threshold, ΔS, since the previous time step, the cell is classified as a HaTSS. Let $HaTSS_{ij}$ be a HaTSS in time slice i associated with roadway segment j. Then,

$$HaTSS_{ij} = \begin{cases} 1, & \text{if } \bar{S}_{i-1,j} - \bar{S}_{i,j} \geq \Delta S; \\ 0, & \text{otherwise.} \end{cases} \quad\quad (7\text{-}1).$$

The HaTSS safety index is computed as in (7-2).

$$\text{HaTSS safety index value} \quad = \quad \sum_i \sum_j HaTSS_{ij} \quad\quad (7\text{-}2).$$

7.3 Case Study

To assess the impact of access-type violation maneuvers on the safety of concurrent flow lane operations with a limited at-grade and buffer separated HOT lane facility, a simulation model, employing the widely used microscopic traffic simulation tool VISSIM (version 5.1), was

created. The model replicates a seven-mile stretch of I-270 in Maryland for a study period consisting of morning peak hours. The simulation model was built on a previously developed and calibrated model of this roadway segment. Details of the geometry of the study segment, including proposed HOT lane design, location of access points, and techniques necessary for modeling adjacent managed and GP lanes with restricted access, as well as results of calibration efforts under existing geometry with HOV lane, can be found in (Miller-Hooks et al., 2009). Traffic demand, vehicle occupancy and composition data provided by Maryland State Highway Administration (MSHA) described in this earlier work was used unless otherwise specified.
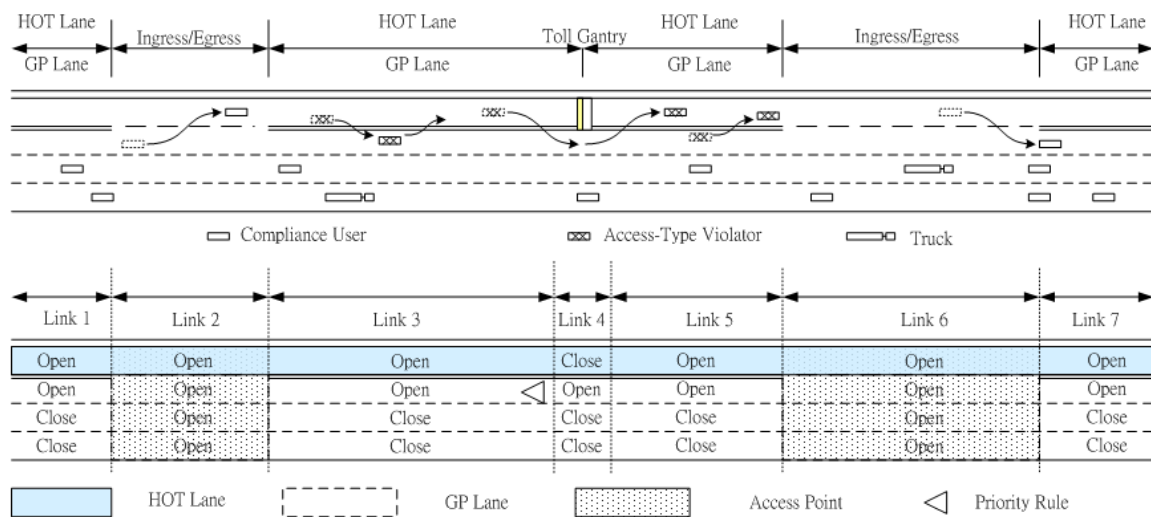
Figure 7-2: Violation maneuvers and associated VISSIM settings in a hypothetical network

In this case study, only access-type violations are considered. Such violations may involve the crossing of the buffer at the convenience of the violating vehicle and the crossing of the buffer immediately prior to a toll gantry so as to avoid paying the toll. These types of violations are depicted in Figure 7-2. Modeling techniques employing appropriate use of Lane Closure properties and Priority Rules by Vehicle Classes as described in (Chou et al., 2010) were used to replicate access-type violation maneuvers.

7.3.1 Experimental Design

Two sets of experiments were conducted: Experiment I was designed to assess the effects of an increase in violation rate, while Experiment II was designed to test system performance with comparable changes in traffic composition with no violation for the purpose of setting a baseline for comparison. Eight vehicle classes, as described in Table 7-1, were employed within the experiments.

Table 7-1: Vehicle classes settings in the simulation

EXPERIMENT I								
Vehicle Class	Vehicle Type	Occupancy	Use HOT lane	Composition (%)				
Class 1	truck	1	No	0.053	0.053	0.053	0.053	0.053
Class 2	truck	1	Yes	0.000	0.001	0.001	0.001	0.001
Class 3	bus	2+	No	0.003	0.003	0.003	0.003	0.003
Class 4	bus	2+	Yes	0.001	0.001	0.001	0.001	0.001
Class 5	passenger car	1	Yes	0.000	0.05	0.10	0.15	0.20
Class 6	passenger car	1	No	0.707	0.657	0.607	0.557	0.507
Class 7	passenger car	2+	Yes	0.188	0.188	0.188	0.188	0.188
Class 8	passenger car	2+	No	0.047	0.047	0.047	0.047	0.047
Adjustment from Class 6 to Class 5				0%	5%	10%	15%	20%
EXPERIMENT II								
Vehicle Class	Vehicle Type	Occupancy	Use HOT Lane	Composition (%)				
Class 1	truck	1	No	0.053	0.053	0.053	0.053	0.053
Class 2	truck	1	Yes	0	0	0	0	0
Class 3	bus	2+	No	0.003	0.003	0.003	0.003	0.003
Class 4	bus	2+	Yes	0.001	0.001	0.001	0.001	0.001
Class 5	passenger car	1	Yes	0	0	0	0	0
Class 6	passenger car	1	No	0.707	0.677	0.657	0.632	0.617
Class 7	passenger car	2+	Yes	0.188	0.218	0.238	0.263	0.278
Class 8	passenger car	2+	No	0.047	0.047	0.047	0.047	0.047
Adjustment from Class 6 to Class 7				0%	3%	5%	7.5%	9%
Comparable Classification from Experiment I				0%	5%	10%	15%	20%

In Experiment I, a portion (set according to the chosen violation rate) of the vehicles falling within Class 6 are reclassified under Class 5, representing an increase in HOT lane users

to account for the addition of violators that will "illegally" use the HOT lane. These reclassified vehicles would have otherwise been restricted to using the GP lanes. A result of this reclassification is an increase in traffic demand along the HOT lane and a corresponding decrease in demand for the GP lanes.

To account for any changes in safety related measures that are due to the simple increase in use of the HOT lane and decrease in use of the GP lanes that occurs through the design of Experiment I, a comparable reclassification is made in developing Experiment II, where a portion (set according to the chosen violation rate for the comparable Experiment I runs) of the vehicles falling within Class 6 are reclassified under Class 7, representing an increase in HOT lane users and decrease in GP lane use. Class 7 users, unlike Class 5 users, will not cross the buffer separating the GP lanes from the HOT lane.

The impact on safety of violation maneuvers can, thus, be ascertained through the comparison of traffic speed contour maps developed from runs in Experiments I and II for a given violation rate.

Because violators (i.e. those vehicles reclassified from Class 6 to Class 5 in Experiment I) move back and forth between the HOT and GP lanes, the impact on traffic volume of these lanes is split. Thus, reclassification rates employed under Experiment II were set to achieve the same level change in volume split between the managed and GP lanes as results from each violation rate (and hence, reclassification level setting) set in Experiment I. That is, for example, a violation rate setting of 5% in Experiment I results in a 3% increase in traffic volume in the HOT lane. Thus, in Experiment II, 3% of the vehicles in Class 6 are reclassified into Class 7 to achieve the same change in volume between lanes that a 5% reclassification of vehicles in Class 6 to Class 5 achieves.

Three traffic demand levels were considered in the experiments: 2006 survey data provided by MSHA, 2006+200 vehicles per lane per hour (vplph) and 2006+400 vplph. To create the traffic speed contour maps, 83 detectors were deployed at intervals of 500 feet within the simulation platform. Average speeds by lane type and segment were computed every 30 seconds. Four speed difference (SD) thresholds (20, 25, 30, 35) were tested. The selection of these threshold values was based on suggested speed differential settings employed by Bertini et al. (2008) for bottleneck identification (i.e. 20 miles per hour (mph)) and Quiroga et al. (2005) for incident alarm (i.e. 25 to 45 mph).

Each VISSIM model run, involving the setting of violation rate, demand level, and seed value, entailed 5,400 seconds of simulation time, the first 1,800 seconds of which was considered as the warm-up period. Average results when provided are based on the 3,600 seconds of simulation run time after warm-up period. Each model run was conducted 10 times with different random seeds. The average number of the HaTSS over the 10 runs was computed and is reported subsequently herein.

7.3.2 Analysis of Results

A total of 300 runs under Experiment I and II were conducted, and 600 contour maps were created and analyzed. Results of these experiments are shown in Table 7-2.

