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Quantifying Incident-Induced Travel Delays on Freeways Using Traffic Sensor Data

by

Yinhai Wang
Associate Professor

Patikhom Cheevarunothai
Graduate Research Assistant

Smart Transportation Applications and Research Laboratory (STAR Lab)
Department of Civil and Environmental Engineering
University of Washington
Seattle, Washington 98195-2700

Mark Hallenbeck
Director

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation Technical Monitor
Ted Trepanier, State Traffic Engineer

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Transportation Northwest (TransNow)
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16. ABSTRACT

Traffic congestion is a major operational problem for freeways in Washington State. Recent studies have estimated that more than 50 percent of freeway congestion is caused by traffic incidents. To help the Washington State Department of Transportation (WSDOT) identify effective countermeasures against such congestion-inducing incidents, a thorough understanding of travel delays caused by incidents is essential.

By using traffic data extracted from archived loop detector measurements and incident log data recorded by the WSDOT Incident Response (IR) team, this research project developed a new algorithm for quantifying travel delays produced by different incident categories. The algorithm applies a modified deterministic queuing theory to estimate incident-induced delay by using 1-minute aggregated loop detector data. Incident-induced delay refers to the difference between the total delay and the recurrent travel delay at the time and location influenced by the incident. The uniqueness of the delay calculation in this study is the use of a dynamic traffic-volume-based background profile, which is considered a more accurate representation of prevailing traffic conditions. According to the test results, the proposed algorithm can provide good estimates for incident-induced delay and capture the evolution of freeway traffic flow during incident duration. Because actual traffic data measured by loop detectors were used in this study to compute vehicle arrival and departure rates for delay calculations, the estimated incident-induced delay should be very close to the reality. Additionally, the proposed algorithm was implemented in the Advanced Roadway Incident Analyzer (ARIA) system. ARIA is a database-driven computer system that automates all the computational processes. More accurate incident delay information will help WSDOT improve its understanding of congestion-inducing incidents and select more effective countermeasures against incident-related traffic congestion on freeways.

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EXECUTIVE SUMMARY

Recent studies have identified traffic incidents as the main cause of more than 50 percent of the traffic congestion on freeways. With a good understanding of incident-induced congestion, transportation agencies will be able to select more effective countermeasures against freeway traffic congestion. Unfortunately, little work has been done to develop a tool or methodology that will improve our understanding of congestion-inducing incidents, especially in Washington State.

This research project developed a new algorithm, based on a modified deterministic queuing theory, for quantifying incident-induced delays (IID) on freeways. The algorithm uses incident log data and loop detector data as inputs. The incident log data were obtained from the Washington Incident Tracking System (WITS) database, and the archived loop data used in this research were downloaded from the Traffic Data Acquisition and Distribution (TDAD) website. Identifiable errors in both incident and loop data were either eliminated or corrected before the data were transferred to the Incident Study (IS) database designed and built specifically for this research. This database can also be utilized to support future incident-related research.

IID refers to the difference between the total delay and the recurrent travel delay at the time and location associated with the impact of the incident. The innovative aspect of the delay calculation in this study was the use of a dynamic traffic-volume-based background profile, which was considered a more accurate representation of prevailing traffic conditions. Recurrent delay was calculated by using the traffic background profiles identified as best fitting the current traffic demand. With the calculated total delay and recurrent delay, IID could be straightforwardly calculated.

The proposed algorithm was implemented in the Advanced Roadway Incident Analyzer (ARIA) system. ARIA is a database-driven computerized system that automates all the computational processes of the proposed algorithm. To verify the accuracy and validity of the algorithm, a microscopic simulation model for the Evergreen Point Bridge on State Route (SR) 520 was developed with the VISSIM traffic simulation tool. The simulation model was calibrated by using data from on-site loop detectors. Virtual loops were placed at exactly the same locations as the on-site loops in the simulation model. Traffic data collected from the virtual loops were used as the inputs to the algorithm, and the measured delays from the simulation model were used as ground-truth data to check the accuracy of the estimation. The validity test results demonstrated that the proposed algorithm can provide reasonable estimates of IID and capture the evolution of traffic flow for the incident duration.

The ARIA system was applied to quantify the IIDs for all the 54 incidents that occurred from November 2002 till January 2003 on the eastbound SR 520 Evergreen Point Floating Bridge and all the 147 incidents that occurred from January through March 2003 between mile post (MP) 1.68 and 15.75 of the northbound I-405 corridor. The IID estimates are valuable information that will allow traffic agencies to better understand the costs of incidents.

