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Analysis of Primary-Secondary Incident Events on Urban Freeways

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ANALYSIS OF PRIMARY-SECONDARY INCIDENT EVENTS

ON URBAN FREEWAYS

by

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ABSTRACT

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Traffic incidents are a major source of congestion on urban freeways. Especially for large incidents, they typically block all or part of roadway facilities, cause traffic backup and increase the risk of secondary incidents occurring in their proximity. Approximately 2% to 15% of all incidents are secondary incidents. They further complicate the traffic conditions, stretch response resources and result in responders' and travelers' severe injuries or fatalities. These significant operational and safety concerns have drawn national and international attention. However, relatively little is known about the characteristics, occurrence, correlations and associated traffic delays of primary and secondary incidents. The objective of this study is to understand the nature of primary and secondary incidents, assess their impacts and explore the implications in traffic operations, safety, and planning. Ultimately, the advances and findings in this research will contribute to promoting an effective incident management strategy to restore disrupted traffic flow as quickly and safely as possible and assist in the planning process to conduct a more accurate impact/cost evaluation for non-recurrent congestion on urban freeways.

To achieve the objective, a queue-based secondary incident identification method was developed and applied based on detailed incident, traffic and geometric data sets from Hampton Roads, Virginia. This identification method can overcome the limitations in

earlier studies and identify secondary incidents in both road directions. An innovative event categorization defines the term "primary-secondary incident event", as one characterized by a primary incident and one or more associated secondary incidents in both directions to capture traffic impact and incident adversity. Primary-secondary incident events are categorized on a three-point ordinal scale as: (1) an independent incident, i.e., an incident not associated with any secondary incidents; (2) one primary-secondary incident pair; and (3) one primary with two or more secondary incidents in the same or opposite directions. Several key analyses were conducted to explore different aspects of primary-secondary incident events.

To observe distributing pattern differences of primary-secondary incident events, two major interests: event frequencies in different categories and durations of primary incidents have been analyzed spatially and temporally. Frequencies of primary-secondary incident events and duration distributions of primary incidents both show considerable spatial and temporal differences across different event categories. The hotspots (i.e. locations that have higher frequency of primary-secondary incident events) were identified.

To understand the occurrence of primary-secondary incident events, two proportional odds models were estimated to explore associations with various factors. In particular, the partial proportional odds model can relax parallel lines assumption and capture unequal contributions of explanatory variables across the event categories. The model suggests that with multiple-vehicle involvement, lane-blockage in a primary incident makes unequal contributions to the occurrence of different primary-secondary incident events, and they are particularly prone to multiple secondary incidents.

This study sought to answer how soon does a secondary incident happen after a primary incident; how far is the secondary from the primary incident; and what factors are associated with near versus far secondary incidents. The appropriate methods and models have been developed to examine the spatio-temporal patterns of cascading incident events and identify associated factors. Time gaps were found to be positively associated with crashes, longer duration of primary incidents, and heavier traffic. In terms of distance, primary crashes, fires, lane-blockage and longer duration are associated with secondary incidents that occur at longer distances after its primary incident. The study found that distance and time vary systematically with characteristics of primary incidents.

Regarding the clearance time of primary-secondary incident events, the event duration is defined and such events were further categorized as either contained events (i.e. clearance time of the secondary is earlier than that of primary incident) or extend events (i.e. clearance time of the secondary extends that of primary incident). The associated major factors were estimated and identified through rigorous statistical models. These two types of events show substantially different incident characteristics and operational response patterns. Primary incident characteristics are dominant in contained events while secondary incident characteristics play a substantial role in extended events, requiring substantial resources from response agencies.

To quantify the total delay associated with primary-secondary incident events, the joint impacts of primary and secondary incidents have been taken into account. Shock wave analysis and microscopic simulations were used to understand and evaluate the associated critical parameters. Three critical contributing factors were evaluated: time gap, physical distance and traffic demand level. The analysis shows the traditional method which treats each incident independently will over- or under- estimate the actual delay of primary-secondary incident events. For those secondary incidents that end after their associated primary incidents, total delays increase as time gap increases and distance decreases.

The study took a major step forward in the research of secondary incidents and expanded the knowledge of secondary incidents. Analyses provide valuable information to evaluate route performance, reduce the likelihood of secondary incidents, improve response to the complex associated incidents, manage traffic queues and minimize the traffic delay. The findings have been translated to the practical tools to support operational decisions and more informed planning.

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I am grateful to my wife Linhong, my son Shuaipeng and my big families including my grandparents, my parents and parents in law, my brothers and sisters (in law) for their endless love and unconditional support.

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CHAPTER 1

INTRODUCTION

1.1 Problem Justification

Urban traffic congestion has been a serious concern in the US for many decades. The total cost associated with traffic congestion reached $115 billion in 2009 (Schrank et al., 2010). Traffic incidents are a common occurrence on urban freeways and result in adverse impacts on traffic operations and safety. They contribute 25 to 60 percent of the congestion in urban areas (Lindley, 1987; Skabardonis et al., 1995; Ozbay & Kachroo, 1999; Kwon et al. 2006). Incidents include crashes, disablement, abandoned vehicles or road debris etc. The majority of incidents on urban freeways occur on the shoulder and have relative minor impacts compared with large incidents (e.g., incidents like a crashed tractor trailer which spills cargo, a vehicle rollover in a tunnel, vehicle fires, and crashes involving several vehicles, major damage, deaths, and injuries). These large incidents are small portion of total incidents, but they have a huge effect on traffic operations. They typically block the partial or all lanes to close the transportation facilities for extended durations. McDade (1990) reported approximately one-third of the total incident delay that occurs in urban areas is due to lane-blocking incidents. Furthermore, these incidents are highly associated with the occurrence of secondary crashes or incidents. Research has showed that incidents can cause 2% to15% secondary crashes or incidents (Raub 1997; Karlaftis et al, 1999; More et al, 2004; Khattak et al, 2009). These secondary incidents further compound the complexity of existing operational problems and cause major disruptions, which often require specialized equipment, a high degree of cooperation and coordination among the various response agencies, and substantially exacerbate travel delay. Among secondary incidents, some tend to be more severe than their primary incidents. These include injuries or fatalities when individuals, such as vehicle occupants, safety patrol team or police, are struck by passing traffic as they exited their vehicles to affect repairs or offer assistance. In summary, secondary incidents present serious operational and safety concerns and threats to regional economic viability.

Since secondary incidents, along with their corresponding primary incidents, are key contributors to travel time uncertainty and traffic congestion in urban areas, the Federal Highway Administration has clearly put secondary incidents as a top priority in addressing non-recurrent congestion. Regionally, the Virginia Department of Transportation (VDOT) indicated that traffic incidents are a major source of congestion in the state. To address this issue, it is assumed that the impact and risk of such incidents are minimized significantly by quick responses and effective incident management tactics and strategies. Therefore, recent VDOT-sponsored research suggests that VDOT should consider initiating a study on the role Safety Service Patrols (SSPs) in reducing primary and secondary incidents and mitigating delays in such situations (Dougald & Demetsky, 2006).

Many studies have analyzed incident characteristics and try to minimize the incident impacts. However, only a few studies have targeted the secondary incidents and no further study focus on multiple secondary incidents perhaps because they constitute a small percentage in the total incidents. Generally, a primary and its secondary incidents are expected to have longer durations than single incidents and therefore to result in larger impacts on traffic, but such cascading incident impacts have been ignored. The critical research issues are as follows.

First, knowledge about the characteristics of secondary incidents especially multiple secondary incidents are limited. Relative little is known about their characteristics including frequency, duration, temporal and spatial distributions and major associations of such event occurrence.

Second, given the correlations between primary and secondary incidents, several important aspects such as temporal-spatial patterns, cascading event duration of primary-secondary incidents, joint traffic impacts and the corresponding operational responses have not been fully investigated yet.

Finally, the implications of secondary incidents for planning purpose and traffic operation have not been deeply explored. An important issue but lightly researched issue is how to predict (and prevent) secondary incidents associated with moderate and large incidents (i.e. primary-secondary pairs and primary-multiple secondary incidents).

It is essential to develop a systematic research approach to identify and classify secondary incident, explore the primary-secondary incident events, and address their implications related to traffic operations, safety and planning. This research takes a major step towards understanding the occurrences of multiple secondary incidents, examining the associations between primary and secondary incidents, investigating event duration, assessing the joint impacts of multiple secondary incidents, presenting the potential benefits to an effective incident management.

1.2 Research Objectives

The primary objective of this study is to understand the nature of primary-secondary incident events and explore their implications for traffic operations, safety and planning.

Different categories for these events are established based on their scale and traffic/safety impacts. This requires the development of a comprehensive identification and classification method for primary-secondary incident events. After analyzing such events, a set of research questions are answered:

- What are the characteristics of the primary-secondary incident events?
- What are major factors associated with the occurrence of such events?
- What do the spatio-temporal associations between primary and secondary incidents look like? What are the major factors of these associations?
- How to define the primary-secondary incident event duration in term of clearance times? What are key factors associated with such event durations?
- How to estimate/predict the joint impacts of primary and secondary incidents and what are the critical attributes associated with them?
- What are the implications for traffic operations, safety and planning?

1.3 Thesis Contributions

The scholarly contributions from this study will facilitate further research on secondary incidents as follows:

- This study developed a systematic research approach to explore multiple secondary incidents, which is complicated but important research issue. To overcome the some limitations in existing identification methods, a queue-based method has been developed to identify the secondary incidents in both directions on urban freeways.

- This study defined a concept of the primary-secondary incident event as a collection of multiple associated incidents. Instead of analyzing primary and secondary incidents separately, as in past research, a primary-secondary incident event links primary and its secondary incidents as a whole to account for their spatio-temporal associations, clearance time and jointed impacts.
- This study conducts several deep and innovative analyses on primary-secondary incident events in term of characteristics, distributions, occurrence, spatio-temporal associations, event duration and jointed traffic delays. These analyses provide new insights into the extent of secondary incident problem.

The potential benefit from this study will help practices in traffic operations, route safety evaluation, and planning purpose as follows:

- Help incident managers to determine when and where to allocate resources to critical segments proactively in order to dispatch and coordinate response agencies efficiently to carry out a quick and safe clearance procedure.
- Help traffic operators to disseminate incident information to alert drivers approaching the incident sites through advance ITS systems and direct upstream traffic diverting to the alternative roads to minimize the non-recurrent traffic impacts.
- Assist planner in identifying secondary incident hot-spots and incident-induced traffic choke points. Using the cascading event as an additional performance measures which can incorporate into the current transportation planning and regional cost evaluation process.
- Transfer and apply this research methodology to another metropolis with heavy

traffic congestion and high secondary incidents problems, thus making this research beneficial on a national or international scope.

1.4 Chapter Structure

The research starts with a comprehensive literature review and identification of major gaps in the literature. In this context, Chapter 2 presents a synthesis of literature related to secondary incident identification, occurrence, duration analysis and non-recurrent traffic delay estimation. A conceptual framework of research method is described in Chapter 3. This chapter also details the study domain, data source, data processing and proposes several key analyses to answer the research questions. Chapters 4-8 present the corresponding methods or models, result analysis, conclusion and/or implications for each key analysis. Finally, Chapter 9 reviews research findings and makes recommendations for future research on secondary incidents.

CHAPTER 2

REVIEW OF LITERATURE

Relevant literature was reviewed to assess the issues related to definition of secondary incidents, the factors influencing secondary incident occurrence, incident duration modeling, and traffic delay estimation.

2.1 Defining a Secondary Incident

Theoretically, if an incident causes (in part) another incident in the proximity of upstream traffic, the prior incident is termed as the primary incident and the following incident as secondary incident. However, it is often difficult to retrieve the primary-secondary incidents relationship from the archived incident data. Due to the scarcity of quality incident data, many of previous research studies are based on the crash data only. Some early studies defined the secondary crash to be any of crash within a certain range in the vicinity (i.e. spatial threshold) and temporal period after a reported crash (i.e. temporal threshold). Raub (1997) and Karlaftis (1999) found that more than 15% of all crashes were secondary by using clearance time plus 15-minute period and one mile distance as identification criteria. Chang et al. (2003) adopted temporal and spatial threshold criteria as: two hours from the onset of a prior incident and two miles downstream of this prior incident location for the same direction. They also attempted to identify secondary incidents that occur in the opposite direction within one-half hour from the onset of a prior incident and a half-mile range around that prior incident at either downstream or upstream direction. They found that 6.8% of all incidents with lane blockage are secondary incidents. However, Moore et al. (2004) obtained the secondary proportion of about 1.5% to 3% on Los Angeles freeways while using two hour and two miles as threshold criteria and excluding duplicities and chain reactions crashes. Although inconsistencies in identified secondary crash rates are possible as reflecting variations in road, traffic and safety situations in the different areas, it is also likely that lack of data on crash duration, or inaccurate spatial and temporal thresholds contribute to inconsistencies among studies.

To overcome the static thresholds criteria used by most existing identification methods, Sun (2010) proposed a dynamic progression threshold method and discovered that the static and dynamic methods can differ by 30% in terms of identifying secondary incidents. Zhan et al. (2009) developed a method to identify secondary incidents based on an estimated maximum queue length. 4.9% were identified as primary incidents, which is much less than 7.9% from their earlier study (2008). Chou and Miller-Hooks (2010) applied a simulation-based secondary incident filtering (SBSIF) method in 6-month achieved incident data and found that there is a significant reduced misclassification rate (e.g. reduction of 58% or greater) as compared with a static thresholds method.

2.2 Factors Associated with the Occurrence of Secondary Incidents

Various factors will impact the likelihood of the secondary incidents. Peak periods and weekdays are associated with more secondary incidents, and the clearance times are also associated with secondary incidents occurrence (Raub, 1997). In the study of Karlaftis et al. (1999), clearance time, season, vehicle type (car, semi) and lateral location are most significant factors for higher secondary incident likelihood. Odds of a secondary crash increase by 2.8% for each minute the primary incident is not cleared. Chang (2003) stated that the likelihood of having secondary incidents increases consistently with the primary incident duration and congestion level based on statistical data. Hirunyanitiwattana (2006) found that secondary crashes occur more often during rush hour and a rear end collision is the predominant secondary collision type, which accounts for about two thirds of all secondary crashes. He also found that the typical secondary crash on a greater than four lane urban highway in California occurs during peak periods, and is a rear end, property damage only, crash and is caused by excessive speed. Zhan et al. (2008) identified five major factors influencing secondary incidents, which include the number of involved vehicles, the number of lanes, the duration of primary incident, the time of day, and the primary vehicle rolling over. In a later paper, Zhan et al. (2009) identified four factors associated with the likelihood of secondary crashes: primary incident type, primary incident lane blockage duration, time of day, and whether the incident occurred on northbound I-95. Khattak et al. (2009) demonstrated that primary incident duration and secondary incident occurrence are statistically interdependent.

2.3 Incident Durations: Associations with Spatial, Temporal, and Operational Factors

Studies of incident durations are plentiful (Golob et al., 1987; Giuliano, 1989; Jones et al., 1991; Nam & Mannering, 1998). Incident durations have been estimated using a variety of techniques, broadly classified as:

- Standard regressions including log-normal distributions (Golob et al., 1987; Garib et al., 1997; Sullivan, 1997), analysis of variance (Giuliano, 1989), regression models (Khattak et al., 1995; Qi & Teng, 2008), discrete choice models (Lin et al. 2004) and Hazard-based models (Jones et al. 1991; Nam & Mannering 1998),
- Decision trees (Ozbay & Kachroo, 1999), classification trees (Smith & Smith, 2001; Kim et al., 2008)
- Bayes classifier (Ozbay & Noyan, 2006; Boyles et al. 2007).

Each approach has its own advantages and shortcomings. Standard regression offers more intuitive and easier interpretation. Hazard-based models show advantages in terms of recognizing that the likelihood of ending an incident depends on the elapsed time from the start of incident (Mannering, 1998). Decision Tree or Classification Trees can be effectively used to discover patterns with or without considering probabilistic distributions. However, the tree-based models require relatively large amounts of data are required. Appropriate use of these methods depends on specific research needs.

In general, the incident duration is associated with incident characteristics, temporal characteristics, environmental effects, geographic information, and operational factors. The identified variables associated with incident durations are: incident type, the number of lanes blocked, the number of heavy vehicles involved in an incident (Ozbay & Kachroo, 1999; Kim et al., 2007), injury or fatality, peak hour (Nam & Mannering 1998; Ozbay & Kachroo, 1999; Kim et al., 2007), longer response time (Khattak et al. 1995), the location of traffic operations center, and the number of vehicles responding from each agency (Kim et al., 2007). Several of these variables are simply associative and not necessarily causal, e.g., presence of more response vehicles does not mean that they are causing the incident to last longer, but simply that they are responding to a major incident.

2.4 Traffic Delays Estimation for Incidents

Traffic delay is the consequence of traffic congestion and has been widely used as a quantifiable assessment of travel experience. Generally accepted methods for delay calculations are: deterministic queuing (Moskowiz & Newman, 1963) and shock-wave analysis (Lighthill & Whitham, 1955; Richards, 1956). The deterministic queuing method requires a cumulative arrival curve, representing normal traffic demand in a freeway segment and a departure curve, representing the traffic volume passing through the location. If demand is less than capacity, then the departure curve exactly follows the arrival curve. If demand exceeds capacity, the two curves will split. The area between the two curves is the total vehicle hours of delay. The shock-wave analysis utilizes the fluid dynamic theory to define flow, density and speed for the description of traffic flow behavior and develop a formula for calculating total delay. Many studies calculated delays using either of these two methods. Morales (1987) first developed a deterministic queuing method to calculate the incident delay on a freeway. Wirashinghe (1978) used shock-wave analysis to determine individual and total delay upstream of incidents. Menendez and Daganzo (2004) applied shock wave analysis to assess the impact of incidents near bottlenecks. To check the interrelationship and consistency of these two models, Chow (1974), Rakha and Zhang (2005) conducted their investigations and both studies found the results from these methods to be identical if a static flow-density relationship is applied in the shock-wave analysis. However, both methods are limited by static demands, which is unrealistic under peak hour or flow fluctuation situations. Khattak et al. (2004) used FREEVAL model, which faithfully replicates the freeway facility methodology in Chapter 22 of the 2000 Highway Capacity Manual (HCM 2000) to estimate incident induced delay for prioritizing and expanding freeway safety patrols service. There are two important improvements of FREEVAL mode. First, it allows analyzing an entire freeway facility consisting of basic, ramp and weaving segments with time-varying demands and capacities at multiple intervals. Second, this model can handle both undersaturated and oversaturated traffic conditions (Eads et al. 2000). Since the above-mentioned methods do not consider route diversion situation in real life, Al-Deek et al. (1995) proposed a loop-detector based method to estimate single incident or multiple incident induced delays on freeways by capturing traffic demand variation due to diversion of traffic. With the development of more sophisticated car-following, lane change etc. models, microscopic simulation is a tool that can be easily used to estimate the incident induced delay.

2.5 Summary

Incidents are a major source of congestion, imposing substantial social and personal costs on road users and they negatively impact traffic operations. Substantial efforts have been made by researchers and management agencies to understand incident duration, secondary incidents and the possible impacts they produced. Several strategies have been applied to mitigate the impacts of both primary and secondary incidents. Researchers generally agree that secondary incidents are the ones occurring in the temporal and spatial vicinity of primary incidents. The main factors associated with secondary incident occurrence can be summarized into four types:

- Primary incident attributes, e.g., incident type, and number of vehicles involved,
- Traffic condition, e.g., speed distribution, and traffic density,
- Roadway condition (e.g., obstructions, inadequate lighting, curvature, and certain routes)
- Environmental factors, e.g., time of day, and bad weather.

The properties of primary incidents are believed to be the main factors that are associated with secondary incident occurrence. However, certain gaps are apparent:

- There is still no standard definition of secondary incidents. Under- or over-estimated may occurred if the fixed thresholds are applied. Therefore, a dynamic threshold method seems promising but need further development and validation.
- Many studies only deal with crashes rather than the entire spectrum of incidents. The limited data typically is lack of accurate duration, may isolate influence from a non-crash prior incident in the downstream of crash and ignore some secondary non-crash incidents caused by a prior crash/incident. Thus they possibly under-estimated the number of secondary crashes/incidents as well as the impact of a primary crash/incident.
- Most past studies separate the primary and secondary incidents in the analysis and disregards the correlations between primary and secondary incidents. Few of them focus on understanding the complex interrelationship between incident durations and the occurrence of secondary incidents. The spatio-temporal patterns of primary and secondary incidents have been not investigated yet. For instance,

how soon and how far does a secondary incident happen after a primary incident? What factors are associated with near versus far secondary incidents?

- To assess impacts of primary and secondary incidents, compared with two single incidents, the interaction of primary and secondary incidents may have larger impacts on traffic operations and incident management. In term of traffic delay, the existing delay estimation models are suitable for analysis of single independent incidents. The delay caused by multiple associated incidents, i.e. primary-secondary incident pairs, has not been analyzed fully and need further research efforts.

CHAPTER 3

METHODOLOGY

3.1 Overview of Research Method

Secondary incidents occur within the influence area of a primary incident. A primary incident can have one or more secondary incidents. The conceptual structure of research is shown in Figure 1. The key objective is to understand the primary-secondary incident events and explore their implications for traffic operations, safety and planning.

The relevant data including incidents, road network, and loop detector data are obtained from local traffic management center or state transportation agencies. The next step uses the definition of the secondary incidents to develop a comprehensive secondary incidents identification method and follows by classifying identified secondary incidents into the different primary-secondary incident event categories for further analysis.

Finally, several key analyses are proposed to explore the various aspects of primary-secondary incident events. The implications of primary-secondary incident events for traffic operations and transportation planning will be deeply explored. The study provides new insights into the nature and impacts of the primary-secondary incident events. The detailed steps are discussed in the following sections.

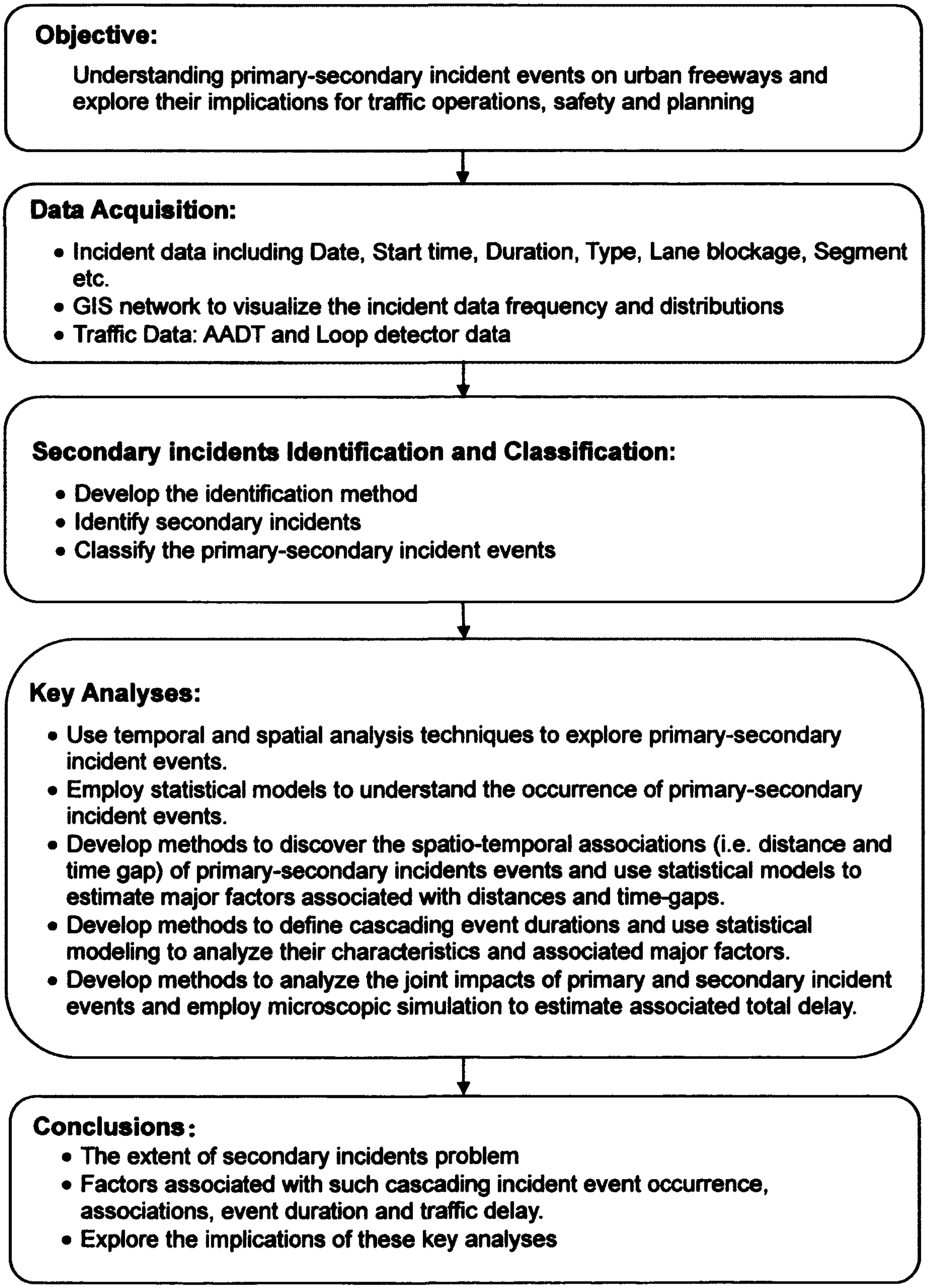


Figure 1 Outline of Proposed Research Methods

3.2 Study Domain Selection and Data Acquisition

The scope of this study is limited to freeway incidents. Research prototype has been developed and applied in incidents on major freeways in Hampton Roads, Virginia. Hampton Roads is located in Southeastern Virginia and includes several municipalities, including cities of Virginia Beach, Norfolk, Suffolk, Portsmouth, Chesapeake, Hampton and Newport News (Figure 2). It has a population of approximately 1.6 million. The Hampton Roads Beltway links seven of the largest cities in Hampton Roads and experiences flows of 100,000 to 150,000 vehicles per day. The Hampton Roads Bridge-Tunnel (HRBT), the Monitor-Merrimac Memorial Bridge-Tunnel (MMBT), and the I-264 Downtown Tunnel, High-Rise Bridge serve as major crossings, and are also traffic choke points with substantial recurrent traffic congestion. According to the VDOT published report (2008), nearly 80,000 incidents occurred in the Hampton Roads area during 2008. Thus, the area experiences major recurrent congestion during peak hours and incident-induced traffic disruptions. They raise growing concerns for local economic development and transportation safety.