Results of Experiment I indicate that the HaTSS HOT lane safety index increases non-linearly with increasing violation rate. This rate of growth in the safety index also increases with congestion level for the levels tested. In addition, the average segment travel time within the HOT lane increased with increasing violation rate. While the HaTSS GP lane safety index was noted to decrease with increasing violation rate, part of the potential improvement due to reduced traffic demand was lost as a consequence of increased congestion due to the effects of queuing

behind vehicles maneuvering to avoid toll payment.

If these results were due to a shift in traffic between the GP and managed lanes (and not necessarily due to the actual violation maneuvering), then the results from Experiment II should be nearly identical to those obtained from Experiment I runs. Through a comparison of results from these two sets of experiments, one can see that the violation maneuvering alone accounts for significant increase in HaTSS HOT safety indices.

Table 7-2: Performance along concurrent flow lanes

EXPERIMENT I: WITH VIOLATION											
		HOT lane					GP lane				
Volume	V.R.	20 SD	25 SD	30 SD	35 SD	travel time	20 SD	25 SD	30 SD	35 SD	travel time
2006 Survey	0%	3	1	0	0	509.9	268	141	46	9	719.3
	5%	6	1	0	0	515.9	217	106	38	6	756.7
	10%	15	5	2	0	522.0	175	76	22	3	852.6
	15%	68	28	9	1	560.9	145	58	16	1	990.3
	20%	193	82	26	5	711.6	146	50	10	1	1103.1
2006 + 200 vplph	0%	6	2	1	0	527.2	387	192	61	9	903.4
	5%	11	4	1	0	532.2	260	122	36	5	853.4
	10%	21	8	2	0	546.7	179	73	19	1	948.1
	15%	66	27	5	0	594.3	175	62	12	1	1153.6
	20%	228	101	28	5	750.4	159	53	9	0	1288.7
2006 + 400 vplph	0%	14	6	2	1	584.4	202	95	29	3	1198.2
	5%	16	7	2	1	588.8	190	84	22	2	1212.2
	10%	27	11	3	1	604.8	141	54	10	1	1201.4
	15%	59	25	7	2	637.8	118	41	9	1	1274.1
	20%	214	95	31	4	782.4	139	47	7	0	1404.6
EXPERIMENT II: WITHOUT VIOLATION											
	HOT lane	HOT lane					GP lane				
Volume	Volume Increase	20 SD	25 SD	30 SD	35 SD	travel time	20 SD	25 SD	30 SD	35 SD	travel time
2006 Survey	0%	3	1	0	0	509.9	268	141	46	9	719.3
	3%	5	2	0	0	513.0	240	125	43	8	717.4
	5%	9	3	1	1	515.8	249	126	39	5	729.0
	7.5%	11	4	1	0	519.4	246	118	38	6	737.1
	9%	14	5	1	0	522.5	272	132	38	7	740.6
2006 + 200 vplph	0%	6	2	1	0	527.2	387	192	61	9	903.4
	3%	8	3	1	0	534.6	328	154	49	7	889.0
	5%	10	3	0	0	534.1	331	157	45	7	899.1
	7.5%	17	6	1	0	542.0	332	159	50	5	920.0
	9%	21	9	2	1	542.9	335	158	47	6	921.3
2006 + 400 vplph	0%	14	6	2	1	584.4	202	95	29	3	1198.2
	3%	13	5	1	0	588.5	186	84	27	6	1209.6
	5%	15	5	1	0	596.9	175	81	25	4	1230.1
	7.5%	16	5	2	0	600.5	151	64	19	4	1240.6
	9%	24	9	2	1	603.0	174	78	23	5	1243.6

This comparison of results between the two experiments also indicates that the actual violation maneuvering results in increased average travel time within the HOT lane. For example, increasing the violation rate from 0 to 20% resulted in a change from 510 to 712 seconds (i.e. by 202 seconds) in average travel time over the seven-mile segment for 2006 survey level demand under Experiment I, and a change of only 13 seconds under Experiment II for a comparable change of reclassification of vehicle classes from 0 to 9%. Additionally, it appears that queuing within the GP lanes that results as a consequence of the violation maneuvers also significantly impacts the average travel time within the GP lanes. The average travel time along the GP lanes of the roadway segment under 2006 survey level demand increases from 719 to 1103 seconds (i.e. by 384 seconds) under Experiment I, while it remains nearly unchanged at the comparable 9% decrease of traffic demand level for Experiment II. Thus, violation maneuvers lead to significant increase in congestion.

The parabolic relationship between safety and congestion that was hypothesized in earlier works mentioned previously appears to be true as one can note from the plotting of the HaTSS safety indices against segment travel time (a surrogate for congestion) obtained in all runs of both experiments (Figure 7-3).
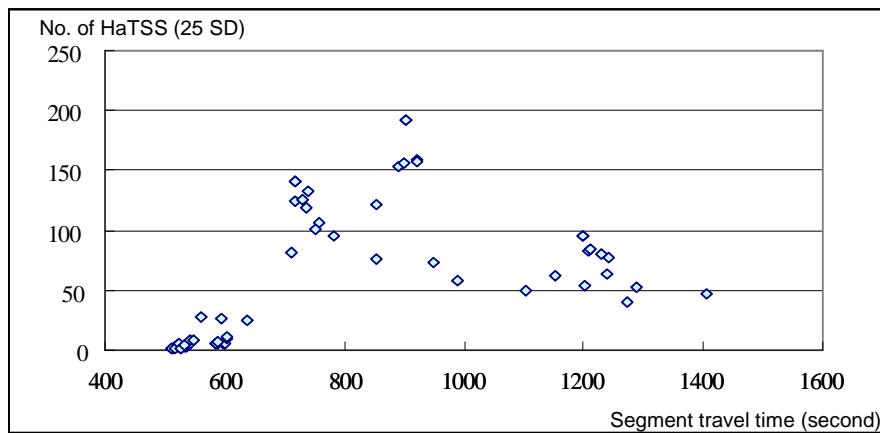
Figure 7-3: Plotting total number of HaTSS vs. segment travel time

7.4 Summary

Results of simulation experiments corroborate the hypothesis given herein that illegal traffic maneuvers between managed and GP lanes operating concurrently contribute to increased speed variation and congestion, factors affecting safety. The proposed methodology has wider application for traffic safety analysis, as well.

Chapter 8: Exploiting Capacity of Managed Lanes in Diverting Traffic around an Incident

8.1 Introduction

Traffic demand, and thus congestion, has been on the rise world-wide, particularly in and around the world's metropolitan areas, for decades and this trend is expected to continue in coming year. Simultaneously, in the United States (U.S.), new roadway construction is losing favor. Thus, it is of even greater import than in the past that our society establish mechanisms to exploit existing roadway capacity to cope with increasing congestion. Concurrent flow lane operations along freeways, consisting of one or more managed lanes and several general purpose (GP) lanes, have been proposed as a possible solution to achieve more effective use of existing roadway capacity. Managed lanes, such as High Occupancy Vehicle (HOV) lanes and Express Toll Lanes (ETLs), or similarly functioning High Occupancy Toll (HOT) lanes, are restricted to qualified vehicles while GP lanes are free of such use limitations. Among the managed lane types, HOV lanes have been part of the roadway landscape for the past two or three decades; only recently, however, perhaps due to improvements in required technologies for toll collection, have HOT lanes been thought of as a viable option. Currently, many states are adding new HOT lane facilities or converting HOV lane facilities to HOT lanes. As several studies have demonstrated, managed lanes have the benefits of offering reduced travel time and improved trip reliability in terms of mobility to motorists.

Traffic incidents, such as accidents involving a collision or stalled vehicles, along any freeway system are unavoidable and can cause very significant delays. Freeways operating

concurrent flow lanes are no exception. In fact, Cothron et al. (2004) noted an increase in incident rates by 41% and 56% associated with collisions involving injury along IH-635 and the northern corridor of IH-35E in Texas, respectively, with the introduction of non-barrier separated, limited access HOV lanes. Poor handling of incidents on roadways operating concurrent flow lanes will undermine public support for these facilities and can jeopardize revenues. Thus, traffic incident management (TIM) programs relying on strategies involving traffic diversion, freeway service patrol, and variable message signing, for mitigating the impact of incidents arising in facilities with managed lanes are important. Despite this, TIM programs designed specifically for concurrent flow lane operations have received little attention in the literature. The Texas Transportation Institute conducted a survey of state-of-the-practice TIM programs designed for facilities with managed lanes across the nation and recommended several strategies for addressing incidents in these facilities. These strategies are listed in Table 8-1 (Cothron et al., 2004). Potential effects in mitigating travel delay from implementing any of these proposed strategies are also synthesized in the table. These approaches, by and large, have not been quantitatively analyzed for their ability to mitigate incident impacts. Moreover, while studies of TIM programs designed for freeways are commonplace, the analyses of similar programs for facilities with managed lanes are rare.