Principal findings of this research are as follows:

1) A countermeasure against non-injury collisions is urgently needed. The frequency of non-injury collisions has increased significantly over the years. In 2005, over 5,500 non-injury collisions occurred on the freeways. Given that non-injury collisions cause longer delays than most incident types except

2) The proposed algorithm and the ARIA system developed in this study are effective for calculating IID. ARIA has the potential to become an analytical tool for quantifying freeway delays and monitoring the impacts of operational changes.

While a number of researchers have confirmed the appropriateness of using a deterministic queuing diagram for delay calculation, several previous studies have found that certain assumptions of the deterministic queuing theory are not appropriate and, therefore, may generate errors in travel delay estimates. Field-collected vehicle delay data are needed to verify the proposed algorithm. Meanwhile, new algorithms, such as those that consider shock wave movements in traffic flow, need to be investigated in future research.

CHAPTER 1 INTRODUCTION

1.1 RESEARCH BACKGROUND

Traffic congestion has been a major traffic operational problem in the Puget Sound region over the past decade. It is mainly a consequence of significant increases in traffic demand in metropolitan areas over the past 25 years. Total vehicle miles traveled (VMT) increased by 78.5 percent from 1980 to 1992 and 23.3 percent from 1992 to 2004 (PSRC 2005). With the fast growth of VMT and limited resources for the improvement of freeway infrastructure, traffic congestion continues to deteriorate. In 2003, the congested period on highways reached 7.6 hours per day (Dutzik and Pregulman 2003). This increases the urgency of mitigating traffic congestion in Washington State.

In the past decade, the Washington State Department of Transportation (WSDOT) invested in multiple traffic congestion- mitigation projects (Hallenbeck et al. 2003). The main objectives of these projects were to improve WSDOT's understanding of traffic congestion causes and impacts, and to identify the most effective countermeasures against such traffic congestion. Recent studies have found that more than 50 percent of freeway congestion is the result of traffic incidents (Transportation Research Board 2000). Special attention should be paid to travel delays caused by incident-related congestion because of the fact that incident-induced congestion may be cost-effectively alleviated through traffic management, control, and incident response.

To mitigate incident-induced delay (IID), a better understanding of incident impacts on traffic and traffic evolution during an incident is indispensable. Unfortunately, little work has been completed on evaluating the impacts and causes of incidents in

Washington’s metropolitan areas. The Washington State Transportation Center (TRAC) developed an algorithm to identify and estimate incident-related congestion on the basis of loop occupancy data from existing loop detection systems (Hallenbeck et al. 2003). The loop occupancy profile extracted directly from loop detector data is compared with a background occupancy profile to identify the occurrence of an individual incident and to estimate its influence. The background occupancy profile is fabricated from the medians of loop occupancy values collected on weekdays without incidents. This algorithm is straightforward to apply. However, test results have shown that this algorithm may not be sensitive enough to capture all incidents. In a preliminary analysis, we found that about 50 percent of incidents were not detected by this loop occupancy-based algorithm (see Table 1-1 for details). This may be due to the fact that its fixed background occupancy profile is unsuitable for traffic conditions that are significantly different from the ordinary scenarios represented by the median occupancy values. Furthermore, using only loop occupancy data cannot accurately represent true traffic conditions on freeways. For instance, high loop occupancies may be a result of either a few slow moving vehicles passing over a loop or many high speed vehicles flowing over a loop. Consequently, a better algorithm for estimating incident-induced delay needs to be developed.

Table 1-1. Percentage of undetected congestion-causing incidents in January and February of 2003 from the loop occupancy-based algorithm

(a) Site one: State Route (SR) 520

Eastbound	Eastbound	Westbound	Westbound
January	February	January	February
34/50	25/39	44/78	27/70
68%	64%	56%	39%

(b) Site two: I-90

Eastbound	Eastbound	Westbound	Westbound
January	February	January	February
21/23	30/34	15/24	34/43
91%	88%	63%	79%

(c). Site three: I-405

Northbound	Northbound	Southbound	Southbound
January	February	January	February
15/82	32/53	32/51	29/64
18%	60%	63%	45%

WSDOT has accumulated a large amount of traffic data from existing loop detection systems and incident log data from the Washington Incident Response teams. With the availability of traffic and incident log data, the development of a new algorithm for quantifying the total travel delay associated with different types of incidents is feasible. This study emphasized the development of such an algorithm. Some known problems associated with previous algorithms were mitigated or eliminated from the proposed algorithm to enhance the accuracy of estimated IID. The proposed algorithm was implemented in a database-driven computer system to automate all the computational processes. All data were stored in a Microsoft Structured Query Language (SQL) server database and could be queried when needed. More accurate estimates of IID will help WSDOT identify suitable countermeasures against incident-related traffic congestion on freeways.