Incident data for this study are obtained from the Hampton Roads Transportation Operations Center (HRTOC), which are primarily based on Safety Service Patrol (SSP) operational records. SSP provides incident management and offer assistance to motorists experiencing problems on freeways. At the time of the study, they covered more than 113 miles, from Newport News to Virginia Beach, 24 hours a day, and 7 days a week. Incident records include incident ID, date, start time, incident duration, lane-effected, route name, direction, segment ID, etc. 2005 incident data was provided by HRTOC at the beginning of this study. Later, 2008 data became available. In 2008, the Virginia

Department of Transportation (VDOT) completed Phase 3 of the Hampton Roads Traffic Management System (HRTMS). With newly installed cameras, roadway detectors and variable message signs, HRTOC has extended their operation and response coverage for the total 113 miles of Interstate highways. Some improvements were made to the incident database collection program including the introduction of a local detailed segment location system. During this time, the coverage of service patrols was also extensive. Thus, the 2008 incident dataset is the most comprehensive data on incidents in the region. Incident data was archived based on fractional mile post-markers, thus providing relatively accurate location information (compared with databases used in various studies to-date).

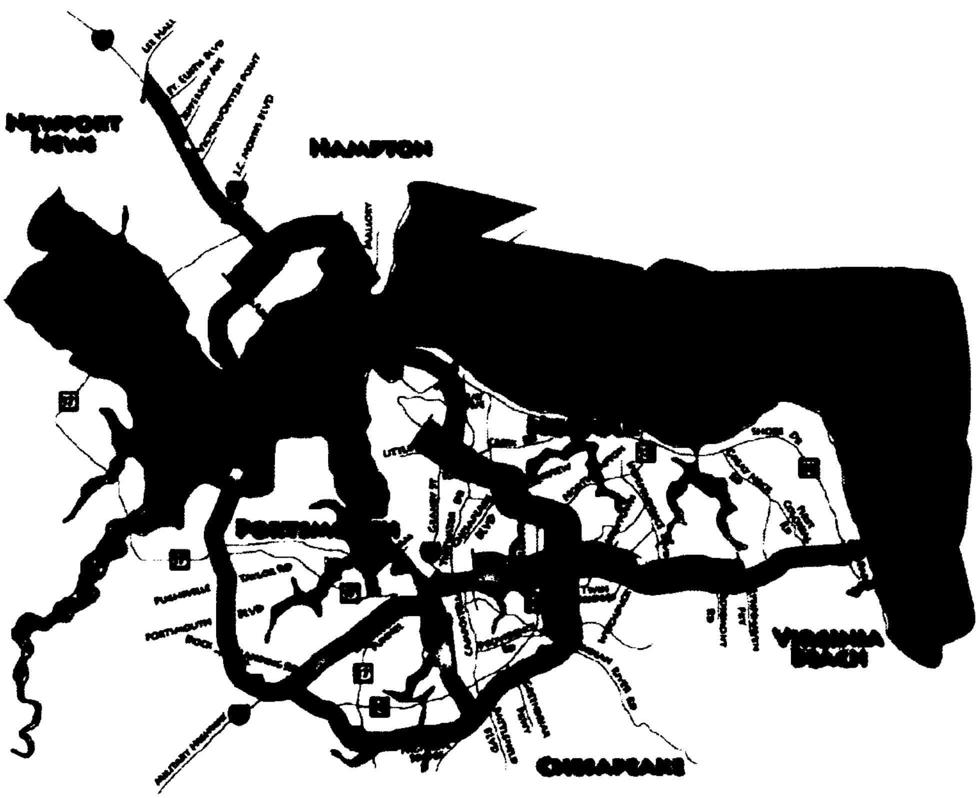


Figure 2 Freeway Safety Service Patrol Coverage in Hampton Roads

Road inventory data and historical traffic count data are relevant for the analysis. Road inventory data and loop detector data are obtained from the Hampton Roads Planning District Commission. Traffic counts are collected continuously by embedded sensors (loop detectors). The annual average daily traffic (AADT) data is obtained from VDOT.

3.3 Traffic Data Analysis

An accurate traffic demand was needed to estimate the queue length of a primary incident for secondary incidents identification. Detector data was used to create link-based (prevailing) traffic profiles including weekdays and weekends. Traffic data in the form of AADT was acquired to determine traffic demand. To obtain prevailing traffic flow distributions for primary urban freeways in the Hampton Roads area, a comprehensive analysis was conducted on 2006 traffic counter data in the Hampton Roads area. The first step was to define the spatial and temporal coverage of traffic data matching with the SSP operational coverage shown in Figure 2. The second step was to pinpoint traffic counters into Hampton Roads GIS network. The appropriate counters were selected based on their physical locations, data availability and queues likely presence. In addition, every selected counter was matched with another one located proximately in its opposite direction as a pair to check the directional traffic pattern. Next, three continuous weekdays from Tuesday to Thursday and weekend (Saturday and Sunday) were selected from three months (July, August, and September). The selected counter data was used to display the information, examine consistency and repeatability, and estimate average daily traffic profiles and average daily traffic flow distribution.

Based on this analysis (Figure 3), the area shows substantial directional differences in traffic counts across some freeways. Finally, daily average traffic profiles in representative links were derived from the selected loop detector data to capture non-homogeneous traffic and directional effects on some freeway sections.

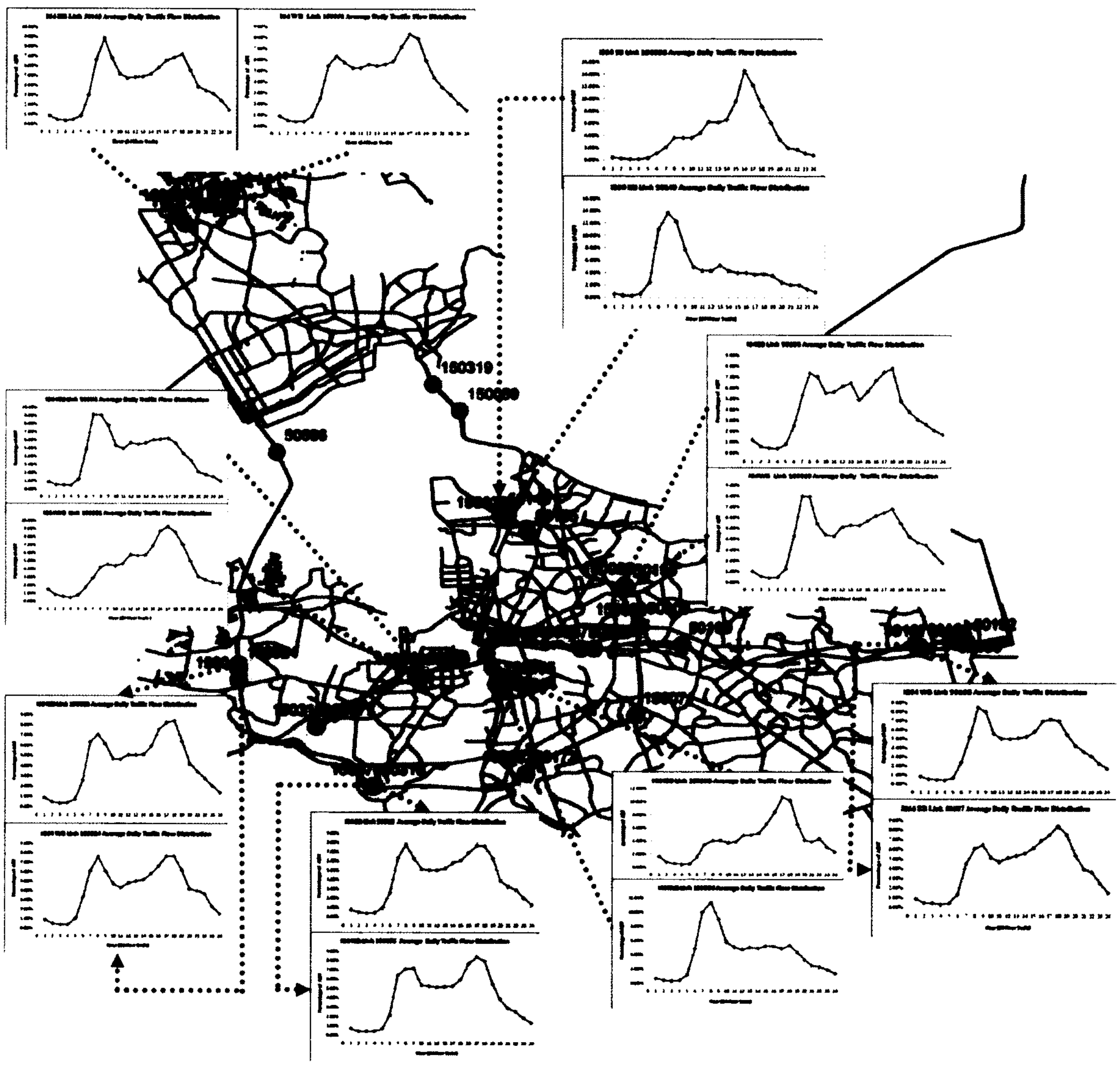


Figure 3 Average Daily Traffic Flow Distributions in Hampton Roads

3.4 Geo-Connection Creation

Every incident was archived according to a roadway section before 2008. It was pinpointed to a fractional mile marker (measured in feet) after 2008, which provides more accurate location information. There are multiple reference mile-markers in each roadway section. Unfortunately, this local geo-coding system is not completely consistent with the Virginia statewide geo-coding system that is used to publish the link-based AADT and loop detector data. Thus extensive work is required to 1) create connections between the two geo-location systems, 2) collect detailed road geometry information, and 3) sort every road segment spatially from downstream to upstream for each route direction using location reference descriptions and Google maps.

3.5 Secondary Incident Definition and Identification

To identify secondary incidents on urban freeways in Hampton Roads, VA, a segment-based identification method was initially developed in our previous study (Khattak et al., 2009). Note that this identification method is only appropriate for incidents on urban freeways and does not take into account the incidents on non-limited access roadways. It is similar to the methods used in the reviewed literature—the only difference is that instead of using a fixed length to identify secondary incidents, the segment-based method uses the segment length as a spatial boundary. Therefore, the identification of secondary incidents is confined to each segment. Although this method is relatively easy to implement and use, it is more likely to under- or over-identify secondary incidents in some circumstances. Three possible limitations for the segment-based method and the previous research methods with a fixed spatial boundary are discussed next (Zhang & Khattak, 2010a).

- Missed counting in the same direction. Figure 4 shows a freeway segment where crashes occur on two different segments. The crash C_2 in Segment 2 is associated with the crash C_1 in Segment 1. They are a pair of primary (C_1) and secondary (C_2) crashes. Because C_2 is beyond the spatial boundary of the prior incident C_1, this primary and secondary pair cannot be captured in the segment-based method or any fixed spatial boundary methods.

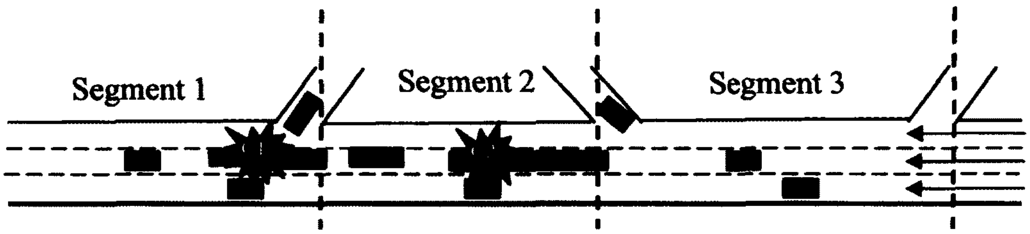


Figure 4 Missed Counting Scenario in the Same Direction

- Over-counting in the same direction. Figure 5 shows that crashes C_4 in Segment 2, C_5 and C_6 in Segment 3, are associated with crash C_3 in Segment 2. In reality, the primary crash is C_3 and its multiple secondary incidents are C_4, C_5, and C_6 but the segment-based identification can show two possible outcomes. Outcome 1: two primary and secondary pairs [(C_3, C_4) and (C_5, C_6)] are identified if C_6 occurs within the duration of C_5. Such over counting can over-estimate the frequency of primary-secondary pairs. Outcome 2: Only one primary-secondary pair (C_3, C_4) with two missing secondary incidents (C_5, C_6) is identified, if C_6 occurs beyond the duration of C_5. Both outcomes will underestimate the magnitude of this primary-secondary incident event.

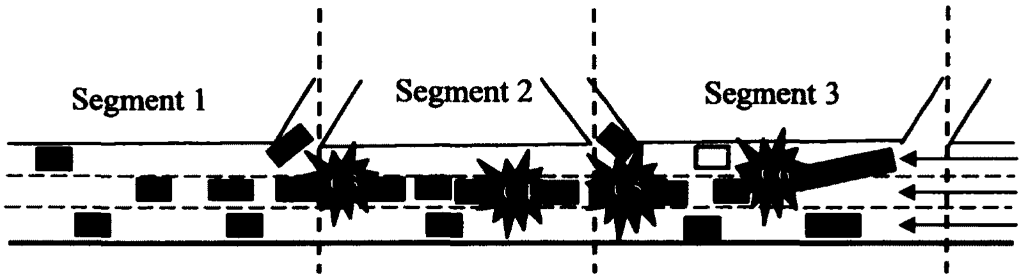


Figure 5 Over Counting Scenario in the Same Direction

- Missed counting in the opposite direction. Figure 6 shows that the crash C'$_3$ in Segment 3 is associated with the crash C_3 in the opposite direction and they are a pair of primary (C_3) and secondary (C'_3) crashes, possibly due to rubbernecking. Although several previous studies did not consider opposite direction incidents, this study identifies opposite direction secondary incidents.

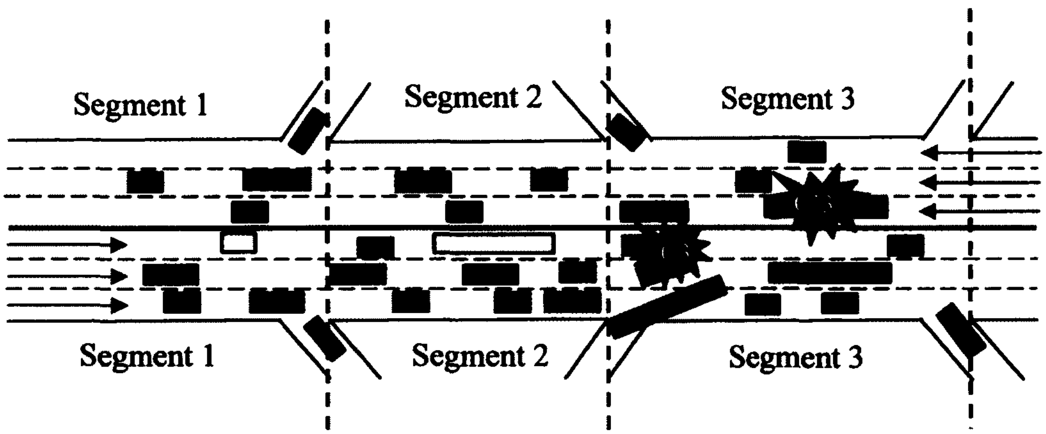


Figure 6 Missed Counting Scenario in the Opposite Direction

The limitations of missed counting and over counting of secondary incidents in the same direction can be overcome if the actual queue length of primary incidents can be determined. Unfortunately, the observed queue length data is unavailable in most cases. To capture cross-segment large primary-secondary incident events and overcome the limitation of the segment-based method, a dynamic queue-based method was developed. The method identifies secondary incidents in the same direction. If a spillback condition is induced by an incident at downstream, its queue length is calculated based on mainline traffic through a deterministic queuing model (D/D/1) (Al-Deek et al., 1998). The identification process is demonstrated in Figure 7.

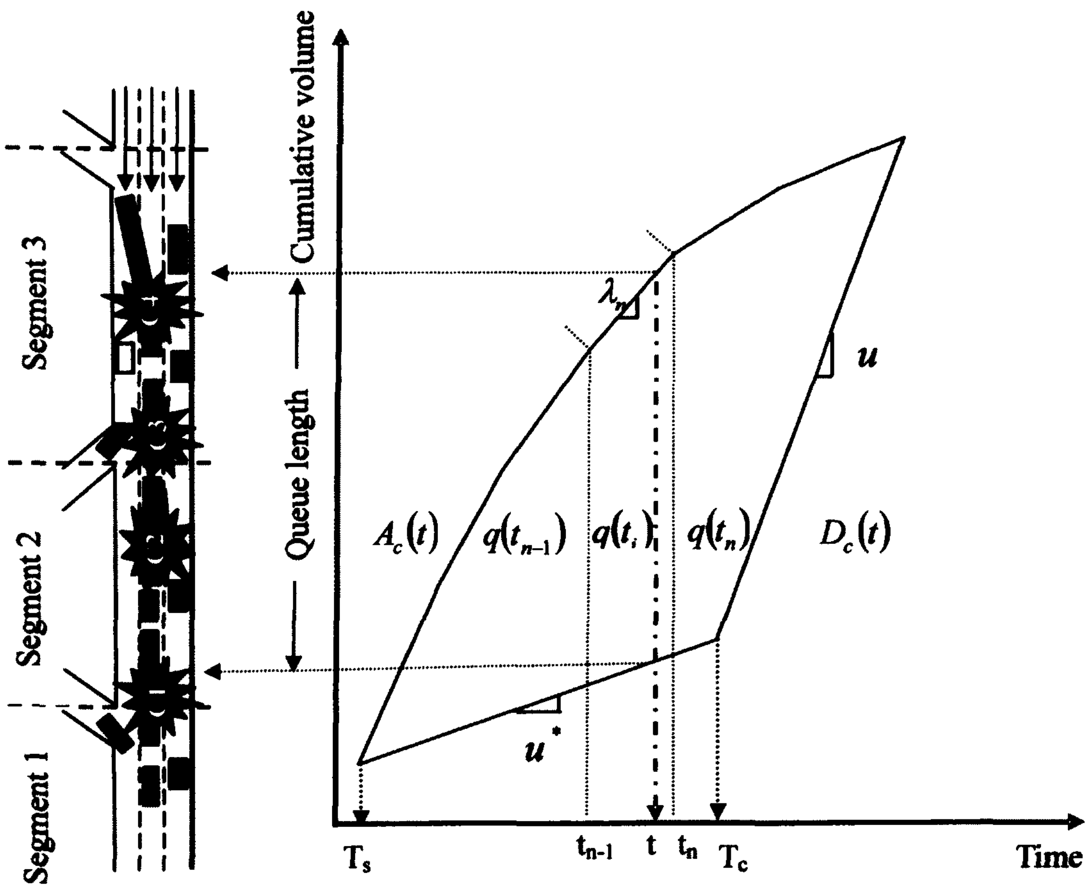


Figure 7 Illustration of Queue-based Secondary Incident Identification

As shown in Figure 7, the horizontal axis is time and the vertical axis denotes the accumulative vehicles. Traffic arrives at the incident location according to curve $A_c(t)$ that consists of a number of small time-dependent arrival rates (the time interval typically is 15 minutes, representing the minimum period when a traffic arrival rate remains steady). The representative traffic profiles in road links are obtained from the traffic analysis in the previous section. The departure curve $D_c(t)$ shows the departure from the incident bottleneck. The departure flow rate is initially μ^*, the reduced capacity of the bottleneck, which is equal to normal capacity times the percentage of remaining capacities (referred to Exhibit 22-6 of the 2000 Highway Capacity Manual) and then after the incident is cleared at time T_c, is the restored capacity, u. t_{n-1}, t_n represent the n-1th and nth time intervals from the incident start and $q(t_{n-1})$, $q(t_n)$ are corresponding queue lengths at t_{n-1}, t_n . λ_n is a constant arrival rate between t_{n-1} and t_n . The queue length calculation at a given time t can be expressed as:

$$q(t) = q(t_{n-1}) + (t - t_{n-1})(\lambda_n - \mu^*) \quad \text{for} \quad t_{n-1,} t < T_c \tag{1}$$

$$q(t) = q(t_{n-1}) + (t - t_{n-1})(\lambda_n - \mu) \quad \text{for} \quad t_{n-1,} t > T_c \tag{2}$$

Note that when $t_{n-1} < T_c < t_n$, equation (1) still applied if $t < T_c$. Otherwise, when $t > T_c$, $q(T_c)$ should be determined using equation (1) first, then T_c can replace t_{n-1} in equation (2) to calculate $q(t)$.

If the queue length exceeds the length of the segment where the primary incident occurred, then the spatial boundary used to identify secondary incidents is extended to the adjacent upstream segment; if the queue still overflows this adjacent segment, then the spatial boundary is extended further to the upstream segment. This recursive process stops when the entire queue is accommodated. As shown in Figure 7, the estimated queue length of the incident C_1 in Segment 2 extends to Segment 3. Incidents C_3 and C_4 are covered by the spatial boundary (that includes Segments 2 and 3). If C_3 and C_4 are within the duration of the downstream primary incident C_1, they will be identified as secondary incidents associated with C_1.

Note that queue lengths based on theoretical models are over-estimated sometimes, especially when they do not account for route diversions (Ullman & Dudek, 2003). Clearly, using observed queue back up to determine the farthest upstream segment where queue extended is desirable to complement derived queue lengths from traffic models. Unfortunately, observed queue lengths were not available for the data set analyzed in this study. However, given that the visual distractions of drivers extend beyond queues, the impacts of over-estimation may be mitigated.

In addition, this secondary incident identification also considers secondary incidents in the opposite direction. To identify these secondary incidents, the length of the opposite segment is set as the spatial boundary. If an incident in the opposite segment occurs within the duration of the primary incident, then it is considered a secondary incident in the opposite direction. To further emphasize the rubbernecking impact and visual distraction caused by a primary incident in the opposite direction, the following two requirements must be met:

1) There is no visual barrier in the median (similar to the study by Masinick and Teng, 2004).
2) One of the following conditions exists:
    - Primary incident in the opposite direction is a crash.
    - Primary incident in the opposite direction is a non-crash; its location is in the left shoulder.

- Primary incident in the opposite direction is a non-crash; it causes a queue back up or blocks a lane.

3.6 Primary-Secondary Incident Events Definition and Classification

Given the correlations between primary and secondary incidents, the primary-secondary incident events are defined in Table 1. Any event can be classified into one of the cells in this table. They go from no secondary in the same or opposite directions to 2 or more in the same direction and opposite direction. Every event category will likely have some impact on urban traffic, with higher level categories having greater impacts on average. All the categories have been used in the categorization of primary-secondary incident events.

Table 1 Categories for Events Showing Various Levels of Secondary Incidents

Secondary Incidents Abbreviation	0 Secondary incident in the opposite direction (O_0)	1 Secondary incidents in the opposite direction (O_1)	2+ Secondary Incidents in the opposite direction (O_{2+})
0 Secondary in the same direction (Σ_0)	Σ_0, O_0	Σ_0, O_1	Σ_0, O_{2+}
1 Secondary in the same direction (Σ_1)	Σ_1, O_0	Σ_1, O_1	Σ_1, O_{2+}
2+ Secondary in the same direction (Σ_{2+})	Σ_{2+}, O_0	Σ_{2+}, O_1	Σ_{2+}, O_{2+}

Note: All cells represent a secondary event. "Σ" represents secondary incidents in the same direction; "O" represents secondary incidents in the opposite direction.