Table 8-1: Incident management tools for managed lane and potential effects

Incident Management Strategies (TTI, 2004)	Potential Effects
GP traffic diversion into managed lanes	Balance traffic demand and use extra capacity on the HOT lane to mitigate incident impact
Pre-positioned response crews	Reduce incident duration
Blocking a managed lane to create a safe work area	Reduce incident duration and reduce capacity
Mutual aid agreements between managed lane and GP lane agencies	Reduce incident duration
Public notification of incidents	Reduce traffic demand around incident scene
Incident responder access path to incident scene	Reduce incident duration

This chapter studies the potential benefits of traffic diversion in incident management for freeway operations of concurrent flow lane facilities. Specifically, savings in average travel time from exploiting the capacity of managed lanes in diverting traffic around an incident arising in the GP lanes are quantified. Barrier and nonbarrier separated facilities are considered. In barrier separated facilities, entry into the managed lane(s) is restricted to predetermined access points. In a non-barrier separated system, under normal operations, qualified vehicles (e.g. HOV 2+) can access the managed lane without restriction (i.e. continuous access) or at designated access points when acess is limited through buffer separation delineated by white lines. Such nonbarrier separation techniques are used where the necessary space required for physical barrier separation and police activities required for enforcement are limited or the construction and maintenance costs of such barriers are prohibitive (see Miller-Hooks et al., 2009 for additional detail). A non-barrier separation technique provides the opportunity for temporarily lifting managed lane regulations and/or buffer marking restrictions in diverting non-HOV/HOT compliant traffic between GP and managed lanes to relieve incident-induced congestion. Thus, traffic can be diverted into the managed lane(s) either by way of designated access points or by crossing the buffer at a more convenient location, presumably just upstream of the incident scene.

As diverting traffic into a managed lane will degrade its performance, trade-offs in overall system performance and the performance of the managed lane must be understood. It appears that no prior study has quantified the potential impact of such a diversion strategy along freeways operating managed lanes.

A simulation-based evaluation platform was developed. The platform employs PTV America's VISSIM (version 5.2) software, a micro-simulation tool for traffic operations modeling. Techniques were created employing VISSIM's Component Object Module (COM)

interface to overcome deficiencies in modeling incidents and possible diversion implementations. The potential for mobility improvement in GP lanes as a consequence of diverting traffic around an incident using existing managed lanes and resulting degradation in managed lane performance is considered on a case study. The case study takes advantage of a previously developed and fully calibrated model of a proposed managed lane facility along a segment of I-270 in Maryland. Under a spectrum of incident properties and prevailing traffic conditions, the effects of diversion in terms of savings in average travel time in the GP lanes and resulting degradation in service levels incurred by traffic using the managed lanes were quantified and trade-offs were assessed through numerical experiments. This chapter describes the evaluation platform, experimental design and results and findings from experimental runs.

8.2 Literature Review

When incidents occur that severely limit roadway capacity, many motorists will seek alternative routes in an effort to avoid the incident scene. Information can be provided to the motorist to aid motorists in locating alternative routes with better service. Preplanned diversion strategies typically utilize parallel arterials. In some locations (e.g. Texas, Virginia, Maryland, and Minnesota), diversion strategies include the use of HOV or HOT lanes (Hoppers et al., 1999). Dunn et al. (1999) conducted a survey of freeway operators in several states within the United States. Details of various types of diversion scenarios, planning processes, selection criteria for choosing alternative routes, deployment decisions for diversion strategies, methods to detect incidents, resources to inform and guide motorists, and satisfaction associated with route diversion strategies across the nation gleaned from the surveys are presented in their work. Although diverting traffic to arterial roads has been extensively studied (e.g. Cragg and Demetsky, 1995; Zhou, 2008), analyses of

diversion strategies that employ managed lanes are scarce.

The decision to open a managed lane to general traffic regardless of the purpose is complex. Hoppers et al. (1999) interviewed six managed lane operation agencies about the possibility of opening managed lanes to general traffic. The agencies identified issues related to agency policy, motorist information and public acceptance that would be difficult to overcome should such diversion strategies be considered. Thus, these system operators only opened the managed lane to general traffic a few times a year in response to incidents. Hoppers et al. present criteria involving incident severity, time-of-day, impact on main lane traffic, and availability of alternative routes for consideration in making such diversion decisions. Similarly, Fenno et al. (2006) suggest a series of factors, including the volume to capacity (V/C) ratio along the managed lane, time-of-day, traffic volume along GP lanes, and incident properties (duration and number of lanes blocked) that can be used in making such decisions. They suggest that diversion is warranted under high levels of congestion along the GP lanes given that there is no more than 20 vehicles per lane per minute in the managed lane(s) and the incident lasts 30 minutes or longer. However, no quantitative analyses were conducted to support the suggestions. Both works consider only barrier-separated systems in which general traffic can be diverted into the managed lane only at designated access points.

These prior studies are qualitative in nature. There have been, however, studies that quantify the impact of traffic diversion to alternate routes. A number of prior studies employed microsimulation tools, such as CORSIM, to analyze the impact of diverting traffic from the freeway to a parallel or alternative arterial street in an effort to mitigate the impact of an incident. See, for example, works by Zhou (2008) and Cragg and Demetsky (1995). Modeling techniques used to carry out these studies do not apply when traffic is to be diverted across a buffer or where

issues of vehicle class and lane-use permission arise. This gap will be addressed herein. The authors know of no other studies that have sought to quantify and systematically study the potential of diversion strategies that exploit capacity of existing managed lanes.

8.3 Diversion Strategies that Exploit Capacity of Managed Lanes

In creating a diversion strategy that exploits capacity of managed lanes for use in the event of an incident, several characteristics of the strategy must be specified. These include: relaxing regulations so as to permit additional vehicle classes to use the managed lane(s) during the diversion period (diversion permitted vehicles); defining or redefining access locations between adjacent GP lane and the managed lane(s), where permitted vehicles can freely merge in and out (diversion access locations); and the time period during which diversion into the managed lane(s) is permitted (diversion period).

8.3.1 Relaxing Managed Lane Regulations

In managed lane systems, lane usage is regulated by the number of occupants in each vehicle (usually requiring two or more occupants) and vehicle type (passenger vehicle as opposed to truck). In managed lane systems operating HOT lanes, single occupant vehicles (SOVs) can use the managed lane(s) by paying a toll. The rules for regulating the use of the managed lane often depend on the severity of pre-incident traffic congestion along the roadway. The worse the congestion, the more limiting the relaxation in regulations will need to be. Diversion strategies can, thus, permit all vehicles to use the managed lane or limit those for whom the restrictions will be lifted.

8.3.2 Defining a Space for Diversion

The simplest approach to setting diversion access locations is to maintain standard access regulations (i.e. the same structure for access as exists under pre-incident conditions). In non-barrier separated facilities, it is possible to consider more flexible design in setting the access locations during diversion. One possibility is to allow access to the managed lane(s) as if the facility supports continuous access, permitting vehicles to cross the buffer between GP and managed lanes along a designated stretch of roadway (e.g. the closest upstream standard access point and the location of the incident). The implementation of such strategies will require the assistance of police officers, incident management personnel, and/or proper signing.

8.3.3 Defining the Diversion Period

The time period following an incident is often described as consisting of verification, response, clearance and recovery phases. Additionally, site management and traffic management/motorist information periods are defined over portions of these phases. This time period is depicted in Figure 8-1 (FWHA, 2003). The completion of each phase is typically recorded by the use of timestamps. The diversion period should, at a minimum, the site management period. It can be extended until pre-incident traffic conditions are restored.
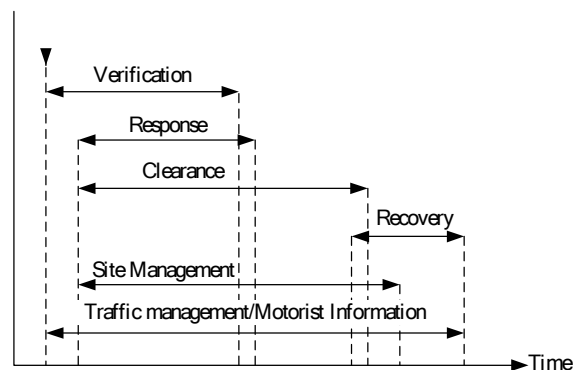
Figure 8-1: Incident and TIM program timeline (source: FHWA, 2003)

8.4 Simulating Incidents and Diversion Maneuvers

The VISSIM simulation software employed within this study is a powerful microsimulation tool that through its COM (PTV, 2009 b) interface permits great flexibility in controlling various aspects of the simulation environment. In this section, steps taken to model incidents and implementation of studied diversion strategies are described. Particular attention is paid to those aspects requiring a certain level of ingenuity in model development. These aspects relate to control of the time of incident occurrence, modeling of the so-called rubber-necking effect for traffic in unaffected travel lanes in the vicinity of the incident, and implementation of access limitation restriction lifting for diversion application during limited time periods.