1.2 RESEARCH OBJECTIVES

The objectives of this study were as follows:

- to set up a database with loop detector data and incident log data to support delay estimation studies and decision making
- to develop an algorithm based on traffic sensor data for quantifying incident-induced travel delays on freeways
- to build a computer system that automates the proposed algorithm delay calculations.

CHAPTER 2 STATE OF THE ART

Traffic incidents result in remarkable travel delays on freeways. To minimize the impacts of traffic incidents, researchers have spent enormous effort developing procedures to detect the occurrence of incidents. Methods used for incident detection include artificial neural networks (Ritchie and Cheu 1993; Ishak and Al-Deek 1998), a loop occupancy-based approach (Lin and Daganzo 1997), and wavelet technique (Teng and Qi 2003). The application of these methods helps shorten the time needed for incident detection and hence reduces incident response time, which consequently lowers incident impacts on traffic movements.

However, those incident detection procedures do not provide information about the impacts of the incidents on traffic congestion. This led to an interest in developing procedures for estimating IID. Existing procedures for calculating IID have been based on either the deterministic queuing theory or shock wave analysis.

The queuing theory-based procedures calculate IID by using the queuing diagram formed by the cumulative vehicle arrival and departure curves. The area between these curves represents the total delay in units of vehicle-hours. Morales (1987) developed an analytical procedure, based on the queuing diagram, for estimating incident-induced traffic delay. The procedure was implemented in Lotus 1-2-3 for quickly and easily computing delay, time to normal flow, and maximum queue caused by freeway incidents. A similar approach was taken by Lindley (1987) in the development of the FREWAY model. Ten years later, Sullivan (1997) developed a two-level incident delay model, called IMPACT, based on the queuing diagram and the FREWAY model. The IMPACT model predicts incident rate, severity, and duration at level one and calculates the traffic delay caused by incidents at the second level. Skabardonis et al. (1996) utilized a queuing diagram to estimate IID and provided several interesting observations, for example, that the capacity reduction is disproportionate to the physical lane blockage. Fu and Rilett (1997) developed an online incident delay model for calculating each individual vehicle's delay on the basis of the arrival time at the incident site and the distribution of the incident duration. This delay model captures the stochastic characteristics of incident duration under real-time traffic situations. In the same year, Fu and Hellinga (1997) presented a fuzzy queuing model that can predict IID by using real-time information on existing queue condition, future traffic arrival, lane closing, and vehicle arrival time.

The queuing diagram approach was also employed by Cohen and Southworth (1999). They proposed a simple model for estimating the mean and variance of time lost as a result of incidents on freeways. Olmstead (1999) showed that the queuing model may underestimate the total delay if the model assumes that the delay due to an average incident is the same as the average delay due to incidents. Queuing theory has also been applied to estimate delays at work zones on freeways (Chien and Chodhury 2000). Li et al. (2006) recently introduced an incident duration model and a reduced capacity model for use with the queuing theory to estimate IID on freeways. Their delay estimation model provides reasonable estimates of the mean as well as the variance of IID.

Traffic flow has some characteristics similar to those of fluid flow. Therefore, several researchers have attempted to use kinematic wave theory to explain the behaviors of traffic flow. These attempts have led to the development and application of shock wave analysis for estimating IID. Shock wave analysis was first applied when Lighthill and Whitham (1955) showed how to characterize traffic flow with an analogy to fluid dynamics. At about the same time, Richards (1956) independently developed a simple model of traffic flow by replacing individual vehicles with a continuous fluid density. Therefore, the first shock-wave-based model was called the Lighthill, Whitham, and Richards model (the LWR model).

Al-Deek et al. (1995) proposed a new method, based on the shock wave analysis, for calculating total incident delay that uses loop data and incident data. The method divides a freeway section into smaller segments, calculates delay on each segment, and then determines cumulative incident delay. Mongeot and Lesort (2000) analytically expressed incident-induced flow perturbation variations in terms of shock waves, perturbation clearance time, and maximum queue length. In addition to shock waves, Gupta and Katiyar (2005) also discussed rarefaction waves and cluster effects in their model.