The structure presented in Table 1 lends itself to having more categories on the ordinal scale. Considering the scarcity of multiple secondary events, this research simplified and aggregated the identified events presented in Table 2. Specifically, Table 2 shows the categorization as follows: 1) an independent incident, i.e., an incident not associated with secondary events, 2) one pair event, i.e. one primary incident and one associated secondary incident in the same or opposite directions, and 3) one primary incident with two or more secondary incidents in the same and/or opposite directions. This scale captures event adversity from a traffic management perspective, with the last category capturing multiple secondary events.

Table 2 Ordered Secondary Events Classification

Categories (J)	Event Types	Expected Event Adversity
1	Σ_0, O_0	Independent incident
2	Σ_1, O_0; Σ_0, O_1	Primary-secondary incident pair
3	Σ_0, O_{2+}; Σ_1, O_1; Σ_1, O_{2+}; Σ_{2+}, O_0; Σ_{2+}, O_1; Σ_{2+}, O_{2+}	Primary-multiple secondary incidents event

3.7 Key Analyses

To answer the research questions, several key analyses in Table 3 are proposed to explore the primary-secondary incident events as follows:

- To identify where and when multiple secondary incidents are more likely to occur on urban freeways, a detailed segment-based spatial analysis is conducted in GIS road network in both directions for primary-secondary incident events. Following the spatial analysis, a temporal analysis is designed and performed to examine monthly, weekly and daily variations of such events. The findings provide practitioners with valuable information on targeting service patrols in areas where are more prone to multiple secondary incidents.
- To understand the occurrence of primary-secondary incident events and quantify key factors that include incident characteristics, roadway geometry and traffic flow.

Two proportion odds models are estimated based on three-point ordinal scale, which was defined in Table 2.

- To answer what the spatio-temporal patterns between primary and secondary incidents look like, and to consider what are the major factors of these associations? The associations between the primary and secondary incidents can be characterized by time gap and distance. Time gap represents the amount of time between a primary incident and its first and second secondary incidents. Distance is defined as the separation between a primary incident and its secondary incident occurring locations. A deeper analysis of distance and time gap is conducted on the basis of a unique 2008 incident and roadway inventory database for Hampton Roads, Virginia.
- To define the cascading event and analyze event duration, a unique event database based on incident and road inventory data from Hampton Roads, Virginia, is created. Single-pair events (one primary and one secondary incident) and large-scale events (one primary and multiple secondary incidents) are analyzed. "Event duration" is defined as the time elapsed from the notification of a primary incident to the departure of the last responder from the event scene after removal of the primary and associated secondary incidents. The primary-secondary incident events can be further categorized based on the clearance time and deeply analyzed using through a set of rigorous models to answer what are associated factors with such events.
- To examine traffic delays induced by primary-secondary incident events, the incident data combined with roadway inventory data from Hampton Roads were

analyzed to retrieve the attributes of primary-secondary incident pairs. Based on these empirical temporal and spatial associations between primary and secondary incidents, the critical parameters for delay estimation: time-gap, physical distance, relative lane blockage, and traffic demand level are evaluated through a microscopic simulation.

Table 3 Key Analyses Summary

Key Analysis	Incident Data Used	Tools/Models
Spatial and temporal analysis for Primary-secondary incident events	2005	GIS
Factors associated with the likelihood of primary-secondary incident events	2005	Ordered logit models
Spatio-temporal patterns of primary and secondary incidents	2008	GIS, Ordinary linear regression
Cascading incident event durations	2005	OLS, truncated regression
Queuing delays associated with secondary incidents	2005	Kinematic wave Microscopic simulation

A complete picture of primary-secondary incident events can be obtained after analyzing these important attributes and aspects of primary-secondary incident events, which including primary-secondary incident events characteristics, spatial and temporal distributions on urban freeways, major factors associated with such events, further categorization of the primary-secondary events based on incident clearance time. More importantly, traffic delays for such events can be evaluated through a microscopic simulation. Research findings and implications from this study provide new insights into secondary incidents in incident management, traffic safety and regional planning.

CHAPTER 4

SPATIAL AND TEMPORAL ANALYSES OF PRIMARY-SECONDARY INCIDENT EVENTS

To examine spatial and temporal distributions of primary-secondary incident events over road segments and identify where and when such events are more likely to occur, two major interests of classified incident events, the frequencies of different events and durations of primary incidents, are analyzed spatially and temporally (Khattak et al., 2010). The segment-based frequencies of primary-secondary incident events along the major freeways are geo-coded into GIS network. Frequency spatial distributions over road segments can be used to observe the considerable pattern differences in both directions, and to identify primary-secondary event hotspots (i.e. locations that have higher frequency of primary-secondary incident events). Frequencies of primary-secondary events grouped by month, weekday and hour were also performed to examine temporal variation over different time scales. Another important effort is to analyze the duration of primary incidents, which is a key surrogate indication of events clearance and analyzed in past studies. The average duration daily distributions for weekend and weekday are plotted to examine temporal distribution patterns. Overall, the results of spatial and temporal analyses are valuable for incident management to appropriately target service patrols teams, especially from the perspective of managing primary-secondary incident events.

4.1 Spatial Analysis of Primary-Secondary Incident Events Summary

Based on 2005 incident data in Hampton Roads, incident distributions on major freeways are summarized in Table 4. Information about the length of major freeway, the number of incidents and the corresponding frequency and percentage of incidents in each route direction is provided. It is evident that I-64 EB and WB, I-264 EB and WB show relative higher frequencies of incidents, owing to their length and heavy traffic.

Table 4 Summary of 2005 Incidents on Major Freeways in Hampton Roads

Routes	Length (miles)	Total Incidents	
		Frequency	Percentage
I-64 EB	53	10,813	28.92%
I-64 WB	53	10,240	27.39%
I-264 EB	25	6,838	18.29%
I-264 WB	25	6,095	16.30%
I-464 NB	5.8	460	1.23%
I-464 SB	5.8	539	1.44%
I-564 EB	2.9	309	0.83%
I-564 WB	2.9	435	1.16%
I-664 NB	20	832	2.23%
I-664 SB	20	823	2.20%
Total	213.4	37,384	100%

The frequency and percentage of identified secondary incidents in each route direction for Hampton Roads are illustrated in Figure 8 and summarized in Table 5. Table 5 also reports the proportions of secondary incidents occurring on the same segments (i.e. the primary and its secondary incidents occur within a single segment), crossing segments (i.e. the spatial boundary covers multiple segments due to queue back up) and opposite direction. Note that the frequency presented in Table 5 is the total number of secondary events while the frequency in Table 4 is the total number of incidents. Every event includes at least one or more associated incidents. Therefore the total numbers (single incidents and events that involve two or more incidents) presented in these two tables are different. Furthermore, a detailed segment-based spatial analysis was conducted in both directions for primary-secondary incident events and the results are shown in Figure 9. Three subplots display the spatial distributions of independent incidents, primary-secondary incident pairs and primary-multiple secondary incident events respectively. The actual height of vertical bar in the legend represents the count number that is marked in the right. Height variations reflect the segment-based event frequency distributions along each road direction. It shows that I-64 (EB, WB), I-264 (EB, WB), I-564 (EB, WB) are problematic routes with high percentages of primary-secondary incident events. Furthermore, the interchange between I-264 and I-64 is a hotspot with the highest frequencies in all three-event categories. This information is valuable in terms of focusing patrol resources, from the perspective of secondary incidents.

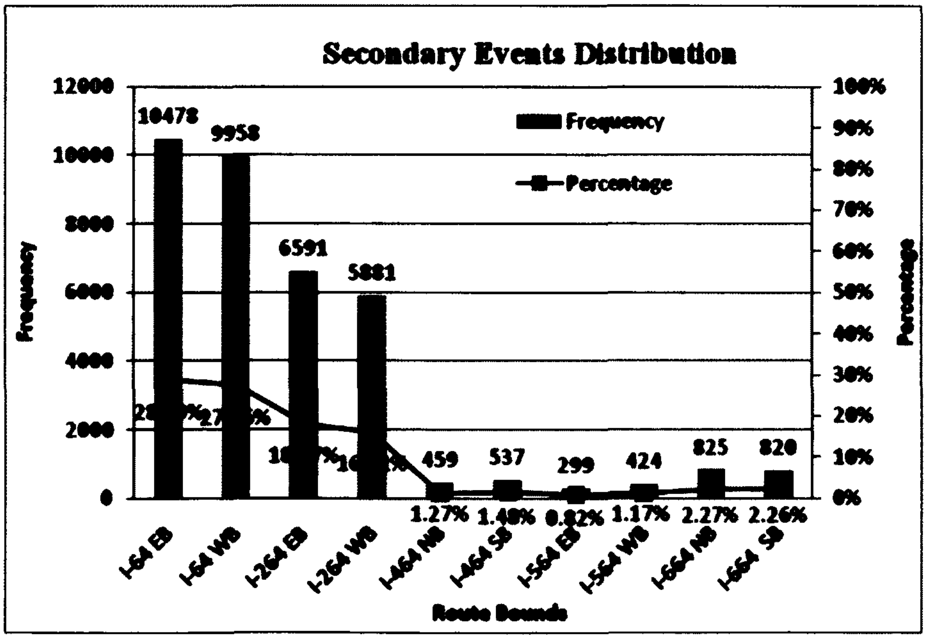


Figure 8 Route Bound-Based Primary-Secondary Incidents Events Distribution During 2005

Table 5 Summary of 2005 Events on Major Freeways in Hampton Roads

Events / Routes	Independent incidents Σ_0, O_0	Primary-secondary pairs $\Sigma_1, O_0; \Sigma_0, O_1$				Primary-multiple secondary incidents events $\Sigma_0, O_{2+}; \Sigma_1, O_1; \Sigma_1, O_{2+}; \Sigma_{2+}, O_0; \Sigma_{2+}, O_1; \Sigma_{2+}, O_{2+}$						Total
	Freq.* (Pct.) **	Same direction Σ_1, O_0		Opposite direction Σ_0, O_1	Freq. (Pct.)	Same direction Σ_{2+}, O_0		Opposite direction Σ_0, O_{2+}	Both directions $\Sigma_1, O_1; \Sigma_1, O_{2+}; \Sigma_{2+}, O_1; \Sigma_{2+}, O_{2+}$		Freq. (Pct.)	Freq.
		Single segment	Multiple segments			Single segment	Multiple segments		Single segment	Multiple segments		
I-64 EB	10,121 (96.5%)	215	42	51	308 (2.94%)	23	13	1	9	3	49 (0.47%)	10,478
I-64 WB	9,693 (97.3%)	190	19	33	242 (2.43%)	12	5		2	4	23 (0.23%)	9,958
I-264 EB	6,369 (96.63%)	123	47	18	188 (2.85%)	11	13	2	6	2	34 (0.52%)	6,591
I-264 WB	5,647 (96.02%)	141	37	30	208 (3.54%)	8	8	2	6	2	26 (0.44%)	5,881
I-464 NB	458 (99.78%)	1			1 (0.22%)							459
I-464 SB	535 (99.63%)	2			2 (0.37%)							537
I-564 EB	286 (95.65%)	11			11 (3.68%)	2					2 (0.67%)	299
I-564 WB	413 (97.41%)	9			9 (2.12%)	2					2 (0.47%)	424
I-664 NB	818 (99.15%)	7			7 (0.85%)							825
I-664 SB	817 (99.63%)	3			3 (0.37%)							820
Total	35,157 (96.93%)	702			979 (2.70%)						136 (0.37%)	36,272

Note that Freq.* —Frequency; Pct. **—Percentage

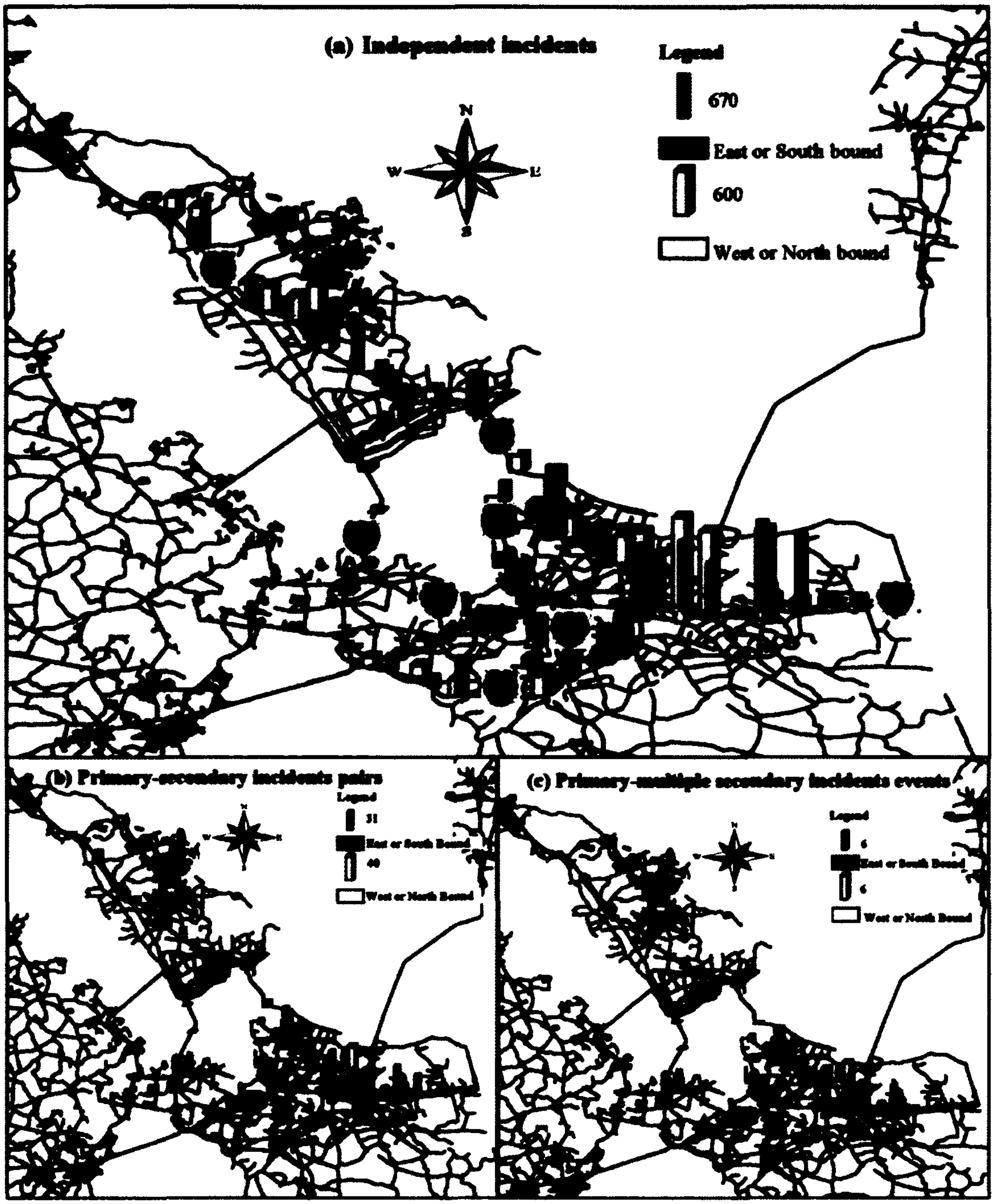


Figure 9 Spatial Distributions of Primary-Secondary Incident Events in Both Directions

4.2 Temporal Analysis of Primary-Secondary Incidents Events

Temporal analyses of secondary events grouped by month, weekday and hour were also performed (Figure 10 and 11). Figure 10 shows independent incident distribution by month. July and August have the highest numbers while the pattern of primary–secondary pair and primary-multiple secondary incidents event are somewhat different (Figure 11). The months of June, August and October show the higher number for primary-secondary pairs. The month with a highest frequency for primary-multiple secondary incident events is March. A relatively high number of such events persist from June to November, covering the summer months. Figures (12, 13 and 14) contain 6 subplots that show the frequency distributions (left column) and incident duration variations (right column) for independent incidents (Figure 12), Primary-secondary pairs (Figure 13) and primary-multiple secondary incident events (Figure 14).

Note that the average incident durations for primary-secondary incident pairs and multiple secondary incident events are the durations of the primary incidents. The frequency distributions for independent incidents are similar to the flow patterns on weekdays and weekends. That is, they show a relatively lower frequency on weekends than on weekdays. For primary-secondary incidents pair, the frequency distribution seems to be concentrated in the mornings and afternoons. Multiple secondary incident events are noticeably only concentrated in the morning and afternoon peak periods.

In terms of durations for independents incidents, the plot in Figure 12 (right) shows a narrow variation by time of day, except those occurring later in the night to early morning. Primary incident durations for the primary-secondary incident pairs show large variations in later night and morning hours (Figure 13 right). Interestingly, the durations during afternoon peaks are consistently low. For multiple secondary incident events (Figure 14 right), the corresponding plot of primary incident duration shows a peak period pattern.

More importantly, the duration magnitudes of primary-secondary incident pairs and multiple secondary incident events are substantially larger than independent incidents.

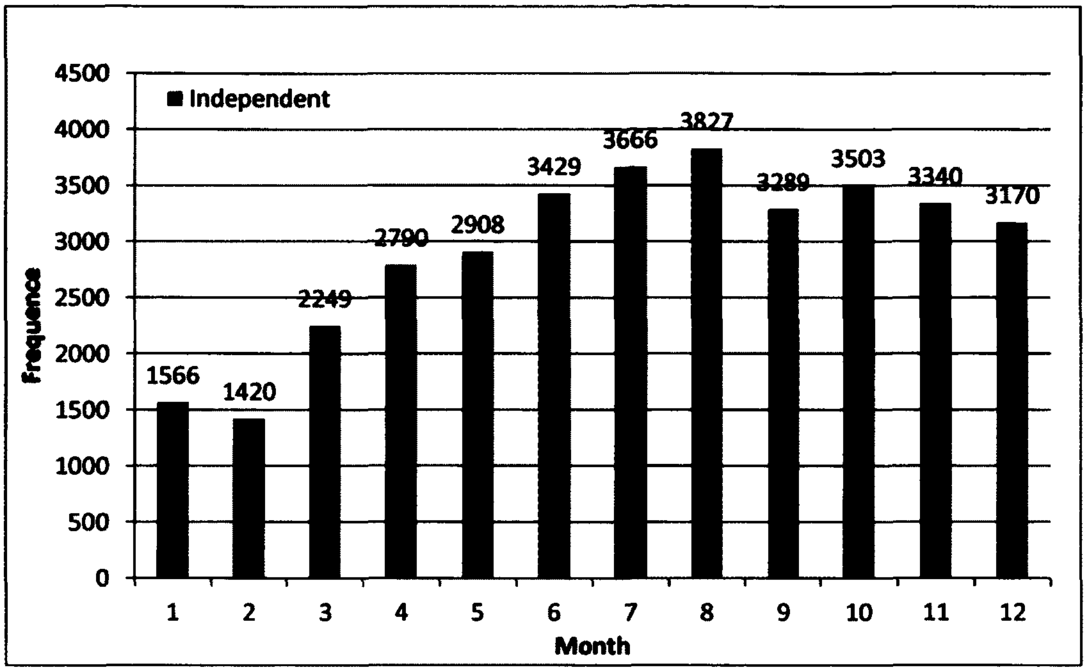


Figure 10 Independent Incidents Distribution by Month

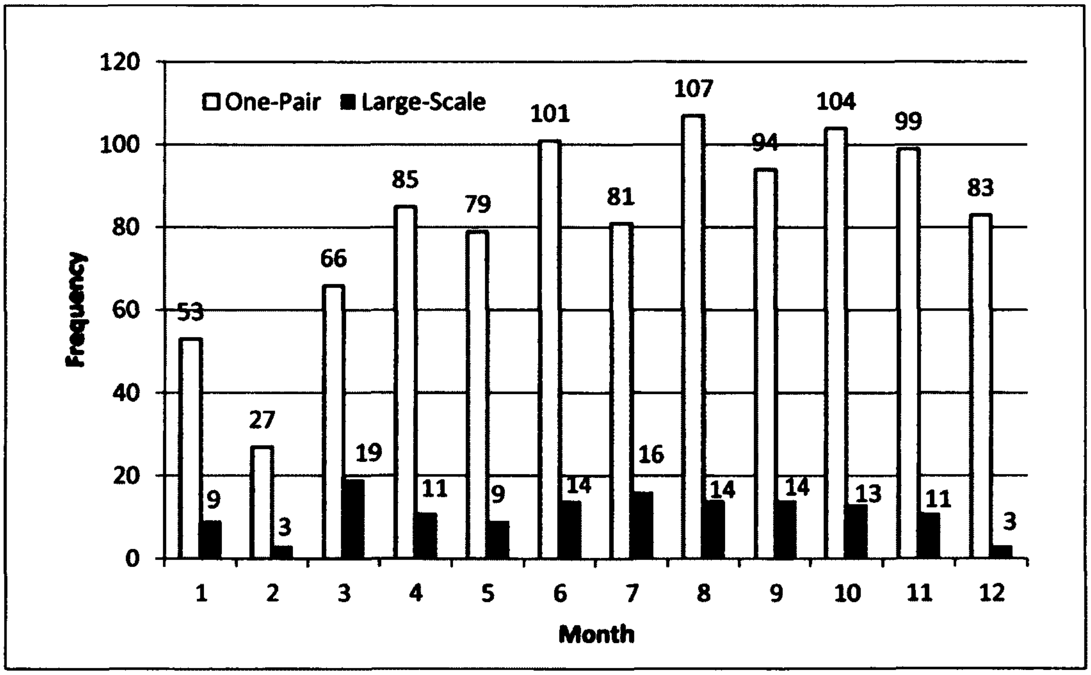


Figure 11 Primary-Secondary Incident Pairs and Primary-Multiple Secondary Incident Events Distributions by Month

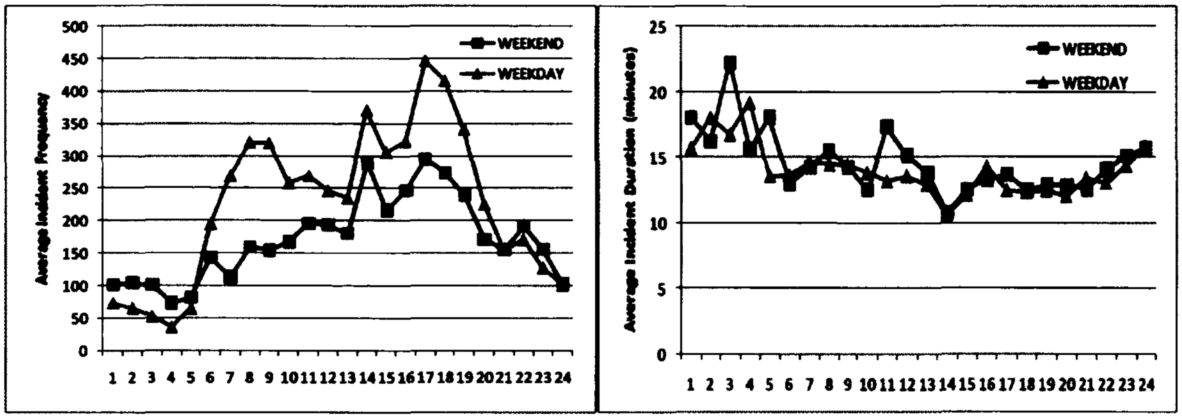


Figure 12 Independent Incident Average Frequency Daily Distributions (Left) and Independent Incident Average Duration Daily Distributions (Right) For Weekday and Weekend

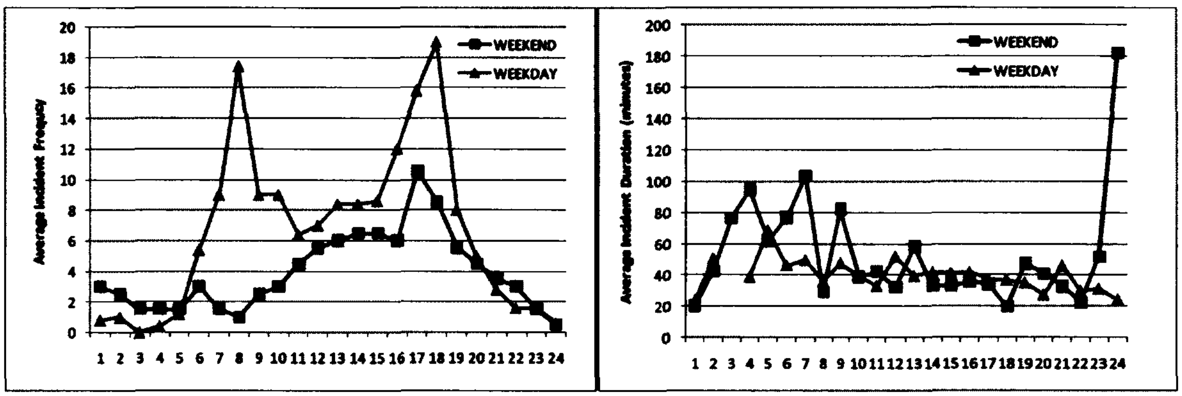


Figure 13 Primary-Secondary Incident Pairs Average Frequency Daily Distributions (Left) and Primary Incident Average Duration Daily Distributions (Right) For Weekday And Weekend

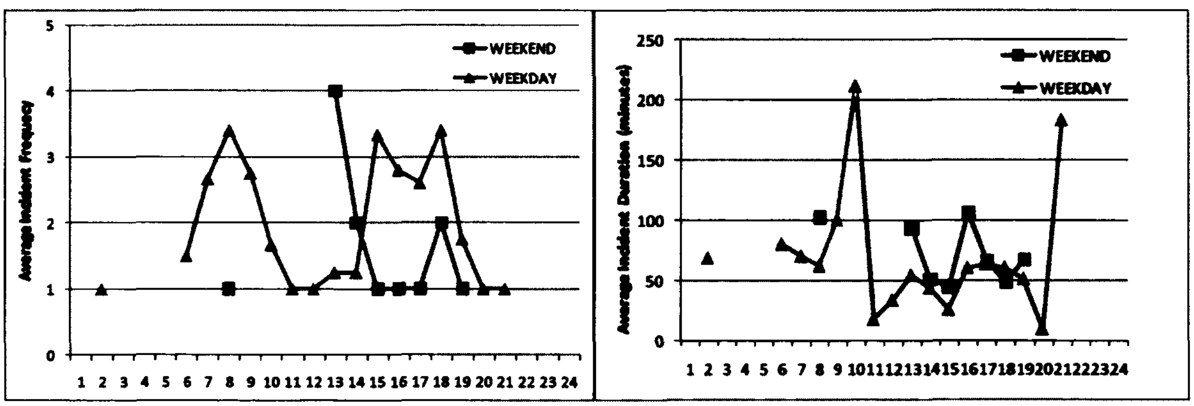


Figure 14 Primary-Multiple Secondary Incident Events Average Frequency Daily Distributions (Left) and Primary Incident Average Duration Daily Distributions (Right) For Weekday and Weekend

4.3 Summary

This analysis characterizes events as primary incidents and their secondary incidents in the same and opposite direction. Roadways and hotspots that are likely to have multiple secondary incidents were identified based on a spatial analysis by using ArcGIS. Primary-secondary incident events grouped by month, weekday, and hour were also analyzed, with practical implications for focusing patrol resources spatially and temporally. Such information is useful for incident management. Overall, the results of spatial and temporal analyses are valuable for incident management to dispatch appropriately target service patrols teams, especially from the perspective of managing primary-secondary incident events. Comprehensive adverse event identification can aid in evaluating route performance to give special attention to routes with higher frequencies of primary-secondary incident events.