8.4.1 Time of Incident Occurrence

The VISSIM software package does not have a specific incident function and its user manual does not discuss modeling of incidents. However, the use of a "Parking Event" is suggested as a special modeling example that is provided with the software package (see PTV training example for detail). Following the demonstrated approach, two simulation entities are employed: "Parking Lot" and "Route Decision." Prior to running the model, a Parking Lot including one space must be placed at the location of a potential incident (the incident scene) and a Route Decision must be set to send an approaching vehicle to the space. If more than one lane is to be blocked by the incident, multiple Parking Lots must be created. The window of time during which the Parking Lot will be present must be predefined. This approach to modeling incidents has been adopted in a number of studies, including, for example, studies by (Wang et al. 2008; Hadi et al. 2007; Pulugurtha, et al., 2002). As noted by Hadi et al. (2007) and Pulugurtha et al. (2002), this approach has deficiencies. Specifically, by this approach, the time of "incident" onset depends on

the decision of a vehicle to enter the parking lot. Thus, the exact time of incident occurrence cannot be controlled and no timestamp is recorded for the incident occurrence. This is problematic for this study, because the incident onset time triggers a number of additional processes, including rubbernecking and diversion, that require a specific start time, even if only set after the incident arises.

Rather than use the Parking Lot approach to incident modeling, an alternative approach is adopted herein. This approach uses the "Addvehicle" function that exists within the COM interface. This function allows users to create and remove a vehicle at a specific point in time and at a chosen location. To replicate an incident with this function, a vehicle is created with a speed of zero. The vehicle is set to be placed in the model at the incident location at the chosen time of incident onset. It is set to be removed at the end of the clearance phase. The period during which the vehicle with zero speed is present is referred to as the "incident active" period. To replicate an incident with two or more lanes blocked, multiple vehicles can be added to adjacent lanes with the same time of placement and removal. The length of roadway blocked by the incident can be controlled by setting the length of the vehicle accordingly. Moreover, changes in the number of lanes blocked over the incident duration can be easily modeled.

8.4.2 Rubbernecking

VISSIM offers a "Reduced Speed Area" function for modeling the effects of rubbernecking in adjacent travel lanes to an incident. The speed value within this area is appropriately set. This function has been successfully used in other studies. In this study, however, the "Reduced Speed Area" function must be synchronized with the incident occurrence, as the incident occurrence is set for only a portion of the simulation period. The VISSIM "Reduced Speed Area" function if

used must be applied over the entire simulation period. To permit the speed to change over the simulation period so as to be reduced only during the incident period, the speed value within the Reduced Speed Area can be set to free-flow speed before the incident occurs and after the incident is cleared, and to the reduced value during the incident with the use of the COM interface. Specifically, the slower speed value is set to "active" when applicable and "inactive" otherwise. When inactive, free flow speeds are maintained.

In this study, a Reduced Speed Area of 500 feet extending from the beginning of the incident scene upstream is employed as recommended in the guidelines for emergency traffic control (University of Kentucky, 2006). A speed of 20 miles per hour for the active period is used in all lanes in the Reduced Speed Area consistent with settings of reduced speed values suggested by Hadi et al. (2007) needed to replicate capacity reduction due to incidents along freeways.

8.4.3 Diversion

Techniques introduced in Miller-Hooks et al. (2009) and Chou et al. (2010) to model non-barrier separated concurrent flow lane operations and lifting of buffer crossing restrictions to replicate violators are applied herein. In these works, techniques are described that can be used to restrict the use of the managed lanes to only a portion of the traffic and to model violators that cross into the managed lanes at locations where such crossing is not permitted. These techniques rely heavily on "Lane Closure" and "Vehicle Type" functions available in VISSIM. A similar modeling approach is adopted in this study with some alterations.

When the managed lane is open to general traffic, it is treated as a GP lane. Vehicles will choose to use the managed lane or other GP lanes based on the relative performance of all lanes.

Additionally, the opening and closing of the managed lane to general traffic is set for a specified period (the active period) associated with the occurrence of the incident. The timing for "Lane Closure" settings associated with the appropriate portion of the managed lane is controlled through the use of the COM interface and is set to occur in line with the incident duration (the active period) and diversion strategy. Once the incident has been cleared and the incident active period has elapsed, "Lane Closure" properties associated with each "Vehicle Type" are restored to pre-incident settings. GP lane users are forced out of the managed lane immediately downstream of the incident, or at the first access point downstream of the incident under limited access scenarios.

To model the access point diversion strategy and ensure that the GP lane users diverted to managed lanes between access points will travel at an appropriate speed, the segment of the managed lane between the affected access points must be treated as a separate link. No changes to other properties, e.g. "Lane Closure" or "Vehicle Type" are required.

A timeline along which actions taken to replicate incident occurrence, rubbernecking effects, and diversion strategy implementation is presented in Figure 8-2.
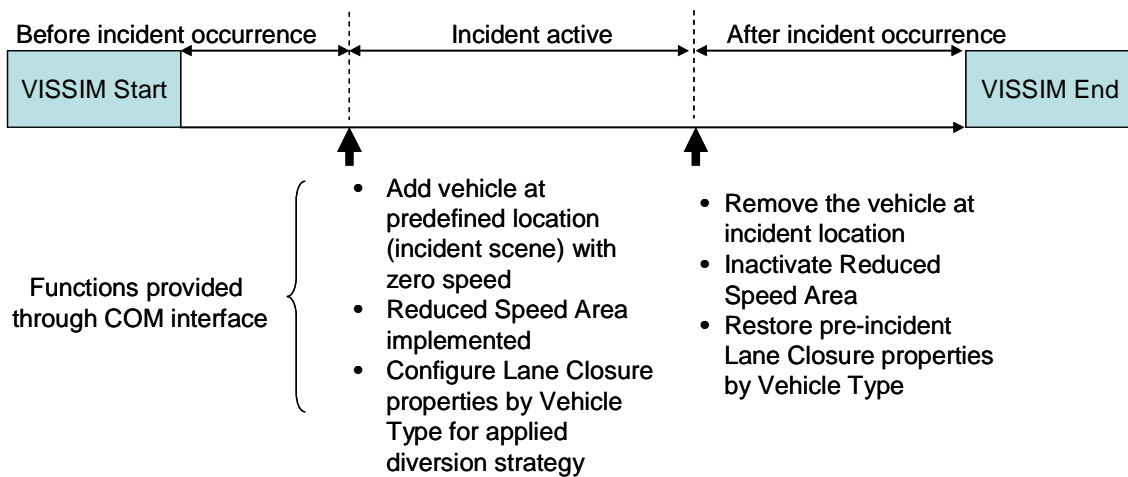
Figure 8-2: COM interface interacting VISSIM model

8.5 Case Study

The potential benefits of diversion strategies that exploit the use of capacity in the managed lane(s) for drivers in the GP lanes, and the potential implications for managed lane performance, are investigated through a simulation-based study of a stretch of I-270 in Maryland. This stretch of roadway includes an operating, continuous-access HOV lane. The State of Maryland is considering several alternative HOT lane conversion designs. In this investigation, one such design is adopted.

8.5.1 Study Site

The case study involves the southbound lanes of a seven-mile (39,952 feet) stretch of I-270 in Maryland. Morning peak hours of operation are considered. As depicted in Figure 8-3, the I-270 corridor is an important conduit for traffic entering the Washington Beltway, which feeds Washington, D.C. and business districts in Virginia and Maryland. A previously developed and calibrated model of this roadway segment with existing HOV lane facility provides a base for this case study.

An alternative to HOV operations is under consideration that involves the conversion of the existing, continuous-access HOV lane to a single limited access HOT lane separated from the GP lanes by a buffer. This alternative design, modeling techniques employed, and calibration results obtained are described in (Miller-Hooks et al., 2009). Traffic demand, vehicle occupancy and composition data were provided by Maryland State Highway Administration and are also described in this earlier work. Vehicle classes with restrictions on HOT lane use were established. Eight such classes were created as listed in Figure 8-3b. Note that Class 5 is meant to replicate single occupant vehicles that illegally use the HOT lane. For the purpose of this study, it is assumed that no vehicles fall within this class.