The delay estimates from queuing theory and shock wave analysis were compared by several researchers. Nam and Drew (1996) concluded that “deterministic queuing analysis always underestimates the overall magnitude of delays compared to shock-wave analysis.” However, Hurdle and Son (2001) and Rakha and Zhang (2005) demonstrated that both theories yield identical delay estimates and should be used together to provide additional understanding of traffic congestion.

Hallenbeck et al. (2003) studied the nature and cause of traffic congestion on freeways in Seattle’s metropolitan area. The occurrence and duration of traffic congestion caused by incidents were identified by comparing the traffic profile of lane occupancy on a day with incidents with a background occupancy profile that represented the typical traffic condition for incident-free days. The difference between the two profiles was used to calculate the delay caused by incidents. However, the test results from the process included traffic congestion that sometimes moved from upstream to downstream locations, which could be questionable. Nonetheless, this study built a solid foundation for further studies on incident detection and delay estimation in Washington State.

CHAPTER 3   INCIDENT DATABASE DESIGN

3.1 INCIDENT DATA COLLECTION

According to the incident data collected by the Washington Incident Response team, over 40,000 incidents occur on Washington State freeway networks each year. Incident log data in Washington have been independently collected by three different organizations: (1) the WSDOT’s Incident Response team, (2) the Northwest Region Transportation System Management Center (TSMC), and (3) the Washington State Patrol (WSP). The incident log data collected by these organizations are stored in different databases: the Washington Incident Tracking System (WITS) database (Incident Response Team), the TSMC incident database (TSMC), and the Computer Aided Dispatch (CAD) database (WSP). The WITS database is a subset of the CAD database and does not contain information sensitive to human privacy.

Even though there are three incident data sources, only the WITS database was used in this study because of its wide range of coverage spatially and temporally, as well as its public accessibility. According to WSDOT personnel who manage incident log data, certain data attributes in the CAD database are confidential and protected; therefore, a large number of CAD data are restricted. As for the TSMC data, coverage is limited to only certain freeway sections in WSDOT’s Northwest Region and certain time periods because of the TSMC’s incident data collection procedures. As a result, the WITS data between 2002 and 2005 for the major freeways and state highways in the Puget Sound region were selected for our analysis.

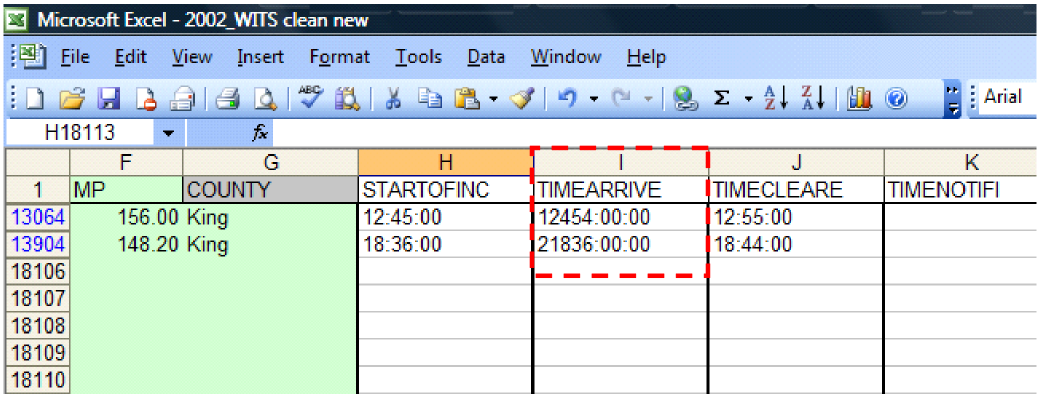
3.2 LOOP DATA COLLECTION

Loop detector data associated with the collected incident log data were downloaded from the Traffic Data Acquisition and Distribution (TDAD) website (http://www.its.washington.edu/tdad/). The standard resolution of loop data on the TDAD website is 20 seconds. After being downloaded, the 20-second loop data were integrated to 1-minute intervals to reduce data fluctuations caused by random traffic arrivals. This task was automatically completed by using a simple computer application developed in Microsoft Visual C# by the research team at the Smart Transportation Applications and Research Laboratory (STAR Lab) of the University of Washington.