CHAPTER 5

FACTORS ASSOCIATED WITH THE LIKELIHOOD OF PRIMARY-SECONDARY INCIDENT EVENTS

To understand the occurrence of primary-secondary incident events and answer the question about what factors are associated with such incident events, two ordered logit models, proportional odds model and partial proportional odds model, are estimated separately. General proportional odds model follows a parallel lines assumption while partial proportional odds model accounts for the unequal contributions for some significant variables. The details are discussed in the following sections.

5.1 Models to Estimate Likelihood of Primary-Secondary Incident Events

In a simple logit model (proportional odds model), category $j = 1$ is defined as the minimum level of variable. $j = 2$ is the next order level and so on for the last category ($j = k - 1$). In this study $j = 1$ represents the category of independent incidents; $j = 2$ donates the primary-secondary incident pairs and $j = 3$ represents the last category of primary- multiple secondary incident events. The probability of a given i^{th} observation Y_i (a total of n observations) above particular category j is calculated by equation (3):

$$P(Y_i > j) = \frac{\exp(a_j + x_{1i}\beta_1 + x_{2i}\beta_2 + \cdots + x_{li}\beta_l)}{1 + \exp(a_j + x_{1i}\beta_1 + x_{2i}\beta_2 + \cdots + x_{li}\beta_l)} \quad j = 1, 2, \cdots, k-1; i = 1, 2, \cdots, n \quad (3)$$

Where α_j is the intercept parameter for j category. The β parameter represents the slope for each explanatory variable ($x_1, x_2, \cdots x_l$), where l represents the number of explanatory variables.

Note that equation (3) for the proportional odds model requires that β s follow a parallel lines assumption, which represents that independent variables contribute equally to all outcome categories. This means each variable only has one coefficient to apply all categories. i.e., β s will be the same for all values of j, and the $k-1$ regression lines are parallel to each other. However, it is important to test the parallel lines assumption, since one or more β s may statistically differ across values of category j in some of cases. If the parallel lines assumption is violated, it needs different sets of coefficients in the model to describe the relationship between independent variables and outcome categories. A partial proportional odds model has been proposed to overcome this limitation, allowing some β s to differ across categories (Zhang & Khattak, 2010a). For example, if the β for X_2 is different from the categories, then the probability of Y_i can be determined by:

$$P(Y_i > j) = \frac{\exp\left(a_j + x_{1i}\beta_1 + x_{2i}\beta_{2j} + \cdots + x_{li}\beta_l\right)}{1 + \exp(a_j + x_{1i}\beta_1 + x_{2i}\beta_{2j} + \cdots + x_{li}\beta_l)} \quad j = 1, 2, \cdots, k-1; i = 1, 2, \cdots, n \quad (4)$$

Here, the explanatory variables vector ($l \times 1$): $X = \begin{pmatrix} x_1 & x_2 & \cdots & x_l \end{pmatrix}$

For both models, the dependent variable is odds of secondary events and the independent variables include the incident characteristics of primary incidents, road geometric variables and traffic information. The model specifications and analysis description is detailed in Table 6.

STATA software was selected to perform these ordinal logit regressions. Note that ologit in STATA is used to estimate the simple ordered logit model. The estimates include cut points, which equal the negatives of alphas expressed in Equation (3). Parallel line assumption test is performed by an add-in package (Williams, 2006). If the parallel lines assumption is violated, then a generalized ordinal logit/partial proportional model (gologit2) will be used to conduct further analysis. This package runs an iterative process to estimate partially proportional odds model, where the parallel lines constraint is only relaxed for those unjustified variables. After gologit2 regression, the parameter estimates for the constrained variables are the same while the estimated unjustified coefficients will be different for each category. Furthermore, STATA calculates the marginal effects, for each independent variable in both models, which corresponds to the difference in probability when independent variable changes from 0 to 1.

Table 6 Ordered Logit Model Specification

Variable Name	Description
Odd of Primary-secondary Incident Events	
Primary Incident characteristics	
Incident type	Binary variable (Crash =1; Others=0)
Incident duration (>0)	in Minutes
Number of involved vehicles (>0)	Number
Outstate vehicle?	Yes/No
Lane blockage	Percentage of lane blockage, ranging from 0 to 100
Truck/s involved	Binary variable (Truck =1; Non-Truck =0)
Road Geometry	
Segment length	Mile
Curve?	(Yes/No)
Traffic	
AADT	AADT/(Lane*1000)

5.2 Model Results

Table 7 provides descriptive statistics for independent variables broken down by three categories: Independent incidents, primary-secondary incident pairs, and primary-multiple secondary incident events. Importantly, information about secondary incidents themselves is excluded partly because the primary and secondary incidents have an associative relationship and it is not suitable to have them both in a statistical model. Most incidents (96.93%, from Table 7) do not involve a secondary incident with an average of 14-minute duration; the second largest category is that of primary-secondary pairs (2.70%) having an average of 40-minute duration of the primary incident, and the multiple secondary events (0.37%) have even longer primary incident durations (68 minutes), as expected. Note that these durations are for the primary incidents and if the secondary incidents lasted longer than primary incident, then there may be an additive extension to the event duration. The results suggest that a longer duration primary incident is associated with multiple secondary events, as expected. Truck involvement is relative higher in the last two categories than independent incidents. On average, the number of vehicles involved (in the primary incident) is increasing with higher secondary event adversity (from 1.07, 1.42 to 2.07). Lane blockage, AADT/(Lane*1000) show similar trends. Shorter segment length (the length of the segment where primary incident occurs) seems to be associated with higher secondary event categories, implying that owing to proximate changes in roadway geometry, shorter segments are more prone to secondary incidents. Owing to their unfamiliarity with the network, out-of-state vehicles and their drivers seem to be associated with more secondary incidents. Overall, the descriptive statistics are reasonable in terms of their means and ranges.

Table 7 Descriptive Statistics of Independent Variables in Primary Incident Analysis

Variables	Number of Observations	Mean	Standard deviation	Min	Max
Independent incident					
Crash? (yes/no)	35157	0.0742	0.2620	0	1
Incident duration (minutes)	35157	13.4951	18.5178	1	470
Truck involved? (yes/no)	35157	0.0350	0.1773	0	1
Number of vehicles (number)	35157	1.0730	0.3566	1	11
Out of state vehicle? (yes/no)	35157	0.1537	0.3586	0	1
Lane blockage (%)	35157	1.6099	8.4512	0	100
Segment length (miles)	35157	1.6348	0.8288	0.45	4.81
Number of lane (number)	35157	3.0661	0.6551	2	4
Curve? (yes/no)	35157	0.5351	0.4988	0	1
AADT/(Lane*1000)	35157	20.3877	7.1400	5.4728	29.6667
Primary-secondary pair					
Crash?* (yes/no)	979	0.3391	0.4737	0	1
Incident duration (minutes)	979	40.3504	37.811	1	366
Truck involved? (yes/no)	979	0.0562	0.2218	0	1
Number of vehicles (number)	979	1.4178	0.8497	1	6
Out of state vehicle? (yes/no)	979	0.1841	0.3854	0	1
Lane blockage (%)	979	8.1339	18.2497	0	100
Segment length(miles)	979	1.6209	0.8422	0.48	4.81
Number of lane (number)	979	3.1869	0.6637	2	4
Curve? (yes/no)	979	0.5638	0.4962	0	1
AADT/(Lane*1000)	979	22.7759	7.8804	8	29.6667
Primary-multiple secondary incidents event					
Crash? (yes/no)	136	0.5956	0.4926	0	1
Incident duration (minutes)	136	67.8971	77.9269	5	793
Truck involved? (yes/no)	136	0.0551	0.2213	0	1
Number of vehicles (number)	136	2.0662	1.2835	1	8
Out of state vehicle? (yes/no)	136	0.2889	0.4532	0	1
Lane blockage (%)	136	20.3914	26.2019	0	100
Segment length (miles)	136	1.4688	0.6619	0.78	4.81
Number of lane (number)	136	3.3015	0.6591	2	4
Curve? (yes/no)	136	0.6029	0.4911	0	1
AADT/(Lane*1000)	136	25.1633	10.6318	12	29.6667

Note that all incident characteristics in the last two categories are for primary incidents only. For instance, incident duration is the duration of primary incident; the number of vehicles is the number involved in the primary incident.

Tables 8 and 9 show two ordered logit (proportional odds) models that capture the propensity toward more secondary incidents. The first model in Table 8 is a simple ordinal regression (proportional odds model) based on restrictive parallel lines assumptions about the estimated parameters. The model in Table 8 is a generalized ordered logit model with relaxed restrictions on model parameters that are applicable to various event adversity levels. More technically, autofit, a backwards stepwise selection procedure, showed that the assumption of the parallel lines model is violated. The main variables of interest in this case are the number of vehicles involved, and lane blockage. Thus a generalized ordered logit model was used to relax the constraints and re-estimate parameters, summarized in Table 9.

Summary statistics show that both models are statistically significant (Likelihood ratio Chi-square tests are significant at 5% level). The McFadden's pseudo-R^2 is only partially equivalent to R^2 in Ordinary Least Squares (OLS) regression, which is the proportion of variance of the response variable explained by the predictors). The p-values for each individual independent variable are used to test the null hypothesis that this independent variable's coefficient is not statistically different from zero. If p-value is less than 0.05, then the null hypothesis can be rejected implying that the independent variable is statistically significant. The constants for these models are only used to estimate response probability. Note that in Table 9, the number of vehicles involved and lane blockage were re-estimated to have different coefficients across the ordinal categories. Effects of the constrained variables in Table 9 can be interpreted to be the same as the first simple ordinal regression model in Table 8. A positive indicates that higher values of the explanatory variable are associated with higher (secondary) event adversity. Both models show that a crash longer incident duration, more involved vehicles, higher AADT and shorter segment length are associated with higher occurrence of secondary events. This is counterintuitive. The possible explanation is that a segment defined in this region consists of a basic freeway segment, and ramps or weaving segments. Within a short segment, merging or diverging create more intense conflict impact than in a longer segment. It possibly causes more secondary incidents in this or upstream segments. Perhaps the most noteworthy result is that the number of involved vehicles and lane blockage are highly associated with multiple secondary events. The variable primary incident duration is difficult to interpret, in the sense that response and clearance times may be longer if secondary incidents are involved. This interdependence between primary incident duration and occurrence of associated secondary incidents was studied (Khattak et al. 2009). Although the coefficient for truck involvement was negatively associated with higher scale events, it is not statistically significant (5% level). Out-of-state vehicle also showed a negative relationship with the likelihood of adverse events, but it is not statistically significant either. The road geometric variable curves are not statistically significant in the models. The difference between the two models is that the partial proportional odds model accounts for unequal contributions of explanatory variables to different event categories. The number of vehicles involved and lane blockage in Table 9 are variables that have different contributions. They are significantly associated with the higher propensity to have secondary incident, and they have a greater associations in the higher category than in the lower category. This means that more vehicles involved and lane blockage in the primary incident are associated with increased propensity to have multiple secondary incidents.

Table 8 Proportional Odds Model for Ordinal Scale of Events

Parameters	Coefficients	Marginal effects		
	β	Σ_0, O_0	$\Sigma_1, O_0; \Sigma_0, O_1$	$\Sigma_0, O_{2+}\ldots \Sigma_{2+}, O_{2+}$
Primary Incident Characteristic				
Crash?	0.7478**	-0.0204	0.0182	0.0022
Incident duration	0.0222**	-0.0004	0.0004	0.0000
Truck involved?	-0.0460	0.0009	-0.0008	-0.0001
Number of vehicles	0.3121**	-0.0062	0.0055	0.0007
Outstate vehicle?	-0.0591	0.0012	-0.0011	-0.0001
Lane blockage (%)	0.0100**	-0.0002	0.0002	0.0000
Road Geometry				
Segment length	-0.0836*	0.0017	-0.0015	-0.0002
Curve?	0.0741	-0.0015	0.0013	0.0002
Traffic				
AADT/(Lane*1000)	0.0886**	-0.0018	0.0016	0.0002
Constant	6.2664			
	8.5480			
Summary Statistics				
Number of observations = 36272				
Log likelihood function = - 4614.9856		LR chi2(10) = 1557.65		
Pseudo R2 = 0.1444		Prob > chi2 = 0.0000		

Notes: * $p<0.05$, ** $p<0.001$; Marginal effects in the table 6 and 7 represent the changes in the dependent variable with a unit change in the independent variable.

Table 9 Partial Proportional Odd Model for Ordinal Scale of Events

Parameters	Coefficients		Marginal effects		
	Σ_1, O_0; Σ_0, O_1	Σ_0, O_{2+}… Σ_{2+}, O_{2+}	Σ_0, O_0	Σ_1, O_0; Σ_0, O_1	Σ_0, O_{2+}… Σ_{2+}, O_{2+}
Primary Incident Characteristic					
Crash?	0.7781**	0.7781**	-0.0215	0.0197	0.0018
Incident duration	0.0222**	0.0222**	-0.0004	0.0004	0.0000
Truck involved?	-0.0423	-0.0423	0.0009	-0.0008	-0.0001
Number of vehicles	0.2783**	0.5145**	-0.0055	0.0047	0.0008
Outstate vehicle?	-0.0531	-0.0531	0.0011	-0.0010	-0.0001
Lane blockage (%)	0.0092**	0.0179**	-0.0002	0.0002	0.0000
Road Geometry					
Segment length	-0.0825*	-0.0825*	0.0016	-0.0015	-0.0001
Curve?	0.0748	0.0748	-0.0015	0.0014	0.0001
Traffic					
AADT/(Lane*1000)	0.0880**	0.0880**	-0.0018	0.0016	0.0002
Constant	-6.2193**	-9.0388**			

Summary Statistics

Generalized ordered logit model significance

Number of observations	= 36272		
Log likelihood function	= - 4600.2501	LR chi^2 (11)	= 1587.12
Pseudo R^2	= 0.1471	Prob > chi^2	= 0.0000

Parallel Lines Assumption Test

Testing parallel lines assumption using the .05 level of significance

Step 1: Constraints for parallel lines imposed for duration (P Value = 0.9828)
Step 2: Constraints for parallel lines imposed for curve (P Value = 0.5293)
Step 3: Constraints for parallel lines imposed for crash (P Value = 0.2784)
Step 4: Constraints for parallel lines imposed for truck (P Value = 0.1822)
Step 5: Constraints for parallel lines imposed for aadt_ln_1000 (P Value = 0.1227)
Step 6: Constraints for parallel lines imposed for outstate_vehicles (P Value = 0.0907)
Step 7: Constraints for parallel lines imposed for length (P Value = 0.0624)
Step 8: Constraints for parallel lines are not imposed for
numvehs (P Value = 0.00026)
laneblkpct (P Value = 0.00799)

Wald test of parallel lines assumption for the final model:

(1) [1]duration - [2]duration = 0
(2) [1]curve - [2]curve = 0
(3) [1]crash- [2]crash = 0
(4) [1]truck - [2]truck = 0
(5) [1]aadt_ln_1000 - [2]aadt_ln_1000 = 0
(6) [1]outstate_vehicles - [2]outstate_vehicles = 0
(7) [1]length - [2]length = 0

chi2(7) = 12.24
Prob > chi2 = 0.0928

An insignificant test statistic indicates that the final model does not violate the proportional odds/ parallel lines assumption

Notes: * p<0.05, **p< 0.001; STATA software procedure gologit2 was used with autofit.

5.3 Summary

Two ordered logit (proportional odds) models explored various factors associated with the likelihood of primary-secondary events. A proportional odds model can be applied first and then the parallel line assumption shall be tested. If this assumption is violated, a partial proportional odds model is employed to further explore the factors that make unequal contribution across multiple outcome categories. Based on primary incidents characteristics, crashes and long durations were found to increase the frequency of secondary incidents associated with a primary incident. More importantly, multiple-vehicle involvement and lane-blockage had a different contribution to the occurrence of secondary incidents, and they are particularly associated with more secondary incidents. Road geometric variables such as curvature and segment length were not statistically significantly associated with more secondary incidents.

This analysis certainly facilitated analysis of multiple secondary events. It suggests a close relationship between a lane blockage and the occurrence of multiple secondary events. Quantified effects of key factors that include roadway geometry and incident characteristics can help reduce the likelihood of secondary incident occurrence. Especially, crashes, longer duration, multiple vehicles involvement, lane blockage, shorter segment length, and high traffic volume are major contributors to the occurrence of multiple secondary incidents. Therefore, when these conditions are present, operation managers can be particularly mindful of the occurrence of secondary incidents. Finally, the study suggested that multiple secondary events need further research attention.

CHAPTER 6

SPATIO-TEMPORAL PATTERNS OF PRIMARY AND SECONDARY INCIDENTS

Secondary incidents can occur in the vicinity of primary incidents, complicating traffic operations. While studies have examined factors associated with incident duration and secondary incident occurrence, a significant number of spatio-temporal variables in incident management are often overlooked. For example, how soon does a secondary incident happen after a primary incident? How far is the secondary from the primary incident? What factors are associated with near versus far secondary incidents? To answer these questions, a deeper analysis of primary and secondary incidents is conducted on the basis of a unique 2008 incident and roadway inventory database for Hampton Roads, Virginia. Time-gaps and distances for secondary incidents in the same direction are examined using appropriate statistical methods. This analysis contributes to incident management by rigorously analyzing time-gaps and distances between primary and secondary incidents and exploring their implications. The results can support more informed planning and operational decisions needed to respond in complex incident situations.

6.1 Time Gap and Distance Calculation

The associations between primary and secondary incidents can be characterized by time gap and distance. Calculation of the time gap between a primary incident and its secondary incidents involves differentiating the start times of the identified primary and secondary incidents. The distance between a primary incident and its secondary incident also can be determined through aggregating distances between neighboring reference mile markers (Zhang & Khattak, 2011). Two kinds of associations between primary and secondary incidents were estimated:

- The time gap between the first/second secondary incident and its primary incident in the same road direction
- The distance between the first/second secondary incident location and its primary incident occurrence in the same road direction.

6.2 Distribution of Time-Gap and Distance

To examine the frequency distribution of time-gap and distance, two bivariate histograms were created to visualize the distributions of first secondary incidents and second secondary incidents in the same direction (Figure 15). It seems that a substantial number of secondary incidents occur in closer proximity to their primary incidents. As queues from primary incidents propagate, the potential distance between primary and secondary incidents increases (since majority of incidents are expected to occur at the end of the queue). As time passes, the queues begin to shrink after incident clearance, and the associated secondary incidents will start occurring in closer proximity to the primary. The proximity relationship is non-linear. Comparing the two corresponding histograms, it is evident that the initial secondary incident is more likely to occur in a narrow range of space and time relative to its primary incident, while the subsequent secondary incident in the same direction shows greater variation, as expected. Subsequent secondary incidents have a longer time-gap and occur at longer distances from the primary incident. Given their greater variability, they may be particularly challenging for incident managers.

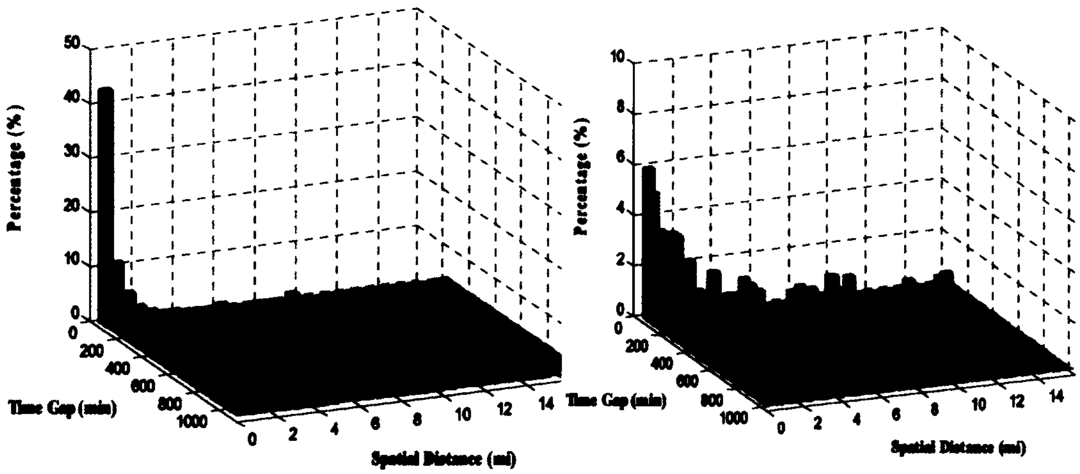
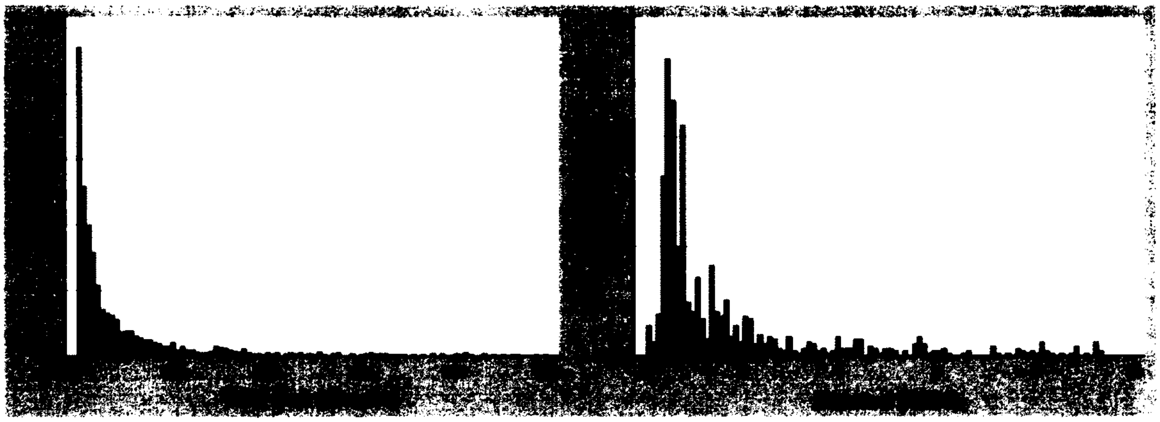


Figure 15 Distribution of (a) Initial Secondary Incidents over Time and Space (b) Subsequent Secondary Incidents over Time and Space

Further analysis of primary-first secondary incidents occurring in the same direction is presented in Figure 16. Once again, the time-gap distributions indicate that a large portion of secondary incidents occur very quickly after their primary incidents, and decay somewhat exponentially. However, the distance distribution appears as a skewed normal distribution. The mode of distance between the primary and first secondary incidents is 0.72 miles and the average of distance is about 1.2 miles. This information can be valuable for incident managers in the region to help them optimize the locations of their patrol teams to reduce the occurrence of secondary incidents. It is recognized that if secondary incidents that occurred 10 hours after a primary vehicle was abandoned and spatially far away from the primary incident are contained in the data , it would result in bias and errors in the model estimation due to their longer time gap and distance, and may over-estimate the effects for such factors. After carefully checking these incidents, 5-hour and 10-mile are used as temporal and spatial thresholds to clean out the extremes and outliers.