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Vehicle Class	Vehicle Type	Occupancy	Using HOT lane?	Composition (%)
Class 1	truck	1	no	0.053
Class 2	truck	1	yes	0.000
Class 3	bus	2+	no	0.003
Class 4	bus	2+	yes	0.001
Class 5	passenger car	1	yes	0.000
Class 6	passenger car	1	no	0.703
Class 7	passenger car	2+	yes	0.188
Class 8	passenger car	2+	no	0.047

8-3a Study Area	8-3b Traffic Composition
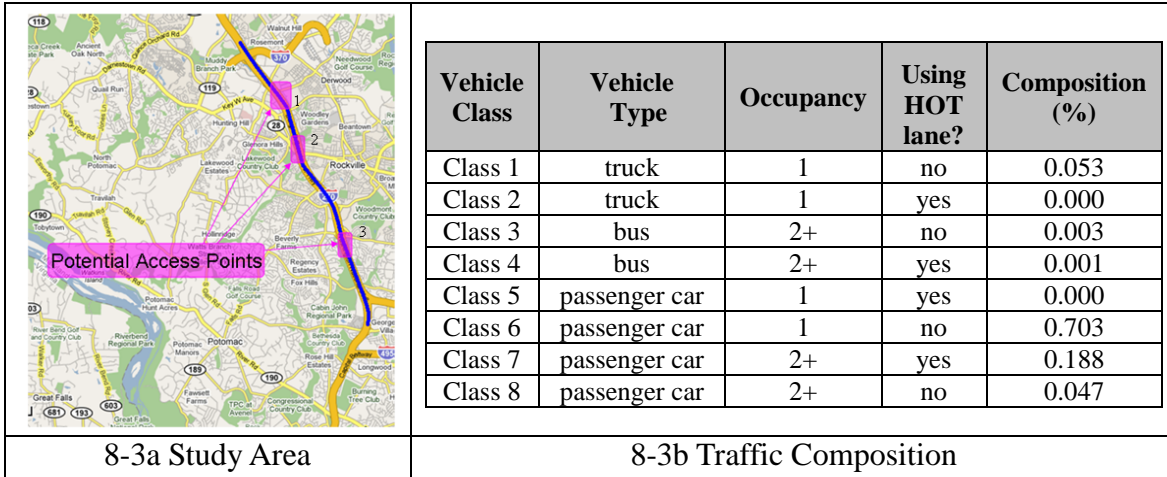
Figure 8-3: Study area and vehicle classification

8.5.2 Experimental Design

The impact on mobility of diverting traffic from GP lanes into the managed lane of specified diversion strategies is studied through extensive simulation runs on the case study. Numerous incident scenarios were systematically defined for experimental testing. Three factors were considered in creating these scenarios. These factors include: incident location along the length of roadway, number and identification of lanes blocked, and incident duration. Three incident locations (X, Y and Z) between the second and the third access points are considered. For each location, five settings in terms of number and choice of lanes blocked are studied (A, B, C, D and E). 10-, 20- and 30-minute incident durations are run. Additionally, three diversion strategies are considered (P: no diversion, Q: access point diversion, R: continuous diversion). All diversion strategies apply to the roadway segment between the second and third access points. Factors contributing to incident scenario definition along with the various diversion strategy implementations are depicted in Figure 8-4. 135 combinations of incident scenarios and diversion strategy implementations are considered.

For each combination of factors, 10 simulation runs are made, each with a different seed

value. The same set of 10 randomly selected seeds are used for each scenario. Parameters, such as those related to car-following and lane changing behavior, determined through extensive calibration efforts mentioned previously, and other input data, including turning rates and 2006 a.m. peak traffic volume levels, obtained through field surveys as described in (Miller-Hooks et al., 2009), were employed herein and set identically across all simulation runs.

It should be noted that the experimental design presumes that diversion strategies are of interest under congested periods as suggested in the literature. Fenno et al. (2006) recommend that such diversion strategies be employed only if the incident if of a duration of 30 minutes or longer and blocks more than one lane for a roadway with three GP lanes. These experiments are designed to assess the veracity of these recommendations.
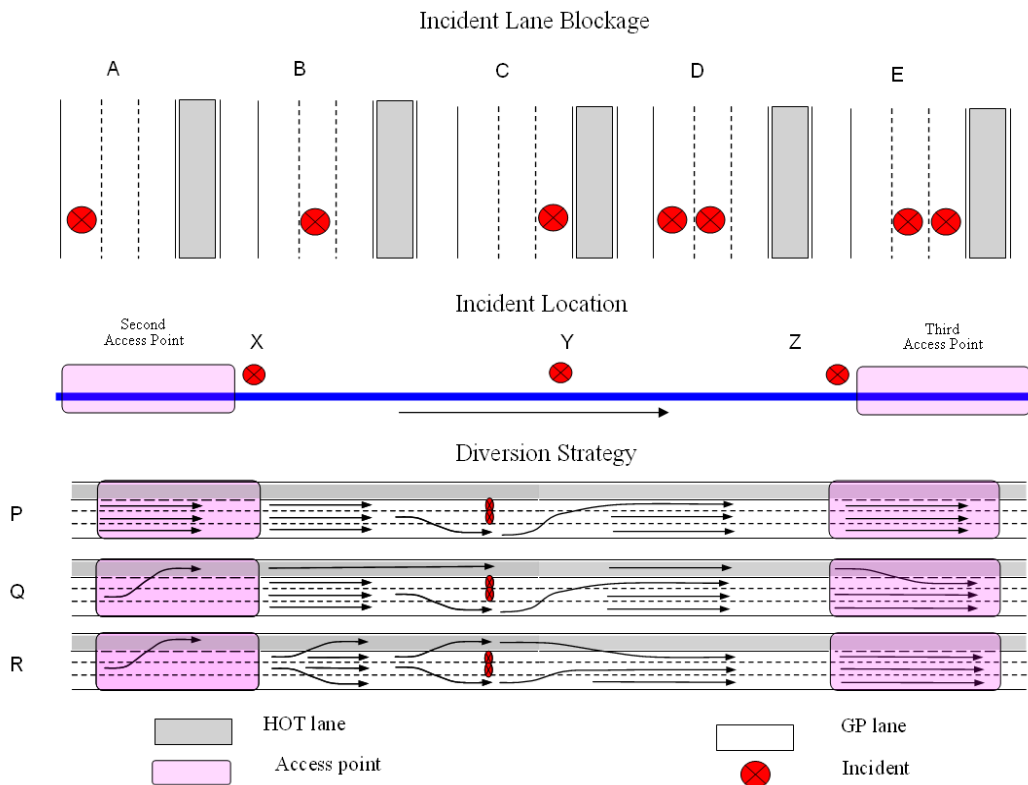
Figure 8-4: Incident scenario factors

One run of the VISSIM model for a given incident scenario and seed involves 5,400 seconds of simulation time, the first 1,800 seconds of which was considered as the warm-up period. Incidents are designed so as to occur after the simulation warm-up period, after 2,000 seconds of simulation time. Average results when provided, unless otherwise specified, are hourly averages based on the 3,600 seconds of simulation run time from each of the ten runs. A total of 1,350 simulation runs were conducted. Each run required approximately 6 minutes on a Dell Precision T7500 personal computer with a 3.20 gigahertz quad core processor, and 12 gigabytes of RAM, running the 64 bit Windows 7 operating system. A Visual Basic for Applications (VBA) code was developed to enable batch runs and automate the process of data collection for analysis.

8.5.3 Analysis of Results

To assess the impact of traffic diversion on performance in the managed or GP lanes, the average travel time incurred by those vehicles traversing the entire length of the managed or GP lane in the study area was computed. Results are categorized by incident duration and performance along either the managed lane (Figures 8-5a ~ 8-5c) or GP lanes (Figures 8-5d ~ 8-5e) as depicted in Figure 8-5. Diversion strategies are compared by considering the percentage difference between incurred travel times as given in Table 8-2.

Average segment travel time along (managed lane)	Average segment travel time along (GP lane)
8-5a: 10 minutes incident duration (managed lane)	8-5d: 10 minutes incident duration (GP lane)
8-5b: 20 minutes incident duration (managed lane)	8-5e: 20 minutes incident duration (GP lane)
8-5c: 30 minutes incident duration (managed lane)	8-5f: 30 minutes incident duration (GP lane)

Figure 8-5: Average travel time along managed and GP lanes under varying scenarios

Table 8-2: Average travel time differences as a percent between pairs of diversion strategies under varying incident scenarios