In addition to the aggregated 1-minute loop data, a portion of high-resolution loop event data (e.g., 60 Hz data) collected in the previous project ("Improving Dual-Loop Truck (and Speed) Data: Quick Detection of Malfunctioning Loops and Calculation of Required Adjustments," Nihan et al., 2006) were used in this study for a better understanding of how traffic evolves during congestion.

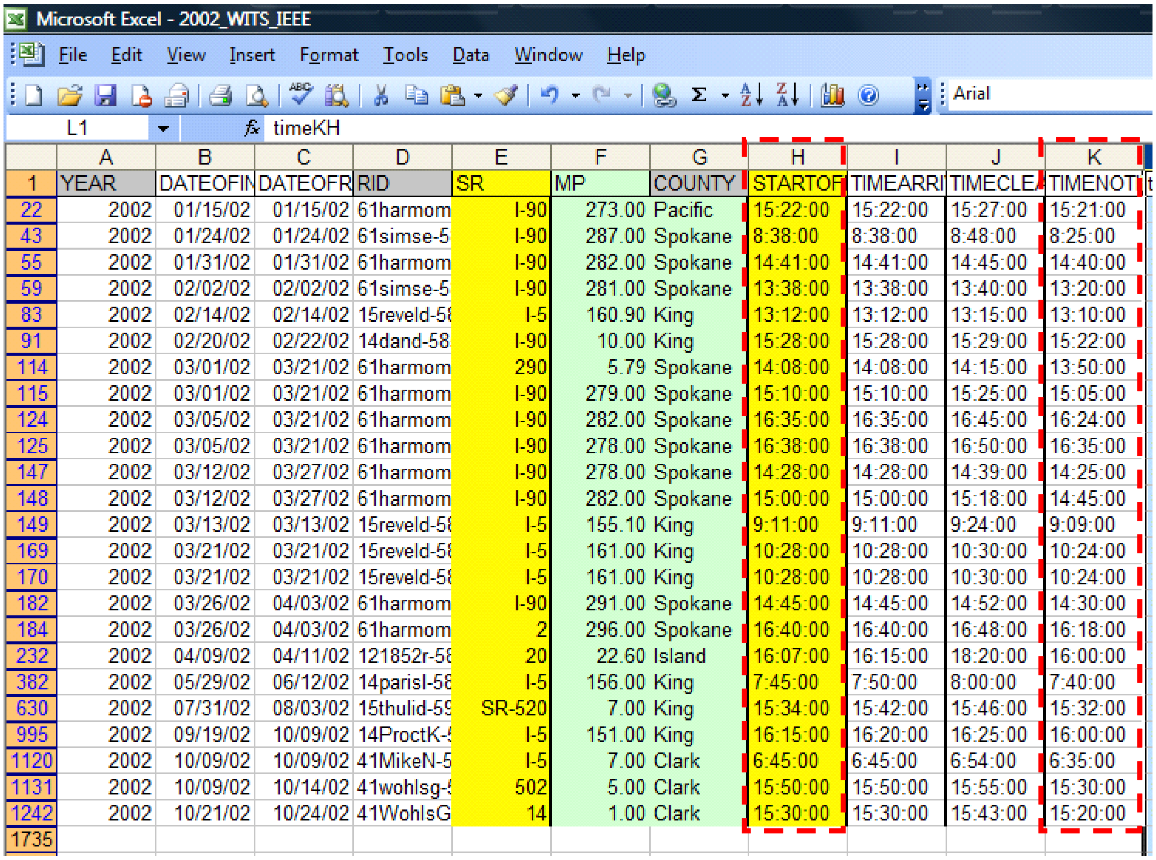
3.3 INCIDENT AND LOOP DATA CLEANSING AND ORGANIZATION

Before the transfer of the collected incident log data and loop data to the database, the data were screened on the basis of a set of static rules implemented in Microsoft Excel for quality control, and data with identified errors were either eliminated or corrected. Through the analysis of data errors, the research team recognized that identifiable errors in the incident data were mainly data input errors, such as data stored in wrong columns, manual typing mistakes, and duplicated inputs. Figures 3-1 and 3-2 show examples of typical errors found in the incident data. Cleaned incident data were then stored in a database table specifically designed for this study.