(a) (b)

Figure 16 Distribution of Time Gaps (a) and Distances (b) between the Same Direction Primary-First Secondary Incidents

Descriptive statistics and definitions of the variables used in analysis are presented in Table 10. A total of 1218 same direction incidents were identified and analyzed. The average time-gaps for the same direction incidents were about 34 minutes. The average spatial distance is about 1.2 miles (with a mode of 0.72). Other variables show reasonable magnitudes, and are used in regression analysis. They include incident types, incident durations, number of vehicles involved in a incident, detection sources, weather, roadway curves, ramps, freeway lanes, lane blocked, AADT per lane, peak hours (morning peak is from 6: 00 am to 9:00 am, afternoon peak covers 4:00 pm-7:00 pm, and weekend daytime 10:00 am-7:00 pm). A purpose for doing this analysis is to investigate whether morning peak, afternoon peak or weekend make unequal contributions to the occurrence of secondary incidents. The AADT data were extracted from VDOT published results. The data were cleaned, error-checked and a few outliers in some of the variables were removed.

Table 10 Descriptive Statistics and Definition for Time-Gaps and Distances between Initial Secondary Incidents and Their Primary Incidents in the Same Direction

Variable	Definition	Observations	Mean	Standard Deviation	Min	Max
Time Gap—same dir.	Time differences between same direction primary-secondary pair (minutes)	1218	33.8937	48.2504	0.08	385.32
LN (Time Gap – same dir.)	Log (natural) transform	1218	2.6347	1.4836	-2.5257	5.9541
Distance	Spatial Distance (feet)	1218	1.1515	1.7673	0	9.3585
Incident type (base: others)	Crash	1218	0.2438	0.4296	0	1
	Debris	1218	0.0394	0.1946	0	1
	Disablement	1218	0.4926	0.5002	0	1
	Vehicle Fire	1218	0.0049	0.0700	0	1
Duration	Incident duration (min)	1218	67.4908	81.0994	0.2	413.8
Numveh	Number of vehicles Involved	1218	1.0584	0.1606	1	3
Lnblkpct	Lane blockage (%) =(# blocked /#lanes)*100	1218	38.4729	39.8788	0	100
DetSrc (base: others)	Detection Source: SSP	1218	0.3818	0.4860	0	1
	CCTV	1218	0.4499	0.4977	0	1
	Phone Call	1218	0.0837	0.2771	0	1
Rain	Rain on segment	1218	0.0649	0.2464	0	1
Curve	Curve on segment	1218	0.3522	0.4778	0	1
Ramp	Ramp present	1218	0.9154	0.2783	0	1
Traffic Peak (base: Offpeak)	Weekday Morning Peak	1218	0.2356	0.4246	0	1
	Weekday Afternoon peak	1218	0.1445	0.3517	0	1
	Weekend daytime	1218	0.1281	0.3343	0	1
AADT_1000ln	(AADT/1000) per lane	1218	20.1178	5.1398	3.3333	33.5

6.3 Model Results

To examine the major factors associated with distances and time gaps, ordinary least squares regression models were estimated. The dependent variables are as follows:

- The time gap between the first secondary incident and its primary incident in the same direction. It was found that log transformation of the dependent variable is appropriate for modeling.
- The distance between the first secondary incident and its primary incident in the same direction. The explanatory variables include the characteristics of primary incidents, road geometry, and traffic.

Two sets of models were estimated with STATA software. Ordinary Least Squares (OLS) regression models were selected, rather than hazard-based duration models due to their simplicity, ease of coefficients' interpretation, and ease of predictions. The log-transformed time-gap model for same direction secondary incidents, presented in Table 11, shows that it is statistically significant overall (N=1218). A full model is presented with several explanatory variables for demonstration, and then a final model with non-significant variables removed is presented. About 40.3% of the variation in the dependent variable is explained by the full model, indicating a relatively good fit. The correlations between explanatory variables were tested using Variance Inflation Factors (VIF) and were reasonably low (VIF was much lower than 10, which is often used as a cutoff). The full model shows that longer time-gaps are associated with crashes and disablements. Longer primary incident durations, and detection by SSP, phone calls, and cameras are associated with longer time-gaps. A host of factors that includes adverse weather and roadway geometry are not statistically significant variables. The parameters can be interpreted appropriately by taking their exponent. For example, in terms of percent change, crashes, as opposed to other types of incidents, are associated with $e^{(0.81251)}$ = 2.25 or 125% longer time-gaps.

Table 12 shows the results for (non-transformed) distances between primary and secondary incidents. It is statistically significant overall (N=1218). Again, a full model is presented with several explanatory variables for demonstration, and then a final model with non-significant variables removed is presented. About 13.8% of the variation in the dependent variable is explained in the full model, indicating a relatively weak fit. Again, the correlations between explanatory variables were tested and were not problematic. Crashes and fires are associated with secondary incidents that occur at longer distances, partly because such incidents cause longer queues. Longer primary incident duration is related to larger distances between a primary and its secondary incident (every minute is associated with a 0.0036 miles increase in distance). More lane blockage is positively associated with a longer distance between primary and secondary incidents. The time of day variable and some of the roadway variables are not statistically significant in the model. However, more traffic is positively associated with longer distances between primary and secondary incidents.

Table 11 Ordinary Least Squares (OLS) Models for Time Gaps between First Secondary Incidents and Their Primary Incidents in the Same Direction

Parameters		OLS Models LN(Time-gap)			
		Full Model		Final Model	
		Coefficient Estimates	p-Value	Coefficient Estimates	p-Value
Primary Incident Characteristics					
Incident type (base: others)	Crash	0.8152	0.000***	0.7516	0.000***
	Debris	0.1394	0.457	0.1122	0.551
	Disablement	0.5740	0.000***	0.5120	0.000***
	Vehicle Fire	0.6430	0.180	0.4516	0.351
Incident duration (minutes)		0.0109	0.000***	0.0113	0.000***
Number of vehicles involved		0.2127	0.309		
Lane blockage (%)		0.0004	0.710	0.0008	0.428
Detection source (base: others)	SSP	0.4600	0.001***		
	CCTV	0.7524	0.000***		
	Phone Call	0.5668	0.001***		
Weather Condition					
Rain		0.1175	0.395		
Road Geometry					
Curvature present		0.0698	0.332		
Ramp present		0.0678	0.575		
Traffic Characteristics					
Peak (base:off-peak)	Weekday morning peak	-0.0562	0.502		
	Weekday afternoon peak	-0.0444	0.660		
	Weekend daytime	-0.1785	0.094*		
(AADT/1000) per lane		0.0119	0.074*	0.0131	0.049**
Constant		0.3151	0.311	1.1359	0.000***
Summary Statistics		Number of obs: 1218 F(17, 1200) = 47.60 Prob > F = 0.0000 R-squared = 0.4028		Number of obs: 1218 F(7, 1210) = 105.11 Prob > F = 0.0000 R-squared = 0.3781	

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$

Table 12 OLS Models for Distances between First Secondary Incidents and Their Primary Incidents in the Same Direction

Parameters		OLS Models Distance (miles)			
		Full Model		Final Model	
		Coefficient Estimates	p-Value	Coefficient Estimates	p-Value
Primary Incident Characteristics					
Incident type (base: others)	Crash	0.7087	0.000***	0.7213	0.000***
	Debris	0.6329	0.018**	0.5641	0.034**
	Disablement	0.0818	0.585	0.0909	0.527
	Vehicle Fire	3.2422	0.000***	3.2564	0.000***
Incident duration (minutes)		0.0036	0.000***	0.0037	0.000***
Number of vehicles involved		-0.1913	0.522		
Lane blockage (%)		0.0038	0.009**	0.0036	0.011**
Detection source (base: others)	SSP	0.1546	0.424		
	CCTV	0.3019	0.093*		
	Phone Call	0.2757	0.241		
Weather Condition					
Rain		-0.0377	0.849		
Road Geometry					
Curvature present		-0.4178	0.000***		
Ramp present		0.0676	0.696		
Traffic Characteristics					
Peak (base: off-peak)	Weekday morning peak	-0.1331	0.266		
	Weekday afternoon peak	-0.0607	0.674		
	Weekend daytime	0.0206	0.893		
(AADT/1000) per lane		0.0407	0.000***	0.0491	0.000***
Constant		-0.2054	0.644	-0.4888	0.033**
Summary Statistics		Number of obs: 1218 F(17, 1200) = 11.31 Prob > F = 0.0000 R-squared = 0.1381		Number of obs: 1218 F(7, 1210) = 24.07 Prob > F = 0.0000 R-squared = 0.1222	

Note: * p <0.10, ** p<0.05, ***p<0.001

6.4 Limitations

Possible contributing factors for length of time gap and distance are: temporal characteristics, environmental effects, geographic information, driver actions, incident characteristics, injury severity and operational factors. Hirunyanitiwattana (2006) found that rear end collision is the dominate incident type among secondary crashes, and accounts for about two thirds of all secondary crashes. Incident severity, driver factors, response variables are desirable in incident management perspective, unfortunately these variables currently are not available on the incident data being analyzed.

6.5 Summary

This analysis developed a unique database that takes advantage of more accurate geo-location information to identify secondary incidents and analyze their spatial and temporal associations. Specifically, this analysis shows distributions of distances and time-gaps between primary and secondary incidents. On average, the distance is about 1.2 miles and the time gap is 34 minutes. However, the distribution shows that many secondary incidents occur within a short time and distance of primary incidents. Comparative visualization of two bivariate histograms further showed that the time-gaps of tertiary (second secondary) incidents are more varied compared with the first secondary.

Ordinary linear regression (OLS) models were estimated to investigate the relationship between time-gaps/distances and roadway/primary incident characteristics. Time-gaps were found to be positively associated with accidents, longer primary incident durations and heavier traffic. In terms of distance, crashes and fires are associated with secondary incidents that occur at longer distances; and longer primary incident duration and lane blockage are related to larger distances between a primary and its secondary incident. Thus the study finds that distance and time vary systematically with characteristics of the primary incidents.

From an incident management perspective, the results have certain implications. The time-gap and distance distributions provide a good sense of how soon and how far secondary incidents will occur after a prior incident. The models generate new knowledge of the factors associated with distance and time-gaps. This can help service patrol teams proactively prevent secondary incidents from occurring. The distance and time-gap analysis generates useful quantitative information for end of queue management. Based on statistical evidence from this study, secondary incidents seem to occur in or near the end of queue caused by prior incidents. The estimated distances represent the influence areas of the associated incidents. Such quantitative information can help to optimize the deployment location of new sensor and information dissemination technologies such as changeable message signs (CMS), which can effectively provide warnings to upstream traffic using flashers and signs, reducing the number of secondary incidents. In addition, information about secondary incidents can be disseminated to a broader audience via commercial radios, telephones, and televisions, so people can divert to alternate routes to avoid incident congestion. Overall, strong consideration should be given to 1) installation of end of queue management technologies in places where secondary incidents are more likely to occur, e.g. hotspot of primary-secondary incident events, and 2) the dissemination of specific secondary incident information (regarding distance and time from primary incident) to the public.

While the research method has been developed and applied in the Hampton Roads area, the research approach proposed in this study can be transferred to other regions, where similar comprehensive incident, traffic, and road geometry data are available. The prediction model can be calibrated based on local data. More broadly, the method can be extended to deal with more generic cases, e.g., when only the approximate location of incidents is known. The historical data on observed secondary incidents can provide quantitative information about the influence area of primary incidents. Future work can focus on the validation of secondary incidents and verification of statistical models.

CHAPTER 7

ANALYSIS OF CASCADING INCIDENT EVENT DURATIONS

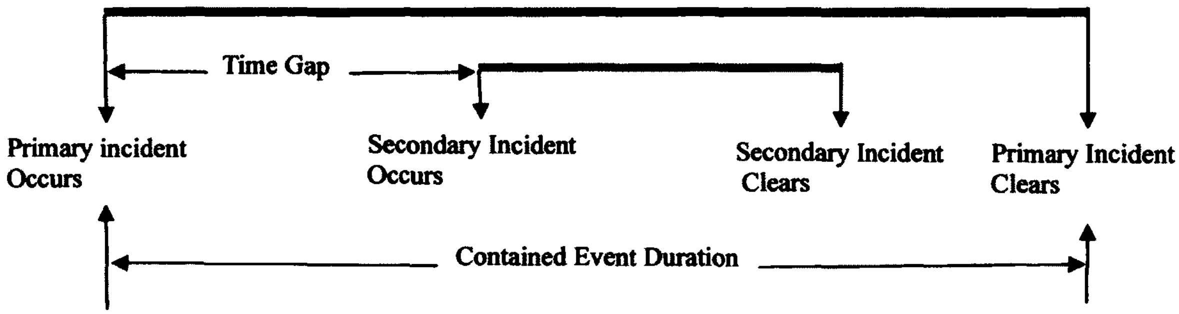
Incident duration is a key performance measure for addressing incident-induced congestion problems and determining effectiveness of incident responses. It is defined as the elapsed time from the beginning of an incident (notification) until its clearance (when the last responder leaves the scene). Analysis of incident duration has drawn substantial research attention over past years. However, most existing duration analyses treat every incident as independent without consideration of associations between associated incidents such as primary and secondary incidents. A primary incident and its secondary incidents can be grouped into one event due to their spatial and temporal proximity. Such events have cascading impacts on traffic and are expected to have longer duration than a single independent incident. Though relatively rare, such cascading events are a major concern for transportation operations. Knowledge of the nature and characteristics of such cascading event is limited. It is also not clear how primary-secondary incident event characters and operational factors are associated with event durations. This analysis answers the following questions: How can the durations of cascading events be defined and analyzed? What factors are associated with such cascading events? What are the implications for incident management?

7.1 Definition and Category of Event Durations

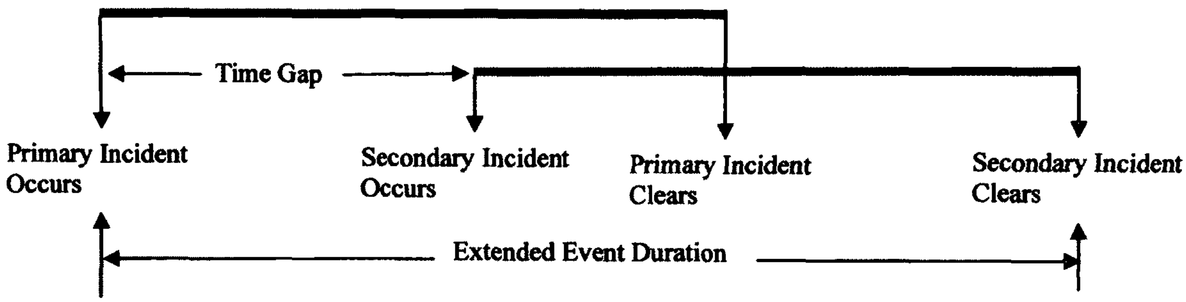
The HRTOC incident database contains incident durations. Events consist of primary and its secondary incidents. Such cascading events are a major concern for transportation operations managers and therefore they are the focus on this analysis. After identifying secondary incidents, a primary incident and its secondary incidents can be grouped into one event because of their spatial and temporal proximity. Event duration is defined as the time between the occurrence of a primary incident and clearance of all associated secondary incidents (Zhang & Khattak, 2010b). Two kinds of event duration patterns are possible:

- Contained Event Duration: The contained event duration means that the durations of all secondary incidents are contained within primary incident duration, as shown in the Figure 17 *(a)*. As a result, the entire event duration will be equal to the duration of primary incident.
- Extended Event Duration: Extended duration means that the duration of one or more secondary incidents partially overlaps with primary incident duration but extends beyond the duration of primary incident as shown in Figure 17 *(b)*.

Event durations are calculated by first deriving the time gap by calculating the time difference between the start times of the primary and secondary incidents. The time to the end of a secondary incident is equal to the time gap plus the duration of the secondary incident. If the time to the end of the secondary incident is equal to or less than the duration of its primary incident, then this is a contained event, and its duration equals the primary-incident duration. Otherwise, it is an extended event, and its duration equals the time elapsed between the primary incident and the end of the secondary incident or incidents.



(a)



(b)

Figure 17 Illustrations of Contained (a) and Extended (b) Event Durations

7.2 Event Duration Database

To conduct statistical analysis on event durations, several steps were taken to convert the original vehicular incident records into the final event duration data format. Note that the original incident data are vehicle-based records, i.e. every vehicle, involved in an incident, has one record and those involved in the same incident have the same identification number. The steps are:

1. Aggregate multiple vehicular records with the same incident identification number into one incident record. Every record has a unique identification number, and a new variable "number of vehicles involved" was created.
2. Identify primary-secondary incidents based on incident records and link the primary and secondary incidents.

3. Extract primary and secondary incidents from the database and calculate the time gap between primary and secondary incidents.
4. Aggregate incidents into events, with each row having total event duration, primary and secondary incident characteristics, and safety service patrol response information.

The unique event database, created in this study, consists of the following columns:

- *Event Columns* include event durations, and event type (Extended event = 1 or Contained event = 0).
- *Primary Incident Columns* include the characteristics of the primary incident, such as incident identification number, occurrence date, day of the week, start time, incident type, lane blockage, the number of vehicles involved in the incident, segment code and response variables such as detection source, when safety patrol arrived on-scene, and other response agencies such fire department and police presence.
- *Time Gap Columns* contain the amount of time between a primary incident and its first and second secondary incidents.
- *Secondary Incident Columns* contain characteristics of the associated secondary incidents.
- *Weather Column* contains weather conditions at time of incidents such as clear, rain, and snow.
- *Road Geometric Columns* include the road segment information such as length, the number of lanes, if the segment is straight or curved, and ramp information.
- *Traffic Column* includes AADT.

7.3 Statistical Analysis

First, event duration summary and descriptive statistics are provided. To test significant differences between contained and extended event durations, a t-test is performed. Next, to identify correlates of contained and extended event durations, Ordinary Least Squares (OLS) regression models and truncated regression models are separately estimated for a comparative analysis. The OLS regression is selected due to its simplicity and intuitive interpretation of coefficients, while recognizing that event duration data are non-negative and the OLS sometime can give negative predictions. In addition, truncated regression accounts for event durations only being observable above a certain threshold and is conceptually more appropriate. In this case, marginal effects are needed to fully interpret the correlates. Separate models are estimated for 1) all event durations combined, 2) contained events only, and 3) extended events only. The explanatory or independent variables in these models include characteristics of primary and secondary incidents, road geometry, traffic information, and related incident response variables (incident detection source, and the time to arrival of safety service patrol at incident scene). A unique independent variable created in the database and used in the specification is the time gap between primary and its secondary incidents. It represents how soon the secondary incident occurs relative to the start of the primary incident. The detailed model specification is shown in Table 13.

Note that some operational variables such as the presence of various response agencies may have an association with event durations but are not necessarily causal. These variables indirectly indicate the severity of an incident. The inclusion of these variables in a model is not appropriate, yet correlation analysis is used to measure the strength and direction of their association. Statistical software package STATA was used to perform statistical analysis.

Table 13 Model Specification Using Events Database

Variable Name	Description
EventDur	Event duration (minutes)
PriIncType	Primary incident type (Crash = 1, Otherwise = 0)
PriLnBlk%	Primary incident's percentage of lane blockage (0 to 100)
PriNvehs	Number of vehicles involved in primary incident
SecIncType	Secondary incident type (Crash = 1, Otherwise = 0)
SecLnBlk%	Secondary incident's percentage of lane blockage (0 to 100)
SecNvehs	Number of vehicles involved in secondary incident
TimeGap	The time difference from start of primary incident until secondary start (minutes)
OnRamp	On ramp presence (Yes = 1, Otherwise = 0)
AADT/1000	Average annual daily traffic (per 1000 vehicles)
FSPDet	Service patrol vehicle detected incident (Yes = 1, Otherwise = 0)
Time2Pri	Response time for service patrol to primary incident (minutes)
Time2Sec	Response time for service patrol to secondary incident (minutes)
ε	Error term
Model formula	$\begin{aligned} \text{EventDur} = \beta_0 &+ \beta_1(\text{PriIncType}) + \beta_2(\text{PriLnBlk\%}) + \beta_3(\text{PriNvehs}) \\ &+ \beta_4(\text{SecIncType}) + \beta_5(\text{SecLnBlk\%}) + \beta_6(\text{SecNvehs}) \\ &+ \beta_7(\text{TimeGap}) + \beta_8(\text{OnRamp}) + \beta_9(\text{AADT/1000}) \\ &+ \beta_{10}(\text{FSPDet}) + \beta_{11}(\text{Time2Pri}) + \beta_{12}(\text{Time2Sec}) + \varepsilon \end{aligned}$

7.4 Implications

If contained and extended event durations are substantially different, then further exploration of the difference in associated factors will be valuable. The linear and truncated regression models can indicate how incident characteristics and response variables are associated with durations of contained or extended events. Exploration of correlations between event duration and presence of response agencies can illuminate how traffic operators respond to cascading incidents. This can in turn help set up measurable targets for preventing or mitigating the adverse effects of cascading events and provide insights into coordination of responses to these incidents and other operational improvements.

7.5 Results

7.5.1 Summary Statistics for Event Durations

Table 14 presents the summary of event duration on major freeways in Hampton Roads. Independent incidents constitute a majority of the recorded incidents (97.4%), while one-pair events are 2.3% (frequency = 870) and large-scale events are 0.3% (frequency = 107). The average incident duration for single incidents is 14 min, but the duration for an event, including one-pair and large-scale events, are three and five times as long, respectively. These results suggest that single incidents and cascading events should be treated separately to understand (and minimize) the durations of cascading events.