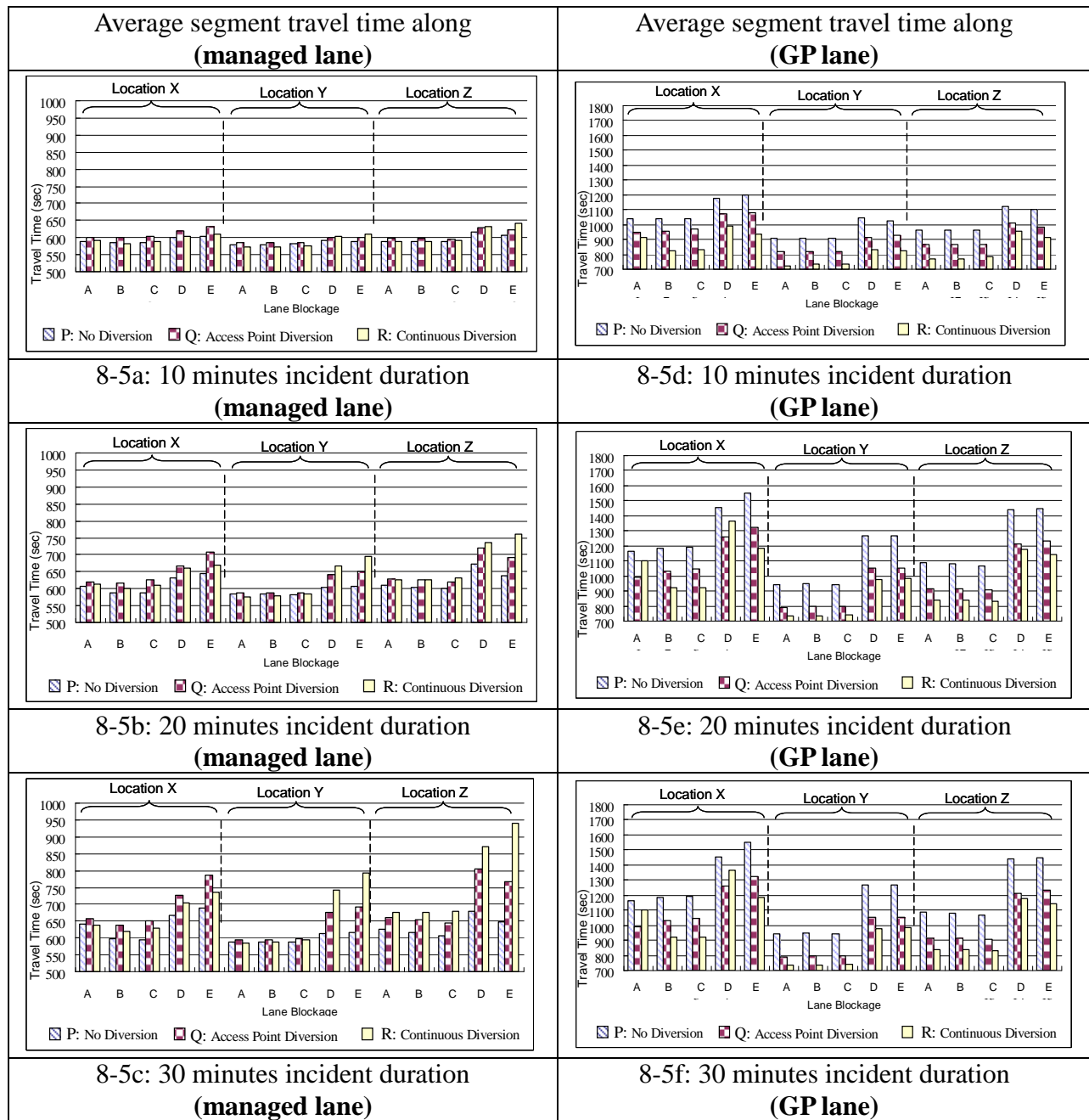| Diversion Strategy Comparison (Travel Time Change in %)		Incident duration: 10 minutes						Incident duration: 20 minutes						Incident duration: 30 minutes					
		HOT Lane			GP Lane			HOT Lane			GP Lane			HOT Lane			GP Lane		
		P|Q	P|R	Q|R	P|Q	P|R	Q|R	P|Q	P|R	Q|R	P|Q	P|R	Q|R	P|Q	P|R	Q|R	P|Q	P|R	Q|R
Location X	L.B. A	2.0	0.2	-1.8	-8.7	-12.0	-3.6	2.0	0.7	-1.3	-14.8	-5.5	10.8	2.7	-0.3	-2.9	-20.8	-4.7	20.4
	L.B. B	2.5	-0.4	-2.9	-7.5	-20.4	-14.0	4.7	2.0	-2.5	-13.0	-22.2	-10.7	7.1	3.7	-3.2	-17.7	-23.7	-7.2
	L.B. C	3.3	0.6	-2.5	-6.7	-20.2	-14.4	6.1	3.2	-2.7	-12.3	-22.8	-11.9	9.2	5.9	-3.0	-17.6	-24.6	-8.5
	L.B. D	3.2	0.7	-2.4	-8.5	-15.7	-7.8	5.2	4.1	-1.0	-13.4	-6.3	8.3	8.6	5.4	-3.0	-13.8	-7.0	7.9
	L.B. E	4.6	1.1	-3.4	-9.5	-21.8	-13.6	10.1	4.2	-5.3	-15.0	-23.9	-10.5	14.2	6.8	-6.5	-16.4	-20.8	-5.2
Location Y	L.B. A	0.7	-1.6	-2.3	-10.4	-20.6	-11.3	0.7	-1.2	-1.8	-15.9	-22.4	-7.7	1.0	-0.7	-1.7	-20.5	-25.3	-6.0
	L.B. B	0.7	-1.3	-2.0	-10.3	-19.6	-10.3	0.5	-1.0	-1.5	-15.9	-22.4	-7.7	1.3	0.2	-1.1	-20.3	-25.6	-6.6
	L.B. C	0.6	-1.1	-1.7	-10.2	-18.9	-9.7	1.1	0.3	-0.7	-15.6	-21.0	-6.4	1.5	1.2	-0.4	-20.0	-24.0	-5.0
	L.B. D	1.4	1.9	0.6	-12.2	-20.2	-9.1	6.1	10.3	4.0	-16.9	-23.0	-7.3	10.2	20.9	9.7	-20.0	-24.7	-5.9
	L.B. E	2.3	3.6	1.3	-9.9	-19.5	-10.7	6.9	14.2	6.8	-16.8	-22.5	-6.9	12.5	28.7	14.4	-20.2	-23.6	-4.3
Location Z	L.B. A	1.4	-0.1	-1.5	-10.4	-19.9	-10.5	2.9	2.7	-0.2	-15.9	-22.6	-7.9	5.6	8.1	2.3	-19.6	-26.0	-8.0
	L.B. B	1.4	-0.3	-1.6	-10.4	-20.4	-11.2	3.1	3.5	0.4	-15.4	-22.5	-8.4	6.0	9.9	3.7	-20.0	-26.2	-7.7
	L.B. C	1.4	0.8	-0.6	-10.0	-18.8	-9.7	3.0	5.1	2.1	-15.1	-22.1	-8.2	6.4	12.1	5.4	-19.1	-25.8	-8.3
	L.B. D	1.9	2.5	0.6	-9.9	-14.8	-5.4	6.7	9.4	2.5	-15.9	-18.3	-3.0	18.5	27.9	7.9	-17.6	-22.5	-5.9
	L.B. E	2.4	5.6	3.1	-10.5	-17.2	-7.4	8.6	19.5	10.1	-14.8	-21.0	-7.2	18.3	45.3	22.8	-18.8	-23.5	-5.8

Results of the experiments show that when no diversion strategy is employed in the event of an incident, average travel times in the managed lanes are significantly lower than in the GP lanes. Figure 8-5 shows that this difference in average travel time ranges from a minimum of 26% when an incident of 30 minutes in duration occurs at location Y blocking one lane (i.e. type B) to a maximum of 171% when an incident of 30 minutes in duration arises at location Z blocking two lanes (i.e. type E). The simulation scenario with no diversion strategy provides a base case for comparison with other diversion strategies.

8.5.3.1 Continuous Diversion Strategy

A continuous diversion strategy is shown to produce significant benefit for GP lane users across all incident scenarios tested in this study. This strategy permits vehicles to divert to the managed lane immediately after detecting queue formation in the GP lanes resulting from the incident and presumes that these vehicles will be forced to merge back into GP lane after passing the incident

scene. The charts of Figure 8-5 indicate that such a diversion strategy consistently results in lower average GP-lane travel times as compared with no diversion and access point diversion strategies under identical incident scenarios. Opening the managed lane significantly increases discharge capacity at the incident scene and saves up to 26% in average segment travel time as compared with the case in which no diversion strategy is implemented. For instance, when an incident occurs with a duration of 30 minutes that blocks one lane (i.e. type B) at location Z, a 26.2% reduction in average GP-lane travel time is noted (see P-R column in Table 8-2). An average (over types A, B and C) reduction of 21% in average GP-lane travel time can be achieved when one lane is blocked by an incident. This figure is 19% savings in average GP-lane travel time when two lanes are blocked (types D and E).

Among the 27 incident scenarios tested in which only one lane is blocked, in 25 (i.e. 93%) the continuous diversion strategy saves greater than 10% of average GP-lane travel time as compared with the no diversion strategy implementation case. In 24 of these 27 scenarios (i.e. 89%) a savings of 15% in average GP-lane travel time is achieved. And, in 20 of these 27 scenarios (i.e. 74%), a savings of at least 20% in average GP-lane travel time is noted. When two lanes are blocked by the incident, the improvement is even greater. Of the 18 scenarios in which two lanes are blocked, 16 (or 89%) lead to a savings in average GP-lane travel time of greater than 10%, 15 (or 83%) lead to a savings of greater than 15% and 11 (or 61%) lead to a savings of greater than 20%.

8.5.3.2 Access Point Diversion Strategy

The access point diversion strategy permits GP lane users to divert to the managed lane(s) at designated access points during the incident clearance phase (i.e. the active phase). The decision as to

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whether or not to enter the managed lane(s) upstream of an incident once restrictions are lifted depend on whether or not the driver is affected by incident-induced queues prior to an access point.