	F	G	H	I	J	K
1	MP	COUNTY	STARTOFINC	TIMEARRIVE	TIMECLEARE	TIMENOTIFI
13064	156.00	King	12:45:00	12454:00:00	12:55:00	
13904	148.20	King	18:36:00	21836:00:00	18:44:00	
18106						
18107						
18108						
18109						
18110						

Figure 3-1. Arrival time of incident without the colon sign (column I)



	A	B	C	D	E	F	G	H	I	J	K
1	YEAR	DATEOFIN	DATEOFR	RID	SR	MP	COUNTY	STARTOF	TIMEARRI	TIMECLEA	TIMENOT
22	2002	01/15/02	01/15/02	61harmom	I-90	273.00	Pacific	15:22:00	15:22:00	15:27:00	15:21:00
43	2002	01/24/02	01/24/02	61simse-5	I-90	287.00	Spokane	8:38:00	8:38:00	8:48:00	8:25:00
55	2002	01/31/02	01/31/02	61harmom	I-90	282.00	Spokane	14:41:00	14:41:00	14:45:00	14:40:00
59	2002	02/02/02	02/02/02	61simse-5	I-90	281.00	Spokane	13:38:00	13:38:00	13:40:00	13:20:00
83	2002	02/14/02	02/14/02	15reveld-58	I-5	160.90	King	13:12:00	13:12:00	13:15:00	13:10:00
91	2002	02/20/02	02/22/02	14dand-58	I-90	10.00	King	15:28:00	15:28:00	15:29:00	15:22:00
114	2002	03/01/02	03/21/02	61harmom	290	5.79	Spokane	14:08:00	14:08:00	14:15:00	13:50:00
115	2002	03/01/02	03/21/02	61harmom	I-90	279.00	Spokane	15:10:00	15:10:00	15:25:00	15:05:00
124	2002	03/05/02	03/21/02	61harmom	I-90	282.00	Spokane	16:35:00	16:35:00	16:45:00	16:24:00
125	2002	03/05/02	03/21/02	61harmom	I-90	278.00	Spokane	16:38:00	16:38:00	16:50:00	16:35:00
147	2002	03/12/02	03/27/02	61harmom	I-90	278.00	Spokane	14:28:00	14:28:00	14:39:00	14:25:00
148	2002	03/12/02	03/27/02	61harmom	I-90	282.00	Spokane	15:00:00	15:00:00	15:18:00	14:45:00
149	2002	03/13/02	03/13/02	15reveld-58	I-5	155.10	King	9:11:00	9:11:00	9:24:00	9:09:00
169	2002	03/21/02	03/21/02	15reveld-58	I-5	161.00	King	10:28:00	10:28:00	10:30:00	10:24:00
170	2002	03/21/02	03/21/02	15reveld-58	I-5	161.00	King	10:28:00	10:28:00	10:30:00	10:24:00
182	2002	03/26/02	04/03/02	61harmom	I-90	291.00	Spokane	14:45:00	14:45:00	14:52:00	14:30:00
184	2002	03/26/02	04/03/02	61harmom	2	296.00	Spokane	16:40:00	16:40:00	16:48:00	16:18:00
232	2002	04/09/02	04/11/02	121852r-58	20	22.60	Island	16:07:00	16:15:00	18:20:00	16:00:00
382	2002	05/29/02	06/12/02	14parisl-58	I-5	156.00	King	7:45:00	7:50:00	8:00:00	7:40:00
630	2002	07/31/02	08/03/02	15thulid-59	SR-520	7.00	King	15:34:00	15:42:00	15:46:00	15:32:00
995	2002	09/19/02	10/09/02	14ProctK-5	I-5	151.00	King	16:15:00	16:20:00	16:25:00	16:00:00
1120	2002	10/09/02	10/09/02	41MikeN-5	I-5	7.00	Clark	6:45:00	6:45:00	6:54:00	6:35:00
1131	2002	10/09/02	10/14/02	41wohlsg-5	502	5.00	Clark	15:50:00	15:50:00	15:55:00	15:30:00
1242	2002	10/21/02	10/24/02	41WohlsG	14	1.00	Clark	15:30:00	15:30:00	15:43:00	15:20:00
1735											

Figure 3-2. Start time (column H) of incident occurrence after notification time (columns K)

Loop data were also checked for errors by using the loop data screening and cleansing criteria developed in Cheevarunothai et al. (2007). This approach works well for identifying data errors caused by loop malfunctions (e.g., loop signal splits, stuck on, and stuck off). The processed loop data were stored together with the incident data in a Microsoft SQL database designed for this study.