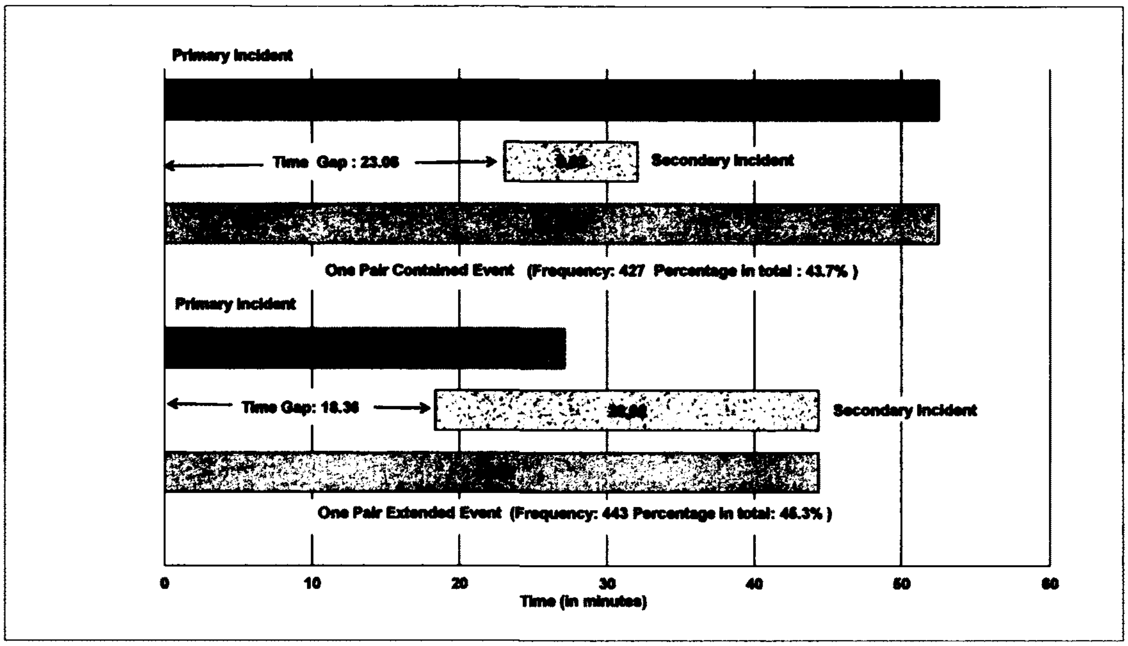
Table 14 Summary Statistics for Various Incident Types

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Total</td><td rowspan="2">Min (minute)</td><td rowspan="2">Max (minute)</td><td rowspan="2">Average (minute)</td><td rowspan="2">Standard Deviation</td></tr>
<tr><td>Count</td><td>Percent</td></tr>
<tr><td>Independent incidents</td><td>Single</td><td>36402[a]</td><td>97.4%</td><td>1</td><td>470</td><td>14.00</td><td>19.00</td></tr>
<tr><td rowspan="3">Cascading Events</td><td>Single-pair</td><td>870</td><td>2.3% (89%)</td><td>1.367</td><td>366</td><td>48.36</td><td>40.83</td></tr>
<tr><td>Large-scale</td><td>107[b]</td><td>0.3% (11%)</td><td>7.65</td><td>416</td><td>76.71</td><td>35.14</td></tr>
<tr><td>Total</td><td>977</td><td>2.6% (100%)</td><td>1.367</td><td>416</td><td>51.47</td><td>43.83</td></tr>
<tr><td colspan="2">Total</td><td>37379</td><td>100%</td><td colspan="4"></td></tr>
</table>

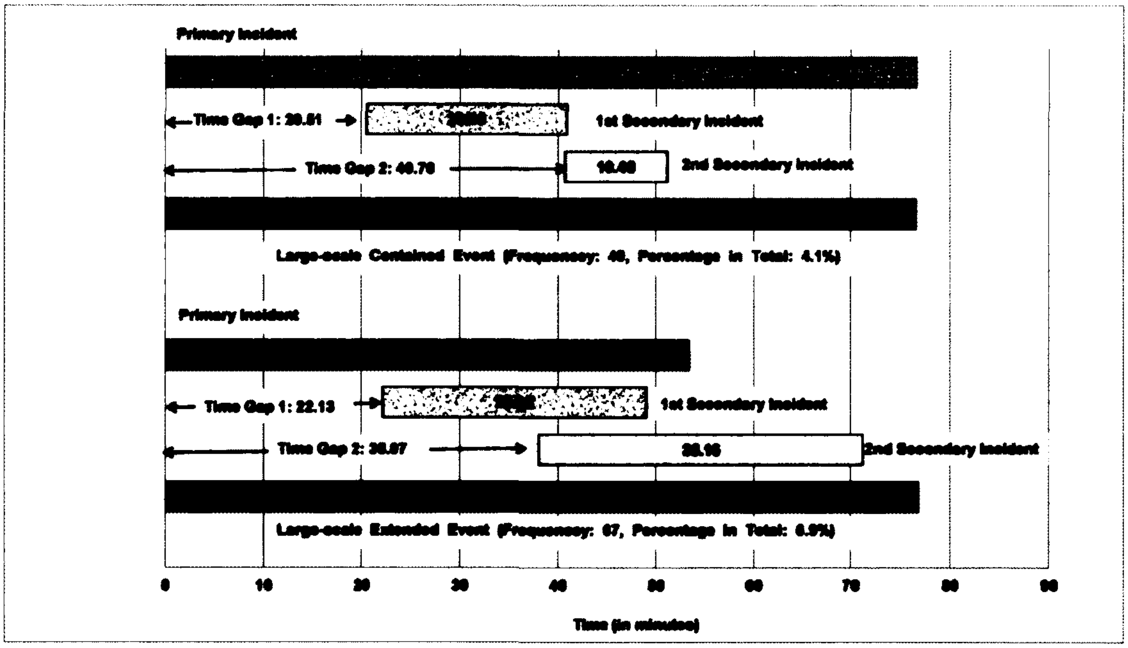
a. Three outlier duration values were removed from the data (1247;1324;1377 minutes)
b. Two extreme duration values were removed from the data (793; 4077 minutes)

7.5.2 Comparison between Contained and Extended Event Durations

The average durations for contained and extended events are shown in Figure 18 *(a)* and *(b)*. The values shown are averages along with frequencies. The one-pair (i.e. primary-secondary incident pairs) contained and extended events break down about equally. The mean event duration for large-scale events (i.e. primary-multiple secondary incident events) is 1.5 times longer than the durations of primary-secondary pairs. The average duration of primary incident for contained events is on average longer than equivalent extended events; while the average duration of associated secondary incidents is usually shorter for the contained events compared with extended events (perhaps the duration of longer primary incident drives the fact that the secondary incidents are contained).



(a)



(b)

Figure 18 Summaries of Contained and Extended Events (a) One- Pair and (b) Large-Scale

To estimate the difference between contained and extended event durations, a two-sample t-test was performed. The one-pair contained event duration is statistically significantly different from extended event durations (t = 2.93, p-value = 0.001), and on average 8 minutes longer. For large-scale event durations, both types of events last about 76 minutes, on average, showing no statistically significant difference (t =-0.01, p-value = 0.98).

7.5.3 Descriptive Statistics for Primary-Secondary Incident Pairs

Table 15 presents the descriptive statistics for incident characteristics, roadway geometry, segment AADT, response variables (incident detection source and response times to primary and secondary incidents), and operational characteristics. The number of observations (observations), the mean value (mean), the standard deviation (SD), and minimum (min.) and maximum (max.) values are reported in the columns for all contained and extended events, respectively. If the primary incident is a crash (typically more severe), then the secondary incident has a higher chance of being contained in it (38.9% for contained events versus 21.2% for extended events). Furthermore, significant differences exist between contained and extended events when a primary-lane blockage occurs, a secondary incident is a crash, a secondary incident blocks lanes, more vehicles are involved in the secondary incident, and the time gap between primary and secondary incidents is longer.

Table 15 also summarizes descriptive statistics for service response and operational variables. Service patrol vehicles detected about 83% of the incidents to which they responded. On average, service patrols were present at a primary incident site about 3 min after detection of the incident. However, it took about 1 min, on average, to arrive at the secondary incident site after the detection, which indicated a prompt response. It seems that, on average, the primary incidents for the contained events are more severe and it takes longer for service patrols to clear them. A fire department responded to about 10% of primary incidents but 6% of secondary incidents in the database. The percentage of primary incidents in which police were present was about 30%, but the percentage of secondary incidents with police involvement was about 16%. Noticeable differences exist in fire department and police presence for contained and extended events. Fire department presence in primary incidents for a contained event was 8% more than for an extended event. Police response to primary incidents for contained events was 18% higher than extended events. However, the fire department and police response to secondary incidents shows otherwise. The fire department responded to about 6% more extended events, and the police were present in about 12% more extended events. Overall, the values seem reasonable, and there are no problematic outliers.

Table 15 Descriptive Statistics for Incident, Roadway, and Response Characteristic in 2005

Variable	Category	Observations	Mean	Std. Dev	Min.	Max.
Event duration (minutes)	All	870	48.4	40.8	1.3	366.0
	Contained	427	52.5	45.2	3	366.0
	Extended	443	44.4	35.6	1.3	259.1
Primary is crash?	All	870	0.299	0.458	0	1
	Contained	427	0.389	0.488	0	1
	Extended	443	0.212	0.409	0	1
Primary Lane blockage (%)	All	870	7.222	17.669	0	100.0
	Contained	427	9.758	21.2	0	100.0
	Extended	443	4.778	12.8	0	66.6
Primary Vehicles involved (number)	All	870	1.393	0.840	1	6
	Contained	427	1.541	0.998	1	6
	Extended	443	1.250	0.622	1	5
Secondary is crash?	All	870	0.188	0.391	0	1
	Contained	427	0.140	0.348	0	1
	Extended	443	0.235	0.424	0	1
Secondary lane blockage (%)	All	870	3.764	12.301	0	100.0
	Contained	427	2.420	10.544	0	100.0
	Extended	443	5.060	13.672	0	100.0
Secondary Vehicles involved (number)	All	870	1.240	0.622	1	7
	Contained	427	1.159	0.458	1	4
	Extended	443	1.318	0.740	1	7
Time-gap (minutes)	All	870	20.7	25.0	0.0	202.4
	Contained	427	23.0	28.5	0.0	202.4
	Extended	443	18.4	20.8	0.0	164.0
On ramp presence?	All	870	0.871	0.335	0	1
	Contained	427	0.867	0.340	0	1
	Extended	443	0.876	0.330	0	1
AADT/(lane*1000)	All	870	21.440	3.747	8.000	29.667
	Contained	427	21.419	3.795	8.977	29.667
	Extended	443	21.460	3.705	8.000	29.667
Service patrol detected?	All	870	0.826	0.379	0	1
	Contained	427	0.808	0.394	0	1
	Extended	443	0.844	0.363	0	1
Response time for service patrol to primary (minutes)	All	870	2.7	7.5	0.0	127.0
	Contained	427	3.5	9.1	0.0	127.0
	Extended	443	2.0	5.5	0.0	62.9
Response time for service patrol to secondary (minutes)	All	870	1.1	3.5	0.0	36.6
	Contained	427	0.6	2.3	0.0	19.25
	Extended	443	1.4	4.3	0.0	36.6
Fire agency presence for primary?	All	870	0.103	0.304	0	1
	Contained	427	0.145	0.353	0	1
	Extended	443	0.063	0.244	0	1
Police presence for primary?	All	870	0.292	0.455	0	1
	Contained	427	0.386	0.487	0	1
	Extended	443	0.201	0.401	0	1
Fire agency presence for secondary?	All	870	0.055	0.228	0	1
	Contained	427	0.023	0.151	0	1
	Extended	443	0.086	0.280	0	1
Police presence for secondary?	All	870	0.155	0.362	0	1
	Contained	427	0.094	0.292	0	1
	Extended	443	0.214	0.411	0	1

7.5.4 Correlations between Event Durations and Operational Responses

Operational responses by the fire department or police presence at an incident site may be associated with longer incident durations, but clearly do not cause longer duration events. The presence of fire department and police reflect a more severe event.

Correlation coefficients between event durations and operational characteristics are reported in Table 16. Specifically, the correlations coefficients, which can range from -1 to +1, indicate that the presence of fire department and police at primary and secondary incidents are correlated positively with longer duration events (although their magnitudes are not high). The presence of fire department and police in the primary incident are more closely associated with longer event durations, perhaps reflecting that they may be tied up with primary incidents than with secondary incidents in contained events. Further, regression analysis between total event duration and response variables showed that if the fire department is present at the scene of the primary incident, then the incident lasts an additional 16.8 minutes, and an additional 9.2 minutes (not statistically significant, 5% level) if the fire department is present at the scene of the secondary incidents. The police variable is also correlated. Regression analysis showed that presence of the state police onsite of the primary incident is associated with 22.2 minutes longer event durations, and if they are onsite for the secondary incident, then the event duration is 13 minutes longer. For a contained event, if fire department and police are present in at the primary incident site, both are statistically significant indication of a longer event. However, their presence on secondary incident sites shows no statistically significant association with event durations. The correlations indicate that for extended events, both incidents play a role and secondary incidents seem to attract more response resources than the contained ones.

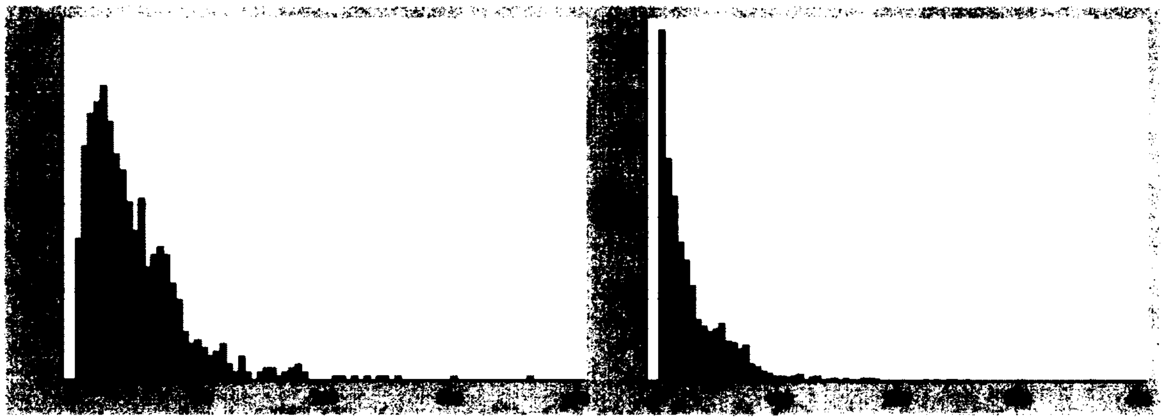
Table 16 Correlations between Event Duration and Operational Response Characteristics

Operational Variables	Event Duration (minutes)					
	All Events		Contained Events		Extended Events	
	Corr.	OLS Coef.	Corr.	OLS Coef.	Corr.	OLS Coef.
Fire agency present for primary?	0.255	16.8**	0.225	18.0*	0.281	15.7**
Police present for primary?	0.333	22.2**	0.255	17.7*	0.420	27.5**
Fire agency present for secondary?	0.144	9.2	0.056	0.1	0.252	9.2
Police present for secondary?	0.200	13.0**	0.087	1.3	0.355	21.3**
Constant		37.6**		42.9**		32.5**
Summary Statistics for OLS Regression Model						
Number of Observations	870		427		443	
Test statistic		F(4,865) =36.62		F(4,422) =9.29		F(4,438) =39.48
Prob. > F		0.0000		0.0000		0.0000
R^2		0.145		0.081		0.265

Note: * P-value <0.10; **P-value <0.05. Corr. represents correlation. The coefficients of OLS regression model are event duration changes for discrete change of dummy variable from 0 to 1.

7.5.5 Regression Analysis

Figure 19 (a) shows the frequency distribution of all event durations, and Figure 19 (b) shows all incident durations for primary and secondary incident pairs (large-scale events involving two or more secondary incidents are not included). The two histograms show somewhat different distributions. Figure 19 (a) indicates a positive skew. The mean and standard deviation for the distribution is 48.4 and 40.8 minutes, respectively. Figure 19 (b) shows a lognormal or log-logistic distribution, with many incidents having small durations. The mean is 28.6 minutes and the standard deviation is 33.2 minutes.



(a) (b)

Figure 19 Duration Histograms for (a) Event Durations (N=870), and (b) Incident Durations of Primary and Secondary Pairs (N=1740)

Three linear and truncated regression models (including their marginal effects) for event duration are reported in Table 17. Note that these models are for primary and secondary pairs, and do not include large-scale events. All models are statistically significant and the R^2 for linear regression and a roughly estimated equivalent R^2 value for truncated regression are reasonable. Note that truncated regression does not provide R^2 and instead an equivalent R^2 is estimated by first correlating and then squaring observed and predicted values. Both models show consistent and similar results. In the total model, the statistically significant and positive correlates of event duration include primary incident being a crash, the secondary incident is a crash, there are multiple vehicles involved in secondary incident, the time gap between the primary and secondary incidents is longer, and the response times for primary and secondary incidents are longer. The marginal effects of the truncated regression model are generally larger than the equivalent OLS model. For example, if the primary incident is a crash, then the event duration is 6.6 minutes longer according to the OLS model, but it is 11.5 minutes longer according to the truncated regression model.

The significant variables (5% level) in the contained and extended duration models are quite different. In the contained event duration model, the statistically significant variables are if the primary incident is a crash, time gap variables, and response times for primary and secondary incidents. The coefficients of significant variables in the contained event duration model generally have larger magnitudes than the equivalent total model. Longer time gaps between primary and secondary incidents are associated with longer event durations. Generally, the characteristics of primary incidents are dominant in the contained event duration model. For extended events, significant associations are observed when the secondary incident is a crash, the number of vehicles involved in secondary incidents, and time-gap; interestingly, secondary incident characteristics have larger magnitudes than primary incident characteristics. For example, if the secondary incident is a crash, then the event duration is lengthened by 14 minutes (according to the OLS model) or 19 minutes (according to the marginal effects in the truncated regression model). If one additional vehicle is involved in an incident, this would be associated with about 5 minute longer event durations in the extended event model (this variable is not statistically significant in the contained event model).

Table 17 Event Duration Regression Models Using 2005 Hampton Roads Incident and Road Inventory Data

Independent Variables	Total Models					Contained Event Models					Extended Event Models				
	OLS		Truncated			OLS		Truncated			OLS		Truncated		
	Coef.	P-value	Coef.	P-value	Marg. Effect	Coef.	P-value	Coef.	P-value	Marg. Effect	Coef.	P-value	Coef.	P-value	Marg. Effect
Primary is crash?	6.625	0.018**	11.443	0.001**	9.976	7.999	0.024**	14.667	0.001**	13.153	3.429	0.431	6.687	0.267	5.734
Primary lane blockage (%)	0.057	0.333	0.075	0.450	0.065	0.105	0.148	0.152	0.205	0.135	-0.093	0.408	-0.199	0.157	-0.168
# of vehicles involved in primary	-1.461	0.279	-1.393	0.403	-1.195	-2.063	0.210	-2.087	0.270	-1.857	-0.183	0.945	-0.127	0.972	-0.107
Secondary is crash?	9.134	0.005**	14.346	0.010**	12.687	3.204	0.593	4.055	0.672	3.640	14.483	0.000**	21.852	0.002**	19.215
Secondary lane blockage (%)	0.083	0.304	0.078	0.524	0.067	-0.002	0.986	-0.057	0.678	-0.051	0.137	0.169	0.174	0.279	0.147
# of vehicles involved in secondary	4.626	0.023**	6.169	0.029**	5.292	5.050	0.278	7.452	0.266	6.630	4.919	0.027**	6.246	0.038**	5.269
Time-gap (minutes)	1.150	0.000**	1.370	0.000**	1.175	1.211	0.000**	1.399	0.000**	1.244	1.030	0.000**	1.299	0.000**	1.096
On ramp presence?	0.312	0.907	0.220	0.956	0.189	2.677	0.494	3.986	0.520	3.512	-2.550	0.487	-4.004	0.403	-3.422
AADT/(lane*1000)	0.260	0.282	0.495	0.259	0.424	0.212	0.547	0.275	0.642	0.245	0.250	0.448	0.571	0.378	0.482
Service patrol detected?	-1.068	0.689	-2.441	0.625	-2.107	-3.312	0.393	-4.681	0.440	-4.200	1.616	0.663	1.713	0.929	0.601
Response time for service patrol to primary (minutes)	0.394	0.002**	0.574	0.009**	0.492	0.361	0.023**	0.526	0.066*	0.468	0.508	0.035**	0.704	0.007**	0.594
Response time for service patrol to secondary (minutes)	0.546	0.035**	0.824	0.008**	0.706	1.341	0.019**	1.852	0.060**	1.648	0.392	0.164	0.645	0.035**	0.544
Constant	9.979	0.149	-17.085	0.155		11.034	0.293	-13.391	0.428		8.759	0.369	-18.758	0.295	
Summary Statistics															
Number of observations	870					427					443				
Test statistic	F(12,857) =105.05		Wald chi2(12) = 326.77			F(12,414) =64.07		Wald chi2(12)=264.32			F(9,500)=40.45		Wald chi2(12)=191.03		
Prob. > F / Waldchi^2	0.000		0.000			0.000		0.0000			0.0000		0.0000		
R^2 / Equivalent R^2	0.595		0.562			0.650		0.553			0.530		0.532		

Note: * p<0.10; ** p<0.05

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Longer response times are generally associated with longer event durations, as expected. Interestingly, longer response times to secondary incidents have relatively larger coefficients in the total model and the contained event model. This implies that response times are more critical in such situations.

Overall, primary incident characteristics are dominant in contained incident events. They usually have long durations and involve more severe situations, requiring more response resources. The contained secondary incidents are less severe, on average. For extended events, both primary incident and secondary incident characteristics play a substantial role. The duration of primary incident is relatively shorter and the secondary incidents are longer and more severe, requiring substantial resources from response agencies.

7.6 Limitations

A limitation of the study is the model specification; some of the excluded variables can have a strong association. The number of personal injuries and the number of vehicles responding from each agency could be important factors in event duration, but were not available in the database obtained. Furthermore, accurate physical location for each incident was not available in 2005 dataset, so the distance between primary and secondary incident was unknown and therefore spatial effects could not be fully investigated. Future research can focus on validation of the secondary incidents, and estimation of alternative event duration models, e.g., hazard-based models and examining the traffic impacts of contained and extended events.

7.7 Summary

The analysis contributes by analyzing cascading event durations. A unique event database is created, based on incident and road inventory data. One pair events (one primary and one secondary incident) and large-scale events (one primary and multiple secondary incidents) are identified and analyzed. Incident events are categorized as either contained or extended, and rigorous statistical methods are applied to explore associations with incident characteristics and response variables. The major findings are summarized as follows:

- The average incident duration for single incidents in Hampton Roads is 14 minutes but the duration for an event including one-pair and large-scale events, are three and five times longer, respectively.
- Contained and extended events show different characteristics and operational response patterns. For instance, one-pair contained events are on average 8 minutes longer than extended events. For large-scale event durations, both types of events last about 76 minutes in Hampton Roads, on average.
- Factors associated with longer cascading event durations include the primary incident being a crash, secondary incident being a crash and multiple vehicles involved in secondary incidents, and longer time gap between the primary and secondary incidents. In addition, longer event durations were associated with longer service patrol response times. While police and fire presence was associated with longer event durations, they would not be necessarily adding time because these incidents were likely more severe.

- Primary incident characteristics are dominant in contained events, while secondary incident characteristics play a substantial role in extended events, requiring substantial resources from response agencies.

The new findings have implications for incident management. Efforts must continue to minimize the occurrence and severity of cascading events. First, new event-based performance measures can be used by incident management agencies for planning purposes. The information provided in this paper can help traffic operations agencies identify problematic road segments, where such events occur, and develop realistic targets, e.g., to reduce not only incident durations but also event durations by a certain percentage over a period of time. Second, in the context of tighter transportation budgets and reduced levels of service patrols, the findings suggest that locations where cascading events occur should be spared from cutting service, and if possible more service response resources should be considered in such locations. Operationally, when severe secondary incidents occur, more response resources should be quickly devoted to the secondary incident site. Third, quick clearance can reduce the potential for incidents from cascading. For example, if detailed investigation of a minor accident can result in significant congestion and potentially a more serious secondary incident, then police and traffic operations should coordinate efforts to quickly clear the accident. Finally, further research is needed into preventing large-scale cascading events, e.g., by implementing quick clearance procedures, disseminating dynamic and detailed information about primary and secondary incidents to upstream travelers through a variety of sources, and close coordination between responding agencies.

CHAPTER 8

EVALUATING QUEUING DELAYS ASSOCIATED WITH SECONDARY INCIDENTS

Incidents cause substantial travel delays on urban freeways. To evaluate the effectiveness of potential incident management strategies and predict incident-induced traffic impact, travel delays are typically calculated for incidents by using deterministic queuing, shock wave analysis or simulation tools. Most existing methods treat every incident independently and use average incident durations for each type to estimate incident delay. However, not all incidents are independent as one incident can cause secondary incidents due to its queue backup. The total delays of primary and secondary incidents interacting in time and space would be different than a simple aggregation of delays caused by two isolated incidents. Available models to estimate traffic delays for primary-secondary incidents pairs may not be used directly since they cannot capture the interactions associated with these multiple incidents (Zhang et al., 2011). This analysis examines the total delays induced by primary-secondary incident pairs by jointly modeling their occurrences. The following research questions are addressed: What are the critical attributes of primary-secondary incident pairs? What are the differences in delays when primary and secondary incidents are analyzed separately versus jointly? What factors are associated with longer delays resulting from primary and secondary incidents, e.g., longer time gaps, longer distance between the primary and secondary incidents, the lane blocked by a secondary incident, demand levels? What are the implications for mitigating congestion induced by multiple associated incidents?

8.1 Critical Factors Affecting Total Delays

To quantify vehicle delays caused by an incident, several key input parameters are needed. These include incident duration (the time period from the occurrence of the event to the clearance of the incident), traffic demand (arrival rates), and normal and reduced capacities. On the other hand, to quantify the total delays of both secondary and primary incidents and to model them jointly, two additional key parameters need to be considered: Time gap and distance between the two incidents. These are important because queuing delays depend on where (along the road) and when capacity and demand changes. Clearly, for an incident to be considered as secondary, it needs to be related to/caused by the primary incident. Therefore, for incidents occurring in the same direction of the highway, the distance between the two incidents should be within the extent of the (spatial) queue length of the primary incident. In terms of the time gap between the occurrence and clearance times of the two incidents, there are two main cases to be considered. Time gap is defined as the period between primary and secondary incident occurrences, which represents how soon the secondary incident happens after its primary incident.

Adopting the definitions of contained and extended events illustrated in Figure 17, any primary-secondary incident pair can be categorized into one of these two types of events. For a contained event, the secondary incident is cleared before the primary incident ends. Its duration is contained entirely within the duration of the primary incident. For an extended event, the secondary incident is cleared after the primary incident ends. Therefore, the total event duration is extended beyond the duration of the primary incident. In addition, it is possible that the secondary incident can even occur after the primary incident ends since the queue of the primary incident dissipates after a certain time period beyond the primary incident is cleared.