Results of the experiments showed that traffic in the GP lanes diverted to the managed lane only when the incident-induced queue was at or near the access point immediately upstream of the incident. When incidents arise at location Y and Z, it takes time for the incident-induced queue to extend to the upstream access point. Consequently, the number of vehicles that divert to the managed lane for incidents occurring at the location X is greater than for those incidents arising at locations Y and Z. For shorter duration incidents at locations Y and Z, queues due to the incident often do not extend as far upstream as the access point. Thus, vehicles do not detect the incident until the opportunity to enter the managed lane has passed (i.e. the vehicle has passed the access point).

As shown in Figure 8-5, as a result of permit access point diversion, an average reduction of over 15% in average GP-lane travel time can be achieved when one lane is blocked by an incident (under incident types A, B and C), regardless of the incident location relative to the access point opening. This figure is also 15% reduction in average GP-lane travel time for incidents blocking two lanes (types D and E).

Among the 27 incident scenarios tested in which only one lane is blocked, in 24 (i.e. 89%) the access point diversion strategy saves greater than 10% of average GP-lane travel time as compared with the no diversion strategy implementation case. In 15 of these 27 scenarios (i.e. 56%), a savings of 15% in average GP-lane travel time is achieved. And, in five of these 27 scenarios (i.e. 19%), a savings of at least 20% in average GP-lane travel time is noted. Of the 18 scenarios in which two lanes are blocked, 14 (or 78%) lead to a savings in average GP-lane travel time of greater than 10%, 8 (or 44%) lead to a savings of greater than 15% and one (or 6%) lead to a savings of greater than 20%.

8.5.3.3 Effects on Managed Lane Users

Adverse effects on managed lane performance are expected as a consequence of opening the lane to general traffic, as an increase in traffic demand for the lane will result. Comparing the performance between the two diversion strategies studied (i.e. Q-R comparison), the access point diversion strategy leads to greater degradation in managed lane performance than does the continuous diversion strategy in the majority of the 45 incident scenarios tested. Specifically, in 28 out of the 45 (or 62% of the) incident scenarios, the increase in average travel time along the managed lane was greater for the access point diversion strategy than for the continuous diversion strategy. It should be noted that 15 of these 28 incident scenarios involved an incident at location X.

With a continuous diversion strategy implementation, average managed lane travel times increase by 0%, 2% and 4% when an incident blocked one lane with a duration of 10, 20 and 30 minutes, respectively, and 3%, 10%, and 23% when an incident blocked two lanes with a duration of 10, 20 and 30 minutes, respectively. With an access point diversion strategy implementation, these figures become to 2%, 3% and 5% when one lane is blocked with a duration of 10, 20 and 30 minutes, respectively, and 3%, 7% and 14% when two lanes are blocked with a duration of 10, 20, and 30 minutes, respectively. The degradation along the managed lane due to traffic diversion from the GP lanes becomes particularly significant when two lanes are blocked for 20 minutes or longer.

8.5.3.4 Trade-offs in Performance of Managed and GP Lanes

Trade-offs in terms of percentage increase in average travel time for the managed lane users and percentage decrease in average travel time for general traffic are investigated by comparing the

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impact of access point and continuous diversion strategies against a do-nothing strategy (i.e. P-Q and P-R comparisons). To facilitate this comparison, Table 8-3 provides an index of benefit based on input from Table 8-2. This index is computed by taking the difference between the percentage decrease in average travel time along the GP lanes and the percentage increase in average travel time along the managed lane directly. One might weight these percentage changes by traffic volume or might compute the impact per passenger rather than per vehicle. The index is set to this difference if its value is positive. Otherwise, it is set to zero. A + sign indicates when no detriment to the managed lane was noted. Thus, the benefits to the GP lane users outweigh the negative impact to the managed lane users in those incident scenarios in which the index has a value greater than 0 or a + sign.

Table 8-3: Trade-off between managed and GP lanes in P-R and P-Q comparisons

Trade-off		P-R Comparison			P-Q Comparison		
		10 minutes	20 minutes	30 minutes	10 minutes	20 minutes	30 minutes
		Index	Index	Index	Index	Index	Index
Location X	L.B. A	0.12	0.05	+	0.07	0.13	0.18
	L.B. B	+*	0.20	0.20	0.05	0.08	0.11
	L.B. C	0.20	0.20	0.19	0.03	0.06	0.08
	L.B. D	0.15	0.02	0.02	0.05	0.08	0.05
	L.B. E	0.21	0.20	0.14	0.05	0.05	0.02
Location Y	L.B. A	+	+	+	0.10	0.15	0.20
	L.B. B	+	+	0.25	0.10	0.15	0.19
	L.B. C	+	0.21	0.23	0.10	0.15	0.18
	L.B. D	0.18	0.13	0.04	0.11	0.11	0.10
	L.B. E	0.16	0.08	0	0.08	0.10	0.08
Location Z	L.B. A	+	0.20	0.18	0.09	0.13	0.14
	L.B. B	+	0.19	0.16	0.09	0.12	0.14
	L.B. C	0.18	0.17	0.14	0.09	0.12	0.13
	L.B. D	0.12	0.09	0	0.08	0.09	0
	L.B. E	0.12	0.01	0	0.08	0.06	0.01

* + indicates that the average travel times for all lanes improved as a result of diversion, and no negative impact was noted on the managed lanes.

In a comparison of continuous versus no diversion (i.e. P-R comparison), in only three out of each of the relevant 45 incident scenarios did the benefit to general traffic not outweigh the cost to the managed lane users. In a comparison of access point versus no diversion (i.e. P-Q

comparison), in only one out of each of the relevant 45 incident scenarios did the benefit to general traffic not outweigh the cost to the managed lane users. In the former case, these three incident scenarios involved type E incidents in which two lanes are blocked and an incident duration of 30 minutes. In the latter case, the one incident was located at incident location Z (furthest from the upstream access point). Again, this scenario involved an incident with a duration of 30 minutes. It is interesting to note that the only case in which diversion's benefits might be questioned based on this measure (assuming barrier separation) is precisely the scenario for which Fenno et al. (2006) would have recommended diversion. Moreover, these experimental results indicate that significant benefits may be achieved through diversion in the case of incidents blocking only one lane and for short durations, cases in which Fenno et al. would not have recommended diversion.

Where nonbarrier separation techniques are deployed, and there is a choice between continuous and access point diversion, which strategy to implement appears to be incident scenario dependent. When the incident is short, on the order of 10 minutes, the continuous diversion strategy is notably better than the access point diversion strategy. Given an incident duration of 30 minutes, the continuous access strategy outperforms the access point diversion strategy for all scenarios involving incidents blocking one lane and the reverse is true in all scenarios but one when an incident blocks two lanes. When two lanes of the GP lanes are blocked, the demand for the managed lane is greater than when only one lane is blocked. The access point diversion strategy reduces the opportunity for vehicles in the GP lanes to switch into the managed lane, helping to maintain higher speeds along the managed lane. In incident scenarios involving One general benefit of a continuous diversion strategy is that the benefits of the strategy can be obtained immediately, regardless of the relationship between queue detection

and access point location. Observations from the animation in the simulation runs also indicate that incident-induced queues are shorter when the continuous diversion strategy is employed as compared with the access point diversion strategy, reducing the time required for the restoration of traffic conditions to pre-incident conditions.

8.6 Summary

This study quantifies the potential benefits and detriments of diverting general traffic into a managed lane when an incident arises along the GP lane. Techniques that exploit the capabilities of the COM interface of the microscopic simulation tool, VISSIM, were devised for modeling freeway incidents and diversion strategy implementations. Both continuous and access point diversion strategies were evaluated using the developed simulation techniques for their impacts on the mobility of general traffic and managed lane users along a concurrent flow lane system on I-270 in Maryland. Results from systematically designed experiments show that the benefit to general traffic due to a diversion strategy is a function of several factors, including the relative location of the incident scene to the start point of the diversion strategy, total length of access to the managed lane under the diversion strategy, incident duration, and number of lanes blocked (i.e. incident severity). While degradation in performance of the managed lanes was noted under either diversion strategy, the benefits of diversion to GP lane users appear to outweigh the detriments in terms of added delay to managed lane users in nearly all incident scenarios, including those in which only one lane is blocked. The benefits are greatest under longer incident durations. Trade-offs derived from the performance difference between managed and GP lane users with either a continuous or access point diversion strategy implementation will be useful in determining under what circumstances the benefits of diversion warrant incurring added delays for managed lane users.

Additional strategies may be considered. For example, one might study the impact of diverting GP-lane traffic into the managed lane at locations prior to queue formation detection. Decisions regarding the opening of a managed lane to general traffic are complex. A system-wide performance measure that combines quantitative and qualitative measures may be developed to facilitate such decisions.