3.4 INCIDENT STUDY DATABASE DESIGN AND IMPLEMENTATION

The Incident Study (IS) database design for the study was principally based on the available incident log and loop data. The database design was based on the Entity/Relationship (E/R) diagram (Garcia-Molina et al. 2002). On the basis of an analysis of incident and loop data, the research team identified four entity sets for the IS database: *"incident," "response team," "vehicle," and "loop station."* Figure 3-3 illustrates the E/R diagram design of the IS database. Each entity set is represented by a rectangle. Ovals stand for data attributes. Entity sets may be relevant to each other, and their relationships are represented by diamonds. Each entity set has its own primary key for efficiently querying and managing data. Incident report ID (shortened to ID in the figure) is the primary key for the *incident* entity set. The *vehicle* entity set uses the license plate number field as its primary key. Similarly, incident response team name and loop station name (represented by a seven-letter code) are the primary keys of the *response team* entity set and *loop station* entity set, respectively. These primary key attributes are underlined in the E/R diagram.

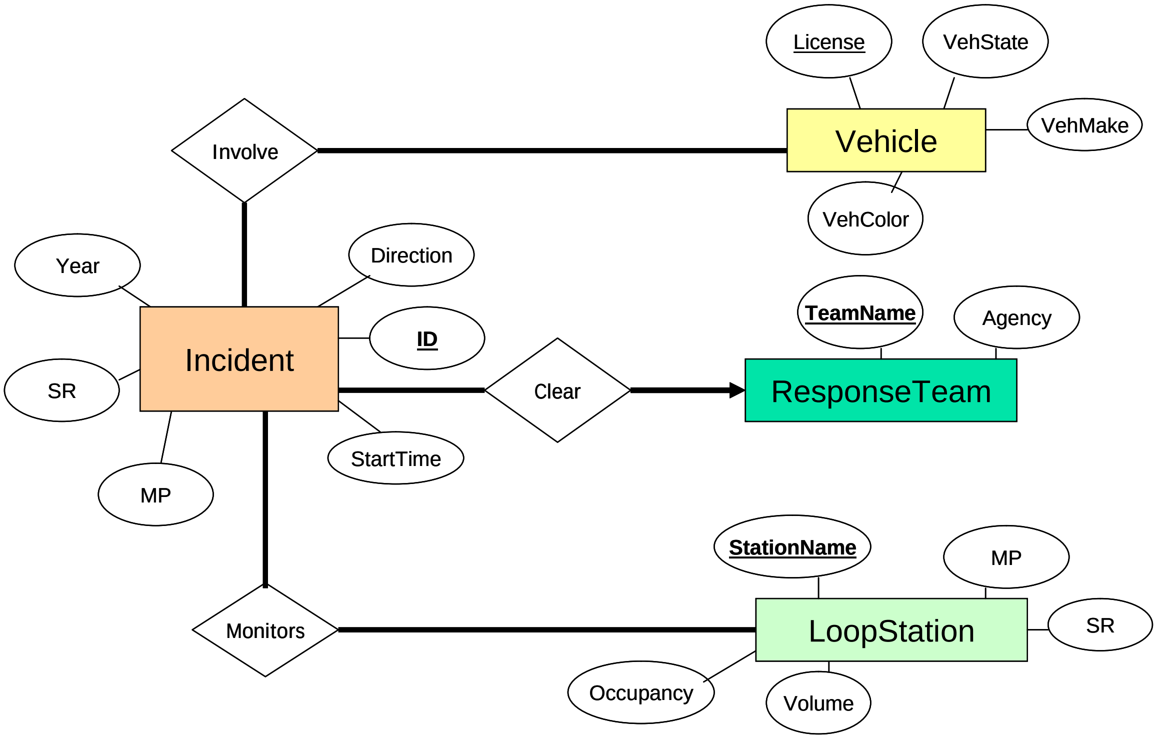


Figure 3-3. E/R diagram design of the incident study database
"ID" = incident report ID, "SR" = State Route number, and "MP" = mile post.

The E/R diagram design can be converted to the following relational schemas:

- Incident (<u>ID</u>, Direction, Year, StartTime, SR, MP, ResponseTeam, TeamName)
- LoopStation (<u>StationName</u>, Occupancy, Volume, MP, SR)
- ResponseTeam (<u>TeamName</u>, Agency)
- Vehicle(<u>License</u>, VehState, VehMake, VehColor)
- Involve (<u>ID, License</u>)
- Monitors (<u>ID, StationName</u>)

Following the E/R diagram design and the converted relational schema, the IS database was implemented in Microsoft SQL server 2005. The Data Transformation Services (DTS) in Microsoft SQL server 2005 was applied to transfer the incident log and loop data into the designed relations in the IS database. To automate all the computational processes of the algorithm for quantifying IID, this database was linked to the computer system application that implemented the algorithm. The incident and loop data in the SQL database could then be easily queried and extracted to support incident and delay analyses.