8.2 Kinematic Wave Interoperation

To gain a theoretical understanding of the impacts of time gap and distance between primary and secondary incidents on total delays, the shock wave analysis is employed to demonstrate how a primary-secondary incidents pair influences traffic flow on a basic freeway section shown in Figures 20-21. To illustrate the main points, several assumptions are made to simplify the presentation. For example, arrival and departure rates are assumed to be constant over certain time periods, and incident-reduced capacities for both incidents are the same.

Another important assumption is conservation law. It simply states that vehicles cannot be created or lost in a highway without entering and exiting traffic. For stationary traffic with smooth flow q and density k, based on conservation law, to ensure that the rates of variation of flow and density in space x and time t are consist with the no entering/leaving traffic hypothesis, the conversation equation can be formulated as below (Daganzo, 1997):

$$\frac{\partial q(t,x)}{\partial x} + \frac{\partial k(t,x)}{\partial t} = 0 \tag{5}$$

Based on the conversation law, the velocity of an interface separating two (t, x)-regions with different stationary traffic states can be further developed in the shock wave analysis.

A triangular relationship between flow and density and several traffic states are shown in Figure 20. Letters correspond to different traffic states. Given a primary incident having occurred in the right lane, its secondary incident occurs within or in the end of primary incident queue and blocked the same lane as its primary incident. This scenario is illustrated for a three-lane freeway section.

The corresponding time-space diagram is shown in Figure 21 according to the flow-density relation and traffic states defined in Figure 20. The continuous light lines are waves and the dark continuous lines represent the interfaces between the traffic states which vehicles pass through. The numbers represent the vertexes and are used to mark the area for delay calculation. D_s denotes the distance between the primary and secondary incidents. T_g is called time-gap. It is the time difference between start times of a primary incident and its secondary incident. Primary incident starts at T_{1s}. After the primary incident have lasted T_g, the secondary incident occurs at T_{2s} and ends at T_{2e}. If this primary-secondary pair is a contained event (i.e. $T_{2e} <= T_{1e}$), the primary incident will be the active bottleneck during the event, the secondary incident does not cause any extra delays. When a secondary incident lasts longer (i.e. $T_{2e} > T_{1e}$), the event becomes an extended case and its overall impact gets complicated. At the very beginning of the extended event (i.e.$T_{2e} <= T_{2i}$), similar to the contained event, the secondary incident just keeps the same speed of queuing propagation induced by primary incident and does not cause any additional delay. When $T_{2e} > T_{2i}$, the secondary incident starts to cause additional congestion, so the total delay induced by this extended event is greater than the total delay of the primary incident. The magnitude of the extra delay depends on the length ofT_{2e}-T_{2i} and on the distance between two incidents.

Based on Figure 20 and 21, for traffic states A and B, the interface velocity U_{AB} is given by:

$$U_{AB} = \left| \frac{q_B - q_A}{k_B - k_A} \right| \tag{6}$$

Where q_A, q_B represent the flows and k_A, k_B are the densities for the states A and B respectively.

The total travel time for any homogeneous time-space region in Figure 21 can be found by multiplying its area by its density. The total delays caused by the incidents over the time-space region upstream of the incidents can be determined as follows:

$$\begin{aligned} TotalDelay\,s &= Area\ of\ 12568 \times (k_B - k_A) + Area\ of\ 2345 \times (k_C - k_A) \\ &+ Area\ of\ 678 \times (k_C - k_A) + Area\ of\ 4567 \times (k_{C1} - k_A) \end{aligned} \tag{7}$$

Where k_A, k_B, k_C and k_{C1} are the densities for each traffic states.

Let $T_5 = T_g + D_2$, where D_2 is the duration of secondary incident; and

$\alpha = \dfrac{w}{w - U_{AB}}$, where w is the wave velocity shown in Figure 20.

D_1 denotes the primary incident duration. Ds denotes the distance between primary-secondary incidents.

After expressing the areas of each homogeneous segment in terms of the known quantities, and substituting T_5, α, k_A, k_B, k_C and k_{C1} into equation (7), the following expression is obtained:

$$\begin{aligned} TotalDelay(T_5, D_s) &= \left[\frac{w \times (\alpha - 1) \times (k_B - k_A)}{2} + \frac{((\alpha - 1)\alpha w U_{AB} + (\alpha - 2)\alpha v w + v w) \times (k_C - K_A)}{2v} \right] \times {T_5}^2 \\ &+ \left[-\alpha \times (k_B - K_A) + \frac{((3 - 2\alpha)\alpha U_{AB} w + (3 - 2\alpha)\alpha v w + 2(\alpha - 1) v w - (\alpha - 1) w^2) \times (k_C - K_A)}{2wv} + (k_A - k_{C1}) \right] \times T_5 D_s \\ &+ \left[D_1 \times (k_B - k_A) + \frac{2\alpha U_{AB} (k_C - k_A)}{2vw} - D_1 \times (k_A - k_{C1}) \right] \times D_s \\ &+ \left[\frac{(\alpha + 1) \times (k_B - k_A)}{2w} + \frac{(-\alpha^2 U_{AB} + 2\alpha v - \alpha^2 v - w + \alpha w + v) \times (k_A - k_C)}{2vw} - \frac{(k_A - k_{C1})}{w} \right] \times {D_s}^2 \end{aligned} \tag{8}$$

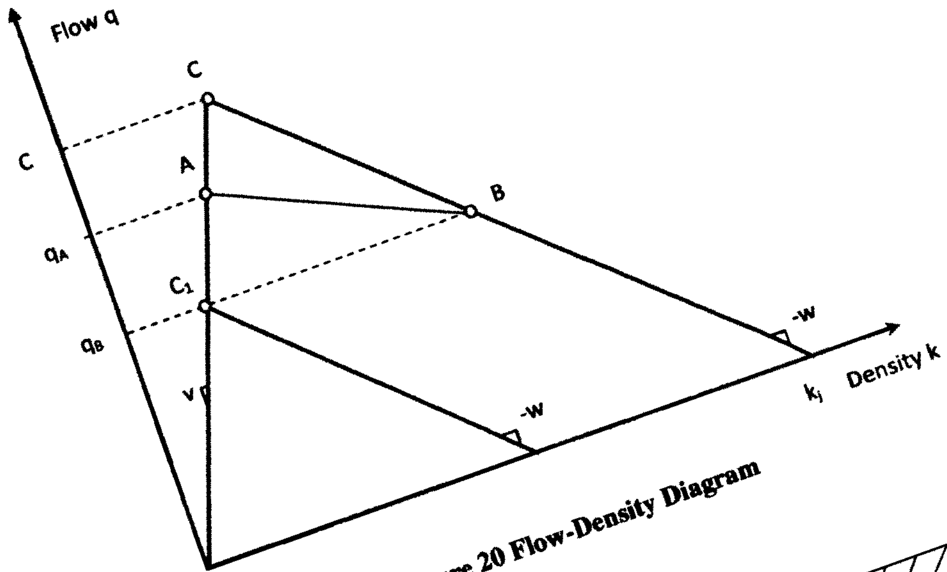


Figure 20 Flow-Density Diagram

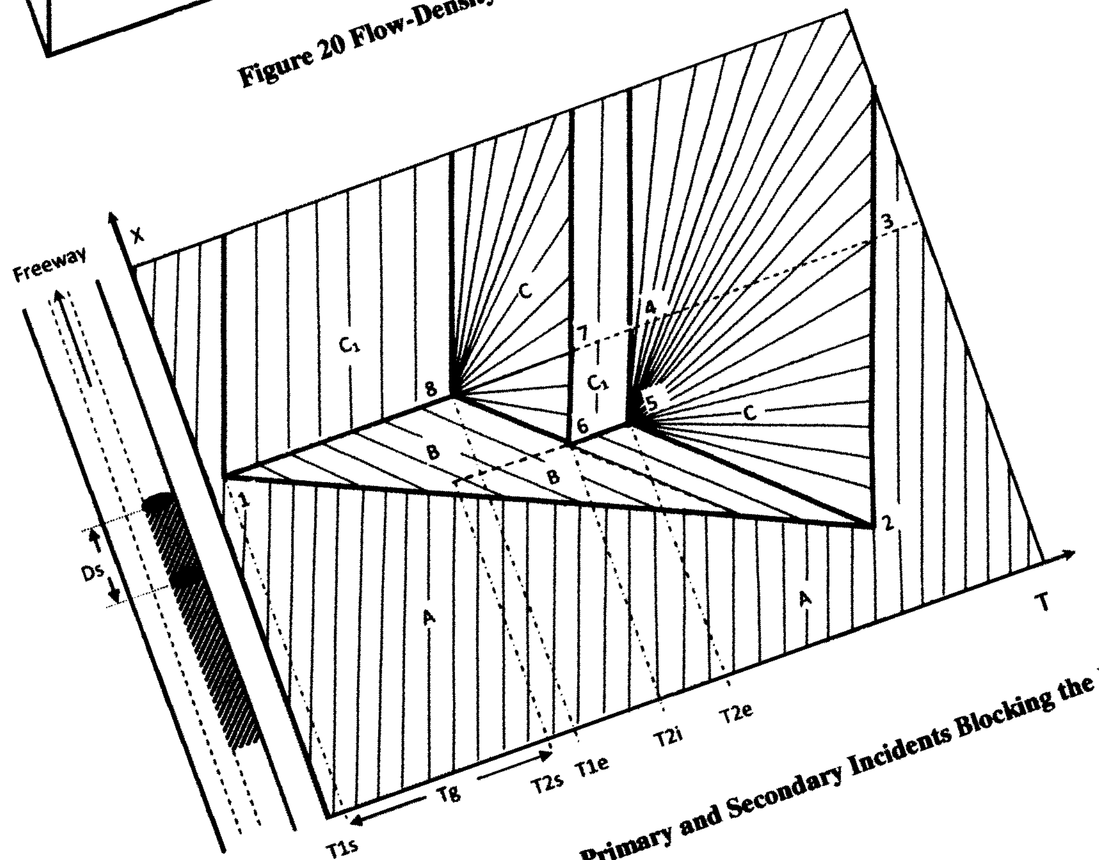


Figure 21 Time-Space Diagram for Primary and Secondary Incidents Blocking the Right Lane

Given a demand level q_A, free flow speed, normal and reduced capacities, jam density, and the durations for primary and secondary incidents, time-gap and distance are two variables affecting the total delay in the equation (8). Considering the complexity of this second-order equation, the total delays can be evaluated by varying these two variables. For demonstration purposes, a three-lane freeway facility with a free-flow speed of 60 mph is selected. Both primary and secondary incidents last half an hour and block the right lane. The remaining capacity is assumed to be 49% of the total capacity, which is adopted from HCM 2000. The capacity and jam density are obtained from microscopic simulator PARAMICS, which is used to conduct further analysis analyses. The time-gap will be constrained within one to thirty minutes while the distance will be confined in the range from 165 feet to 5280 feet. With these input parameters, equation (8) is implemented in Matlab software to calculate total delays. The variation of total delay over time-gap and distance is plotted in Figure 22. The constant horizontal plane represents the simple sum of total delays of the primary and secondary incidents.

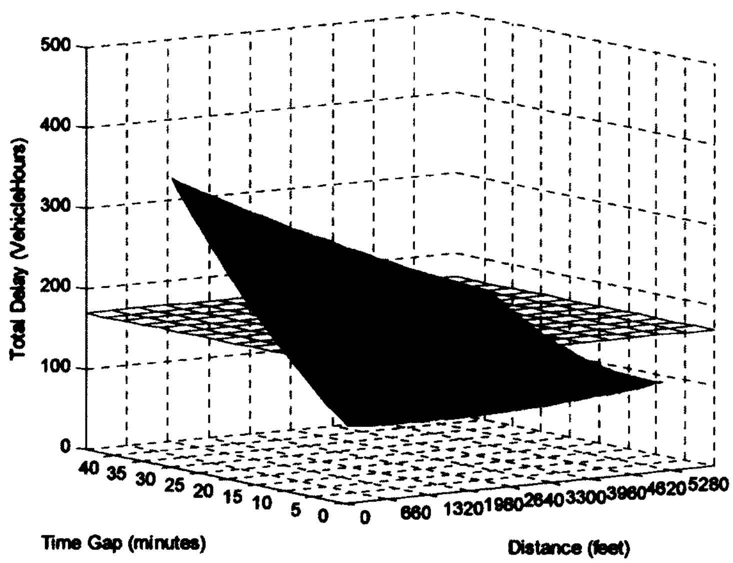


Figure 22 Total Delays as a Function of Time Gap and Distance

As it can be observed in Figure 22, the total delay increases with increasing time gap and decreasing distance between the primary-secondary incidents. Depending on the values of these two factors (i.e., time gap and distance), the total delay is either higher or lower than the simple sum of delays of two independent incidents that have the same characteristics. As explained above, this sum is indicated by the horizontal mesh that is parallel to the time gap - distance plane in Figure 22.

To summarize, if the primary and secondary incidents are treated and analyzed independently, then the total delay contributed by these two incidents will be the simple summation of the delays calculated for primary and secondary incidents separately. This simple aggregation cannot capture the spatial and temporal interactive effects caused by primary and secondary incidents and result in overestimation or underestimation as illustrated in Figure 22. Thus, it can be concluded that time gap and distance between two associated incidents play a critical role in accurately estimating total delays of primary and secondary incidents. This is further demonstrated in microscopic simulations conducted in this study. The main objectives of this study are:

a) To evaluate how total incident delay is impacted by the relative time and distance between the primary and secondary incidents.
b) To analyze the extent to which the delays would be over or under estimated if primary and secondary incidents are modeled independently (i.e., without considering the interactions of their queues in time and space).

To answer these research questions, a systematic approach is taken to model the scenarios that will likely be encountered in the real world as explained in the following section.

8.3 Methodology

In order to evaluate how different factors contribute to the total delays caused by secondary incidents, a number of scenarios need to be developed. First, based on historical incident data, primary-secondary incidents are identified, and their characteristics are investigated. Based on the summary statistics of primary and secondary incidents, various scenarios are designed and tested in a microscopic simulation environment. After considering several popular simulation tools and their capabilities of modeling incidents, PARAMICS (2009) was selected for this study. PARAMICS is a widely used microscopic simulation tool, which provides a comprehensive incident module. An incident can be created by specifying where it occurs on the link, when it starts and ends, how many lanes are blocked and the average passing speed of vehicles passing by the incident site, etc.

8.3.1 Analysis of Historical Incident Data

To get an understanding of how time gap varies and of the durations of primary and secondary incidents in the real world, the 2005 incident database of Hampton Roads (HR) in Virginia is analyzed. The database was obtained from the HR Traffic Operations Center and the incidents were geo-referenced. Secondary incidents were identified as those occurring in the same direction as the primary incident and within the duration of the primary incident by using the queue based method (Zhang & Khattak, 2010a). Summary statistics for primary incident duration, secondary incident duration, and the time gap between them are provided in Table 18. Based on these results, the number of extended incidents is slightly larger (245) than contained incidents (213). The durations of both primary and secondary incidents are similar (about 27 minutes) for the extended case, whereas the durations of secondary incidents for the contained case are very short (8.7 minutes, on average). The average time gap for contained incidents is slightly longer (22 minutes) than extended incidents (18 minutes).

For contained events, the percentage and the mean for lanes blocked by primary incidents are about 20% (=42/213) and 1.48, respectively. Furthermore, the secondary incidents show that in 5% of the cases there is lane blockage (11/213); the mean number of lanes blocked in these cases is 1.18. Clearly, the contained secondary incidents are not very severe. On the other hand, for extended events, 12% of (29/245) primary incident cases show lane blockage with a mean of 1.10. The equivalent for extended secondary incident cases is 14% (34/245) with 1.20 lanes blocked, on average. Clearly, for contained events, more lane blockage severity and frequency are observed for primary incidents and less for the secondary incidents. However, nearly equal lane blockage severity and frequency of primary incident and secondary incident are observed for extended events. These results were used to guide simulation scenarios.

Table 18 Primary-Secondary Incident Pair Attributes for 3-Lane Freeway Segments in Hampton Roads During 2005

Variables	Observations	Mean	Standard Deviation	Min	Max
Contained Incidents					
Primary incident duration(minutes)	213	50.61	42.32	4	244
Time gap (minutes)	213	22.05	27.21	0.15	167.82
Secondary incident duration (minutes)	213	8.72	11.90	1	70
Lanes blocked by primary	42	1.48	0.71	1	3
Lanes blocked by secondary	11	1.18	0.60	1	3
Extended Incidents					
Primary incident duration (minutes)	245	27.00	22.89	1	118
Time gap (minutes)	245	17.84	19.00	0.017	87.52
Secondary incidentduration(minutes)	245	26.63	26.54	1	175
Lanes blocked by primary	29	1.10	0.31	1	3
Lanes blocked by secondary	34	1.20	0.47	1	3

8.3.1 Simulation Network

A 6-mile section of a three-lane freeway with 60 mph free flow speed was created in PARAMICS as the experimental network. Only one direction traffic flowed on this facility with a single mainline entrance and exit. Most of the default parameters within PARAMICS were kept the same except all vehicles were set to be passenger cars.

8.3.2 Capacity Reduction Due to an Incident

To estimate incident-induced total delays the capacity of the bottleneck created due to the incident needed to be determined. In all the scenarios considered in this paper it was assumed that only one lane is blocked. According to Exhibit 22-6 in HCM 2000, when one lane in a three-lane facility is blocked, the reduced capacity is only 49% of the original roadway capacity. An even higher reduction was reported based on Hampton Roads traffic data (Smith at al., 2003). The incident reduced capacity and normal capacity cannot be directly defined in microscopic simulators. By measuring traffic throughput from several traffic counters as capacity, Hadi et al. (2007) simulated reduced capacities in several micro-simulators and found that, by using default parameter settings, they are lower than the reduction factors reported in the HCM 2000 for a one-lane-blocking incident on a three-lane freeway segment. Therefore, for this study, it was necessary to calibrate the models to match the specified capacities in HCM 2000. Since PARAMICS parameter "passing speed" near incident site is related to the remaining capacity, a sensitivity test was conducted to examine the relationship between reduced capacities versus a set of passing speeds.

To obtain a reasonable capacity value, the passing speed was adjusted iteratively to keep the reduced capacity in line with the value suggested in HCM 2000. Various tests of passing speed near an incident site versus reduced capacities were performed in PARAMICS. Ten random seeds were selected to run the simulations under a high constant demand: 5000 vehicles per hour. The simulated incident with one-hour duration blocked the right lane in a three-lane basic freeway section. Three detectors were located downstream, nearby this incident site to measure the pass-through traffic as the reduced capacity. The relationship in Figure 23 is the best estimate of how the capacity depends on the passing speeds. Each point represents the average capacities from the ten random seeds. The error bar corresponds to one standard deviation. The average capacities show upward trends with increasing passing speeds. The capacity increases dramatically when the passing speed is increased in the low end (i.e. 10, 15, 20 mph) and then it increases with a decreasing rate as passing speeds become larger (i.e. 25, 30 mph). When passing speed is 15 mph, the reduced capacity is closest to the 49% remaining capacity. After selecting an appropriate passing speed, two sets of simulations will be conducted for contained and extended cases.

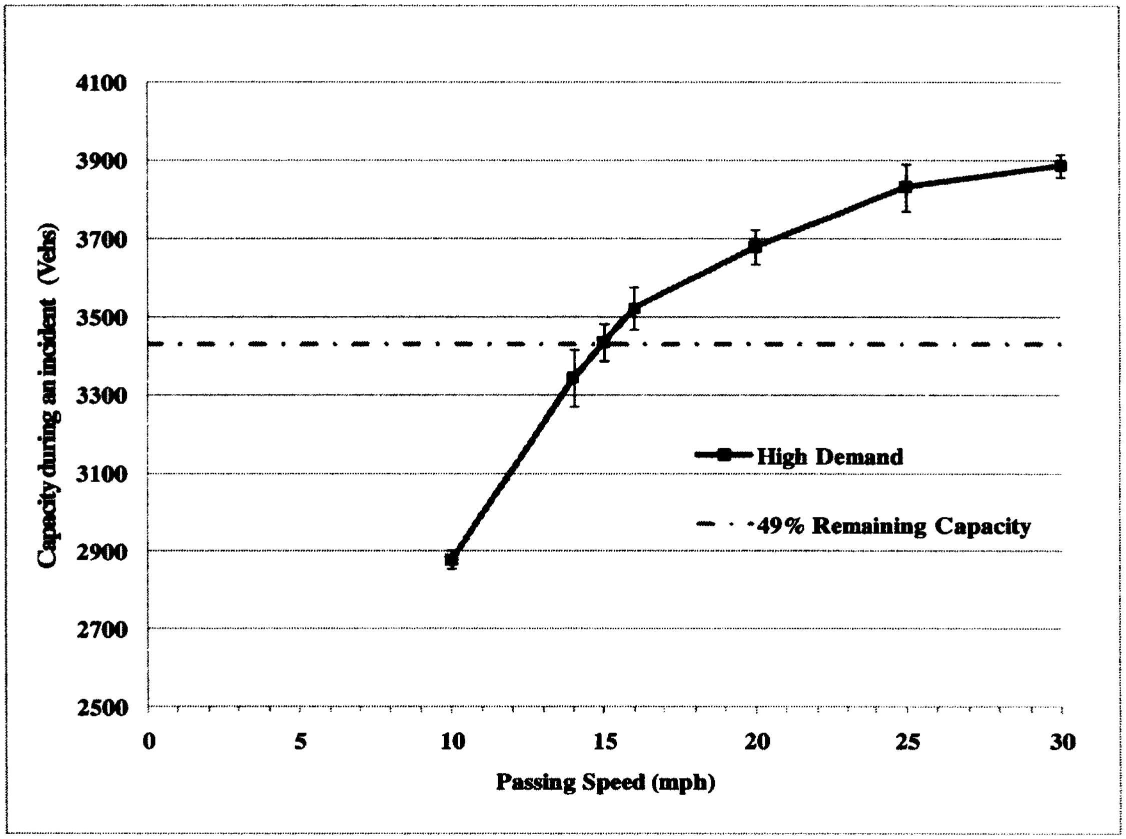


Figure 23 Incident Remaining Capacity vs. Passing Speed

After selecting an appropriate passing speed that closely matched HCM2000 capacity reduction, two sets of simulations were conducted for contained and extended cases.

8.3.3 Design of Scenarios

To assess the impacts of primary-secondary incidents in simulation, numerous scenarios were designed to represent the incident blockage and traffic demand fluctuations. The scenarios were partly based on analysis of real-life incidents in Hampton Roads (presented in Table 18). To allow traffic to be restored to normal flow after primary-secondary incidents, all the simulations were run for 3 hours. The scenarios were designed to consider all combinations of the variables: demand, time gap, and spatial distance. The basic assumption of secondary incident occurrence is that the physical location of the secondary incident is always inside or near the end of queue of the primary incident. To capture the spatial queuing extension caused by primary incident, the primary incident was simulated first and maximum queue length was obtained by post processing. The secondary incidents simulated here were located within or near the end of the queues caused by the primary incidents. Note that the queue length depends on simulation random seeds, traffic demand level and lane-blockage severity. In some cases, for a small time gap, the queue induced by primary incident may not reach far enough to the designated location of secondary incident when secondary occurs.

The scenarios analyzed here are grouped by whether the secondary incident is contained within the primary or it extends beyond the duration of the primary, as illustrated in Figure 17. In addition, two levels of demand are considered: a moderate demand of 4,000 vehicles per hour and a high demand of 5,000 vehicles per hour. Common parameters in all incident scenarios included:

- The primary incident always occurs 30 minutes after the simulation starts
- Both primary and secondary incidents block only one lane, but secondary incident blocks the right lane or middle lane.

The details of simulation scenarios are presented in Table 19. The incident durations and time gaps were selected to be close to the values reported in Table 16. For the distance between the two incidents, eight values were considered: 660 feet (~1/8 miles),1320 feet (~1/4 miles), 1980 feet (~3/8 miles), 2640 feet (~1/2 miles), 3300 feet (~1/2 miles), 3960 feet (~6/8 miles), 4620 feet (~7/8 miles), and 5280 feet (~1 miles). Similarly, time gaps were increased from 5 to 30 minutes at 5 minutes incremental interval.

Based on the parameter combinations in Table 19, a total of 192 simulation scenarios were designed. Each simulation case was run ten times with different speeds, so the total number of simulation runs was 1,920. The results were averaged to account for random variations in simulations. After simulating with and without incident conditions, the incident-induced total delay is calculated by differencing travel times observed in two cases (with and without incidents) for all vehicles that traveled during the simulation.