This study assumes diversion to be effective immediately after an incident occurs. In reality, the implementation of a diversion strategy will lag incident occurrence and depends on the speed with which the responder arrives at the scene and comes to a decision to allow diversion of general traffic into the managed lane(s). Additional experiments can be run to assess the impact of taking quick decisions to implement diversion. In addition to utilizing the managed lane, a shoulder lane, when available, may provide necessary capacity to handle traffic diverted from the GP lanes in the event of an incident. Simulation techniques provided in this chapter can be applied directly to study the potential of shoulder use in incident management.

Chapter 9 Conclusions and Extensions

9.1 Thesis Contributions and Benefits

Despite significant technological achievements over past decades, and institutional support for Intelligent Transportation System (ITS), it is not possible to prevent all traffic incidents and every day along U.S. freeways, numerous incidents occur. TIM programs have been proposed and implemented to mitigate the impact of incidents. In considering the implementation of a TIM program for a given location, it is important to ensure that the benefits of the program will be worth the costs of its implementation. Additionally, traffic violations along freeways can impact traffic operations in a similar way as other traffic incidents. Because the violation duration and the period of impact is much shorter than typical incidents involving disabled vehicles or collision, the violations can be thought of as "mini" or transient traffic incidents. This dissertation proposes numerous tools to aid in the evaluation of proposed TIM programs and the impact of violations on concurrent flow lane operations, contributing, thus, to the general study area of freeway incident management.

A Simulation-Based Secondary Incident Filtering (SBSIF) method is proposed for identifying secondary incidents from archived incident data. The proposed methodology is computationally efficient and overcomes deficiencies of existing techniques. Specifically, with inputs of a primary incident's properties and prevailing traffic conditions, a unique impact area can be delineated through simulation results or a set of regression models. The simulation results and regression models provide the corner points of the impact area. These corner points can be utilized to identify secondary incidents through establishing a geometric relationship between pairs of primary-secondary incidents in a time-space (x-y) coordinate system. Unlike existing

static threshold methods in which fixed impact time and location values are applied for all primary incidents, the SBSIF method considers the uniqueness of the impact area for each primary incident, improving the accuracy of secondary incident identification from archived data. This method has general applicability, with utility in any context in which the study of secondary incidents is warranted.

A three-stage time-saving process for conducting TIM program benefit evaluations is proposed. The proposed process relies on a developed Property-Based Incident Generation (P-BIG) procedure designed for sampling a relatively small set of good quality incident scenarios that can represent historical incident data in simulation studies. This method aids in overcoming the computational burden encountered when evaluating TIM program's benefit by simulation, a common practice. The procedural steps have general applicability, with utility in benefit analyses for FSP, traffic diversion, VMS/DMS systems, and AID systems, among other TIM program, that seek to mitigate incident impact by reducing incident duration or controlling traffic demand around the incident scene.

Modeling techniques customized for a widely available simulation tool, VISSIM, are proposed for simulating violations associated with the operation of concurrent flow lanes. Such violations are known to be commonplace in many systems, yet it appears that no attempt was previously made to quantify their impact. Novel simulation modeling techniques were developed in this dissertation. Vehicle trajectories were studied to ensure that these techniques properly replicate violation maneuvers. The modeling techniques are employed within a three-step simulation-based methodology for assessing safety impacts of violation maneuvers. Specifically, the methodology quantifies safety impact by measuring the variation of discontinuity in traffic speed contour maps (i.e. HaTSS) resulting from increase of violation rates along the freeway

systems. The proposed simulation techniques and methodology have wider application for mobility and safety analysis of traffic operations of concurrent flow lane systems. Results of a case study show that vehicles choosing to violate restrictions placed on a non-barrier separated, limited access concurrent flow lane facility significantly impact roadway mobility with a trend growing nonlinearly when high violation rates of more than 10% of roadway users are noted. Illegal traffic maneuvers between managed and GP lanes operating concurrently contribute to increased speed variation and congestion, and affect safety. Findings from this portion of the dissertation have immediate utility for assessing potential enforcement strategies.

Traffic diversion in which exploiting the residual managed lane capacity to cope with increasing congestion along the GP lanes when incidents occur is a specific type of TIM program aim at mitigating incident impact on concurrent flow lane operations. As no ready-to-use module exists in standard traffic simulation packages for modeling traffic diversion in response to incidents, a simulation-based evaluation platform employing the VISSIM COM interface was developed to model freeway incidents and possible diversion implementations. The potential for mobility improvement in the GP lanes as a consequence of diverting traffic around an incident, any resulting degradation in service levels incurred by traffic using the managed lanes, and trade-offs in implementing either a continuous or assess point diversion strategy are assessed on a case study. Results show that the proposed diversion strategies can efficiently mitigate incident impact along the GP lanes, with benefit to the general traffic that outweighs the detriments to the managed lane users in nearly all studied scenarios.

One might envision the assimilation of techniques proposed in this dissertation within an integrated TIM program evaluation system as depicted in Figure 9-1. Such a system would aid in quantifying the benefits of TIM strategy implementations in terms of mitigating the negative

impact of incidents on safety and mobility. The simulation techniques developed herein for modeling incidents (including violations) that block one or more traffic lanes and incident management strategy implementations (e.g. diversion strategies) can be applied to quantify mobility impact. Likewise, the SBSIF method for identifying secondary incidents and the HaTSS safety index can assist in assessing safety impact. Moreover, the time-saving technique, the P-BIG procedure, enables system operators to efficiently evaluate TIM program benefits. Results from performance assessment can provide important information for improving program offerings, resulting in safety and mobility improvements along freeway systems.
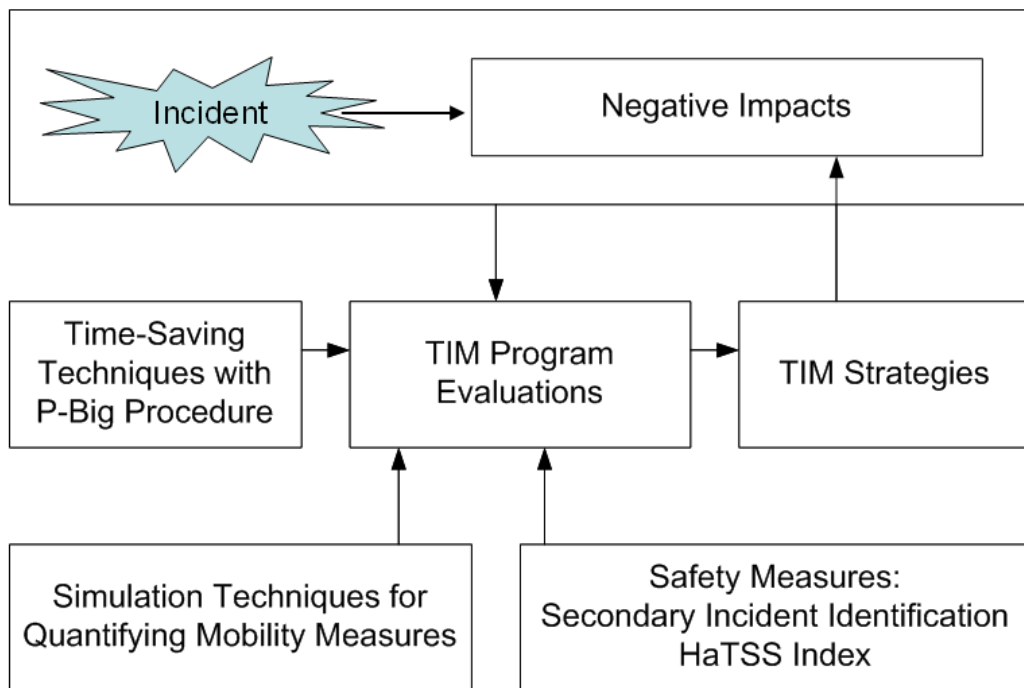

Figure 9-1: Integrated TIM program evaluation system

9.2 Extensions

Further studies related to secondary incidents might focus on exploring their properties and relationships to primary incidents, and estimating and predicting their occurrence. The

geometric-based regression model for delineating the boundary of incident impact area has broad application and value. It would be useful to consider methods for calibrating such models so as to minimize any differences between predicted and observed incident impact areas. With accurate and fast incident impact area delineation capabilities that rely on time-space traffic flow contour maps, one can predict travel times and speeds through the incident scene in real-time.

This study focused on occupancy and access violations along concurrent flow lane systems. The impact on mobility and safety of other moving violations, such as speeding and aggressive driving, or apprehensive driving causing platooning of vehicles, might be studied.

It may be useful to consider the development of a system-wide decision tool that combines both quantitative and qualitative measures associated with opening a managed lane to general traffic for the purpose of improving general operations during incident clearance. Effects of lifting lane usage and buffer crossing regulations for only a portion of vehicle classes or for specific short segments might be studied.

Incidents arise not only along freeway systems, but along arterial roadways, as well. In future work, one might tackle impact analyses of arterial incidents and TIM programs designed to mitigate their impact.

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