Table 19 Scenarios for both Contained and Extended Incidents and Their Parameters

	Incident Durations (in minute)			**Incident Locations**		**Correlations**	
Demand (veh/hour)	Event Type	Primary	Secondary	Primary	Secondary	Time Gap (minutes)	Distance (feet)
4000 or 5000	Contained	45	15	Right Lane	Right Lane	5, 10,15, 20, 25,30	660
							1320
							1980
							2640
	Extended	30	30				3300
							3960
							4620
							5280

8.4 Simulation Results

The analysis of the total delays for primary-secondary incident pairs based on the micro-simulation results is discussed in the next two subsections. For contained and extended events, two tables (Table 20 and 21) with the same structure are presented based on two-levels of demands. The "Correlation Parameters" column in the table lists the time gaps and distances between primary and secondary incidents. The "Total Vehicles Delay" column presents the delay results derived from two methods. The "Sum of two Incidents" column has only two aggregated values when two incidents are analyzed as independent events, regardless of their correlations. Their values are equal to the summation of the total delays of primary and secondary incidents derived from two separate simulations under two demand levels. The "Joint Analysis" column presents the simulation results when primary and secondary incidents are modeled concurrently in the same simulation run to capture the interactions of primary-secondary incidents. The two sub-columns list the results under two different demand levels. The last column contains the percentage change of joint analysis results compared with the result in the "Sum of two Incidents" column. In addition, the simulations results for each case are displayed in two 3D plots (Figures 24-25). The results are discussed below.

8.4.1 Analysis of Total Delay for Contained Primary-Secondary Incident Pairs

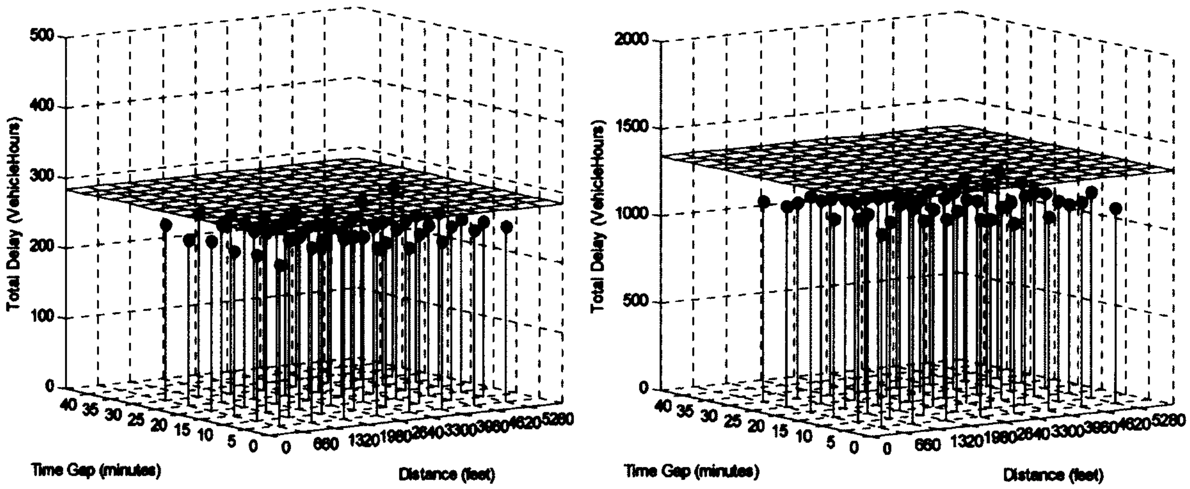
For contained events, the simulated total delays under two demand levels are presented in Table 20. Figure 24 displays the total delays over time-gaps and distances in 3D plots. Based on these presentations, it is evident that the total delay increases substantially (up to five times) as the demand increases from 4000 vph to 5000 vph. So the demand level is a critical contributor to the total delay.

In comparing results from two methods (i.e. sum of two separate incidents versus the joint analysis), total delays do not change substantially as time-gap and distance vary in the defined range because the secondary incident is contained within its primary incident. In other words, the primary incident governs the bottleneck. In term of the percentage change, the simulated total delay is less than the simple summed delay about -19% to -5%. The magnitude is comparable to percentages of secondary incident in total delay 13% (i.e. 37/284) for moderate demand and 14% (189/1343) for high demand. The variations are similar to the level of the random variation within simulations. The results imply that the secondary incident in a contained case does not induce additional delays. So, their delays should not be counted in determining the overall delays. Therefore, the traditional method (i.e. simple summation of the delays of two separate incidents) over-estimates the actual delay induced by a contained case.

Table 20 Simulation Results for Contained Primary-Secondary Incident Pairs (Ten Random Seed with Incident Passing Speed 15 Mph)

Correlations		Total Vehicle Delay (veh-hr)			Comparison of Total Delays	
Parameters		Sum of two Incidents	Joint Analysis		(%) Difference (with the sum of two incidents)	
Time Gap (minute)	Distance (feet)	Primary (45 minutes) Secondary (15 minutes)	Moderate Demand (4000veh/hr)	High Demand (5000 veh/hr)	Moderate Demand (4000 veh/hr)	High Demand (5000 veh/hr)
5	660		230	1109	-19.1	-17.4
	1320		250	1239	-12.0	-07.8
	1980		256	1159	-09.9	-13.7
	2640		240	1134	-15.5	-15.6
	3300		235	1097	-17.3	-18.3
	3960		239	1111	-15.9	-17.3
	4260		249	1178	-12.3	-12.3
	5280		249	1122	-12.3	-12.3
10	660		237	1169	-16.6	-13.0
	1320		253	1136	-10.9	-15.4
	1980		248	1123	-12.7	-16.4
	2640		249	1156	-12.3	-13.9
	3300		234	1087	-17.6	-19.1
	3960		242	1200	-14.8	-10.7
	4260		247	1154	-13.0	-14.1

	5280		250	1183	-12.0	-11.9
	660		235	1136	-17.3	-15.4
	1320		256	1145	-09.9	-14.8
	1980		246	1187	-13.4	-11.6
	2640		254	1132	-10.6	-15.7
15	3300	247+37 =284 under moderate demand (4000veh/hr)	236	1170	-16.9	-12.9
	3960		241	1109	-15.2	-17.4
	4620		241	1176	-15.2	-12.4
	5280		246	1085	-13.4	-19.2
	660		241	1236	-15.2	-08.0
	1320		261	1207	-08.1	-10.1
	1980		251	1190	-11.6	-11.4
	2640		247	1165	-13.0	-13.3
20	3300	1154+189 =1343 under high demand (5000veh/hr)	236	1150	-16.9	-14.4
	3960		237	1117	-16.6	-16.8
	4620		241	1091	-15.2	-18.8
	5280		248	1191	-12.7	-11.3
	660		236	1154	-16.9	-14.1
	1320		253	1171	-10.9	-12.8
	1980		239	1134	-15.9	-15.6
25	2640		248	1153	-12.7	-14.2
	3300		239	1114	-15.9	-17.1
	3960		239	1140	-15.9	-15.1
	4620		233	1156	-18.0	-13.9
	5280		237	1152	-16.6	-14.2
	660		250	1152	-12.0	-14.2
	1320		261	1127	-08.1	-16.1
	1980		254	1125	-10.6	-16.2
30	2640		247	1115	-13.0	-17.0
	3300		247	1123	-13.0	-16.4
	3960		248	1120	-12.7	-16.6
	4620		254	1161	-10.6	-13.6
	5280		270	1186	-05.0	-11.7



(a) **(b)**

Figure 24 Total Delays for Contained Cases which Both Primary and Secondary Incidents Blocked the Right Lane in a Three-Lane Freeway Facility under a Moderate Demand Level (a) and a High Demand Level (b)

Note that the horizontal constant plane represents the summation of the total delays caused by primary and secondary incidents when they are treated as two independent incidents. It keeps a constant value over entire time gap and distance plane without regard to temporal and spatial correlations between primary and secondary incidents. The points with perpendicular represent the total delays specified by time gap and distance derived from the joint analysis.

8.4.2 Analysis of Total Delay for Extended Primary-Secondary Incident Pairs

For extended events, Table 21 presents the total delay estimation under various scenarios at two demand levels. Figure 25 presents the same results for a 3D visualization. Comparing the two columns under the "Joint Analysis" heading, it is evident that total delay will have a multiple-fold increase as demand changes from moderate to high. So the demand level is one of the most critical parameters in delay estimation.

As indicated in Table 21, if the two incidents are treated as independent events, their delays are 229 and 1168 veh-hours for the moderate and high demand scenarios respectively. Since both the primary and secondary incidents are 30-minute long, each causes the same amount of delay.

Table 21 also provides the total delays when they are modeled jointly. These delays are either larger or smaller than the values reported under "Sum of Two Incidents" column. A justification for negative or positive percent changes in the "Comparison of Total Delays" column can be theoretically explained by referring to the shock wave analysis presented before. Obviously, time-gap and distance both affect the delay. Note most of negative percentage changes appeared at shorter time gaps (time gap = 5 or 10 in Table 21) because those secondary incidents are still contained in the queue influence area of its primary incident (i.e., $T_{2e} <= T_{2i}$ in Figure 21), this confirms the point that we made for a contained event. Given a sufficient large time-gap (i.e. greater than 15 minutes in this case), if distance is smaller, T_{2e} tends to extend beyond T_{2i}, and ($T_{2e} - T_{2i}$) becomes positive and larger. Therefore, the percent changes are positive. The simple summation of the primary and secondary incidents induced delays will under-estimate the actual delays. On the other hand, when distance increases, ($T_{2e} - T_{2i}$) tends to be closer and eventually T_{2e} is less than T_{2i} (i.e. secondary incident will be contained within the influence area of its primary incident), the percentage will become negative again. The summation of the delays from two separate incidents will over-estimated the actual delay. Overall, the total delay variations in Figure 25 (a) and (b) are consistent with the pattern observed in Figure 22, which is derived from the macroscopic shock wave analysis.

Table 21 Simulation Results for Extended Primary-Secondary Incident Pairs (Ten Random Seed with Incident Passing Speed 15 mph)

Correlations		Total Vehicle Delay (veh-hr)			Comparison of Total Delays	
Parameters		Sum of two Incidents	Joint Analysis		(%) Difference (with the sum of two incidents)	
Time Gap (minute)	Distance (feet)	Primary (30 minutes) Secondary (30 minutes)	Moderate Demand (4000veh/hr)	High Demand (5000 veh/hr)	Moderate Demand (4000 veh/hr)	High Demand (5000 veh/hr)
5	660	114.5+114.5 =229 under moderate demand (4000veh/hr)	149	717	-34.9	-38.6
	1320		168	809	-26.6	-30.8
	1980		146	716	-36.2	-38.7
	2640		141	700	-38.4	-40.1
	3300		142	673	-38.0	-42.4
	3960		145	675	-36.7	-42.2
	4620		152	707	-33.6	-39.5
	5280		146	720	-36.2	-38.4
10	660		191	903	-16.6	-22.7
	1320		199	865	-13.1	-25.9
	1980		179	877	-21.8	-24.9
	2640		174	864	-24.0	-26.0
	3300		168	839	-26.6	-28.2
	3960		176	856	-23.1	-26.7
	4620		184	846	-19.6	-27.6
	5280		164	835	-28.4	-28.5
15	660	584+584 =1168 under high demand (5000veh/hr)	232	1155	1.3	-1.1
	1320		229	1096	0	-6.2
	1980		200	1024	-12.7	-12.3
	2640		191	1031	-16.6	-11.7
	3300		194	968	-15.3	-17.1
	3960		194	968	-15.3	-17.1
	4620		189	943	-17.5	-19.3
	5280		184	1008	-19.6	-13.7
20	660		289	1383	26.2	18.4
	1320		281	1342	22.7	14.9
	1980		250	1251	9.2	7.1
	2640		237	1201	3.5	2.8
	3300		226	1164	-1.3	-0.3
	3960		225	1132	-1.7	-3.1
	4620		211	1133	-7.9	-3.0

	5280		210	1111	-8.3	-4.9
25	660		324	1542	41.5	32.0
	1320		304	1498	32.8	28.2
	1980		274	1385	19.6	18.6
	2640		260	1361	13.5	16.5
	3300		242	1327	5.7	13.6
	3960		241	1299	5.2	11.2
	4620		228	1264	-0.4	8.2
	5280		197	1242	-14.0	6.3
30	660		367	1790	60.3	53.2
	1320		340	1719	48.5	47.2
	1980		308	1639	34.5	40.3
	2640		288	1591	25.8	36.2
	3300		272	1547	18.8	32.4
	3960		265	1543	15.7	32.1
	4620		234	1423	2.2	21.8
	5280		211	1348	-7.9	15.4

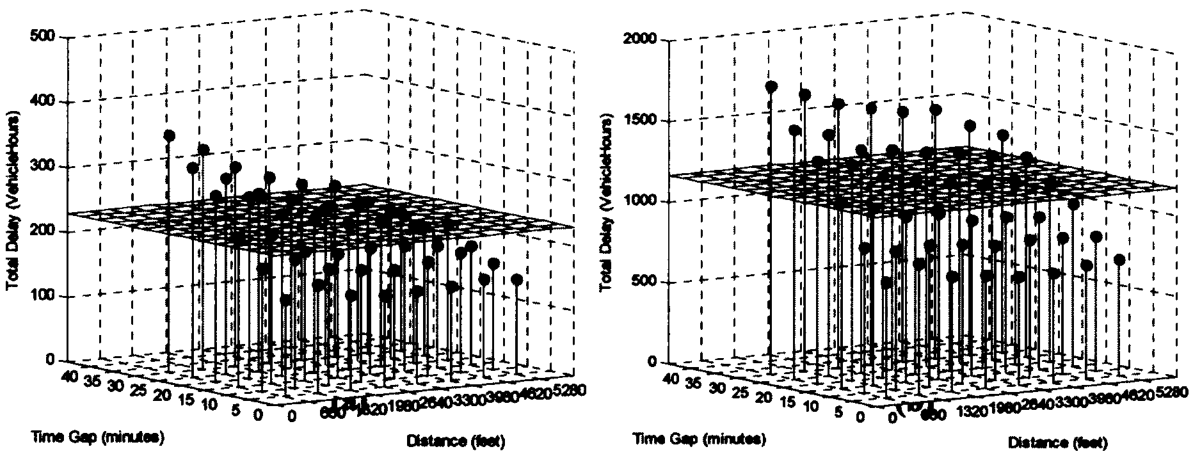


Figure 25 Total Delays for Extended Cases which Primary and Secondary Incidents Blocked the Right Lane in a Three-Lane Freeway Facility under a Moderate Demand Level (a) and under a High Demand Level (b)

Note that the horizontal constant plane represents the summation of the total delays caused by primary and secondary incidents when they are treated as two independent incidents. It keeps a constant value over entire time gap and distance plane without regard to the temporal and spatial correlations between primary and secondary incidents. The points with perpendicular represent the total delays specified by time gap and distance derived from the joint analysis.

8.5 Implications

Based on these results the following practical considerations can be highlighted:

- The demand level is a critical factor in determining the total delay caused by primary and secondary incidents. If primary and secondary incidents occur during peak hours, it is desirable to clear these incidents as soon as possible. Alternatively, diverting the traffic to the alternative roads is also another effective way to reduce traffic demand and mitigate the total delay at these associated incidents sites.
- In calculating the delay impacts or costs of incidents, it is important to identify secondary incidents and analyze them jointly with their primary counterparts, because their delays depend on their relations (in terms of location and time) to the associated primary incidents.
- Not all secondary incidents are very problematic from the perspective of event durations and delays. When a secondary incident is cleared before its primary incident and both incidents block the same lane, the time gap and distance parameters do not impact results substantially and this secondary incident does not cause additional delays, and its primary incident controls the bottleneck capacity.
- When the secondary incident is not contained (i.e., clearance time of the secondary extends that of the primary), incident responders and managers need to be more concerned about the secondary incidents that occur at larger time gaps

and/or closer to the primary incident since these will create larger total delays. This is true no matter where in the queue the secondary incident occurs. Therefore, such incidents need to be cleared as quickly as possible.

8.6 Limitations

This study only analyzes a basic 3-lane freeway segment for a demonstration purpose. If sufficient inputs such as geometric data, loop detector data in mainline as well as ramps for major freeways are available, then some critical roadway sections can be simulated and calibrated in PARAMICS to assess their impacts more realistically. In addition, traffic demand, incident durations and lane blockages could be varied with time. Additional scenarios are needed to obtain a more complete picture of delays when secondary incidents occur. While the simulation model behaves in accordance with the expectations, and provides reasonable outputs, a formal validation with field data has not been conducted yet.

8.7 Summary

This study contributes by providing a quantitative assessment of primary-secondary incident pairs in terms of their attributes through analysis of real-life data, and total delays through the kinematic wave and microscopic simulation. The temporal and spatial correlations between two associated incidents are considered in the total delay estimation. The major findings are summarized as follows:

- In real-life situations, secondary incidents that extend the duration of the event (such as those that occur in close proximity to the primary incident and last longer than the primary incident) are problematic. They are on average about the same duration as their primary counterparts (about 27 minutes on 3-lane roadways in Hampton Roads), and nearly equal in terms of lane blockage severity and frequency. Such events are also challenging from the induced delay perspective, as they are associated with longer delays.

- Given the durations and lane blockage severity of primary and secondary incidents, traffic demand, time-gap and distance between primary and secondary incident occurrences contribute substantially to the total delay. For instance, when the duration of the secondary incident is beyond that of the primary (i.e., extended case) the total delay increases as the time gap increases and the distance decreases.
- The traditional incident delay estimation approach, which treats incidents independently, does not consider the correlations between primary and secondary incidents in time and space and their co-effects. Thus it is unable to estimate the total delay caused by primary-secondary incidents accurately. Both underestimation and overestimation would be a problem for transportation planning to calculate the total delay costs.
- For real time delay prediction in traffic operations, underestimation of total delays will be a particularly serious problem. System managers may rely on this inaccurate information to make the response decision and may not realize the full extent of problems.
- It is essential to identify secondary incident and develop a new traffic delay estimation model that accounts for correlations between the primary and secondary incidents. Further development may extend to broader cases like

multiple incidents in close proximity or an incident close to a recurrent-bottleneck location.

Future research will focus on analyzing additional scenarios where having a lane blockage due to incidents and/or recurrent bottlenecks, collecting field observations such as passing speeds, time-varying lane blockage information, and queue length etc. on associated incident sites, and developing a comprehensive traffic delay model for a real-time delay prediction for incident management and accurate cost evaluation for region planning purpose.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Findings

Traffic incidents are a major resource of traffic congestion on urban freeways. Some incidents cause secondary incidents. Such cascading impacts on traffic further exacerbate congested freeway systems, stretch response resource and result in responders' and travelers' severe injuries or fatalities. Appropriate responses to such multiple associated incidents are limited by little understanding of their nature and under-estimation of their impacts. This study contributes by answering fundamental research questions about complicated primary and secondary incidents. The study explored primary-secondary incident events. Different categories for primary-secondary incident events are established based on their scale and traffic/safety impacts. The major accomplishments and finding are summarized as follows:

- A queue-based methodology was developed to identify secondary incidents, capturing secondary incidents over multiple segments and in the opposite direction. This method used queue length and actual incident duration of a primary incident as spatial influence range and temporal threshold respectively to overcome the limitations of at least some earlier studies that have used fixed spatial and temporal boundaries.
- Primary-secondary incident events are categorized on a three-point ordinal scale as: (1) an independent incident, i.e., an incident not associated with any secondary incidents; (2) one primary-secondary incident pair; and (3) one primary with two or more secondary incidents in the same or opposite directions. This

scale captures event adversity from a traffic management perspective, with the last category capturing multiple secondary events. Problematic routes, segments with high percentage of such events, and hotspots can be identified by using segment-based GIS presentation. Temporal patterns of primary-secondary incidents events can be examined using daily distributions of the frequency and incident duration of primary-secondary incidents events, grouped by month, weekday and hours. Such information is valuable for incident management. Service patrols can target the problematic routes and times that are associated with higher chances of multiple secondary events.

- To understand the occurrence of primary-secondary incident events and quantify the associated factors, one proportional odds model and one partial proportional odds model were estimated based on primary incidents characteristics, roadway geometry and traffic flow. Longer duration crashes, shorter segments and heave traffic are associated with higher propensity for primary-secondary incident events. More importantly, partial proportional odds model can account for unequal contributions of explanatory variables across the event categories. Multiple-vehicle involvement and lane-blockage had a different contribution to the occurrence of primary-secondary incident events, and they are particularly associated with the events having two or more secondary incidents.
- This study analyzed the temporal-spatial associations between primary and secondary incidents previously neglected in past researches. Rigorous statistical models were employed to investigate the relationship between time gaps/ distances and roadway, primary incident characteristics. Longer time gaps were

found to be positively associated with accidents, longer duration of primary incidents, and heavier traffic. In terms of distance, crashes and fires are associated with secondary incidents that occur at longer distances; and longer primary incident duration and lane blockage are related to larger distances between a primary incident and its secondary incident. Thus, the study found that distance and time vary systematically with characteristics of primary incidents. The time-gap and distance distributions provide a good sense of how soon after and how far away from a prior incident a secondary incident will occur. The results support more informed planning and operational decisions needed to respond to complex incident situations.

- Primary-secondary incidents events are further categorized as either contained or extended based on clearance order. A unique event database was first created based on incident, road inventory data and primary-secondary incident events. Instead of single incident duration, rigorous statistical methods were applied on event durations to explore associations with incident characteristics and response variables. 1) Contained and extended events show different characteristics and operational response patterns. For instance, primary-secondary incident pair contained events are on average 8 minutes longer than extended events. For primary-multiple secondary incidents event durations, both types of events last about 76 minutes, on average. 2) Factors associated with longer cascading event durations include the primary incident being a crash, secondary incident being a crash and multiple vehicles involved in secondary incidents, and longer time gap between the primary and secondary incidents. In addition, longer event durations were associated with longer service patrol response times. 3) While police and fire presences are associated with longer event durations, they would not be necessarily adding time because these incidents were likely more severe. Primary incident characteristics are dominant in contained events, while secondary incident characteristics play a substantial role in extended events, requiring substantial resources from response agencies.

- In calculating the delay impacts or costs of incidents, this study examined delays caused by primary-secondary incident pairs that occur on the same stretch of a freeway within a short time. The shock wave analysis and micro-simulation were employed to interoperate and model primary and secondary incidents occurrences jointly. Some concerns arisen from traditional methods in the delay estimation. The findings suggest that traditional methods treat all incidents independently and often under- or over-estimated the actual delay due to neglecting the associations between primary and secondary incidents. It is important to identify secondary incidents and analyze them jointly with their primary counterparts, because their delay impacts depend on their relation (in terms of location and time) to the associated primary incidents. When the secondary incident is not contained (i.e., clearance time of the secondary extends that of the primary), the secondary incidents occurring at larger time gaps will create longer total delays.

Overall, this study explored nearly all of important aspects of primary-secondary incident events such as spatial and temporal characteristics for three types of events, important attributes (time-gaps and distances between primary and secondary incidents start times), cascading event durations, associated delays. These finding provides new insights into secondary incidents in traffic operations, safety and planning.

9.2 Research Findings Translation to Practice

Findings from this study have been translated into two tools that enhance the incident management (Khattak et al., 2011, 2012): secondary incident identification and real-time incident predication that can be used throughout Virginia commonwealth and transferred to major metropolises.

- Secondary incident identification tool is used to identify secondary incidents from historical database. After identification and categorization of primary-secondary incident events, frequency and durations can be used as additional performance measures to identify problematic routes, evaluate current practices in incident management and facilitate proactive planning to reduce the number of secondary incidents.
- The real-time incident predication tool is capable to predicting important performance measures including incident durations, chances of secondary incident occurrence, and remaining delays. The model results can help traffic operations managers to develop effective incident management strategies to response secondary incident properly and mitigate the impacts of secondary incidents.
- This research also provide valuable information for implementing the advanced ITS devices, disseminating travel information, minimizing traffic delay and

assisting planner to accurately estimate the cost/delay of incidents by using an advanced delay estimation models.

9.3 Future Research

- Due to data limitation, the high resolution traffic data for 2005 and 2008 were not available at study time. So the validation of primary-secondary incident events has not been conducted in this study. For future research, collaborating with traffic management centers, the field observations of primary and secondary incident events and high resolution traffic data can be collected through a sufficient period. The desirable measures are the durations of associated incidents, relative lane blockage, the time-gaps and distances between primary and their secondary incidents, queue lengths, travel time and delay, traveler information, injury severity, detailed response variables.
- To estimate the total delays caused by different primary-secondary incident events in a real life, along with required input data, a comprehensive analytical/numerical model needs to be developed and calibrated based on historical data. Further theoretical investigation and more micro-simulations are needed to evaluate the impact of multiple secondary incidents on urban freeways. The future research can focus on exploring the complexity, optimization and validation of online prediction models that will be capable to handling the multiple associated incidents simultaneously over a large urban freeway network. Finally, a comprehensive model can be applied to predict the remaining delay for

traffic operations and estimate regional costs due to secondary incidents including congestion assessment and environment impacts for planning purposes.

- This study is based on Hampton Roads area, Virginia. Further study of model transferability can be conducted in a national or international scope. The established methods and models can be applied in other metropolitan regions where similar data are available to check for model consistency or identify diverse incident management issues.

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