CHAPTER 4   STATISTICAL ANALYSIS OF INCIDENTS

4.1 OCCURRENCE FREQUENCY BY INCIDENT TYPE

Statistical analyses of incident log data are essential for understanding incident frequency and therefore incident-induced congestion on freeways. In WITS, incidents are classified into seven main categories: fatality collision, injury collision, non-injury collision, blocking disabled vehicle, disabled vehicle, abandoned vehicle, and debris blocking traffic. Table 4-1 shows the frequency of each incident category from 2002 through 2005. We can see that the top five incident categories were disabled vehicle (at shoulder), abandoned vehicle, blocking disabled vehicle, non-injury collision, and debris blocking traffic. Among them, a disabled vehicle incident was the most frequent category, accounting for about 50 percent for all years. Being the second most frequent incident category, abandoned vehicle represented 13 percent to 18 percent over the four-year period. Fortunately, these two major incident types are not lane-blocking, although they do affect freeway capacity under certain circumstances.

Additionally, four supplemental categories are associated with the main incident categories: WSDOT property damage (PD), fire (F), haz-mat (HM), and other contact (OC). Their descriptions are as follows: “WSDOT Property Damage–there is damage to property other than the vehicles involved in a collision, e.g., guardrail, landscaping, fencing, etc.; Fire–there is a fire whether a collision occurs or not; Haz-Mat–hazardous material is spilled, collision or not; Other Contact–contact is made for another reason, such as an informational contact” (WSDOT 2003). The frequency of main incident categories in each year from 2002 through 2005 is displayed with different supplemental categories in tables 4-2 to 4-5. Because supplemental category information is optional on an incident report, some incidents do not have supplemental categories and are marked "No SC" in the column. Even though main incident category information is required, the research team still found several incidents without this information. These incidents are summarized under the "N/A" row in Table 4-1.

Table 4-1. Incident categories by year

Main Category	**2002**	**2003**	**2004**	**2005**
Fatality	133 (0.7%)	126 (0.3%)	107 (0.2%)	142 (0.2%)
Injury Collision	843 (4.7%)	1,452 (3.2%)	1,493 (2.8%)	1,587 (2.7%)
Non-Injury Collision	1,551 (8.6%)	3,657 (8.2%)	4,526 (8.6%)	5,549 (9.5%)
Blocking Disabled	1,552 (8.6%)	3,505 (7.8%)	3,874 (7.4%)	4,349 (7.5%)
Disabled Vehicle	8,618 (47.6%)	21,478 (48.0%)	26,022 (49.6%)	28,009 (48.2%)
Abandoned Vehicle	2,302 (12.7%)	7,966 (17.8%)	9,160 (17.5%)	10,259 (17.7%)
Debris Blocking Traffic	1,765 (9.7%)	4,417 (9.9%)	5,133 (9.8%)	5,965 (10.3%)
N/A	1,343 (7.4%)	2,114 (4.7%)	2,140 (4.1%)	2,260 (3.9%)
Total	**18,107**	**44,715**	**52,455**	**58,120**

Table 4-2. Incident categories in 2002

	No SC	PD	F	HM	OC	PD,HM	F,OC	PD,F	HM,OC	PD,OC
Fatality	110	10	4	2	-	2	2	1	1	1
Injury Collision	777	47	9	6	2	1	-	1	-	-
Non-Injury Collision	1,390	124	13	6	9	6	1	1	-	1
Blocking Disabled	1,506	10	17	3	14	1	1	-	-	-
Disabled Vehicle	8,514	8	33	18	41	-	1	3	-	-
Abandoned Vehicle	2,289	2	1	2	8	-	-	-	-	-
Debris Blocking Traffic	1,731	11	3	4	16	-	-	-	-	-
N/A	-	81	74	35	1,135	4	2	4	3	5

Table 4-3. Incident categories in 2003

	No SC	PD	Fire	HM	OC	PD,HM	F,OC	PD,F	HM,OC	PD,OC
Fatality	111	7	3	-	2	1	1	1	-	-
Injury Collision	1,282	107	25	12	14	8	1	1	1	1
Non-Injury Collision	3,476	129	11	15	16	8	-	2	-	-
Blocking Disabled	3,467	3	18	1	13	1	1	-	-	1
Disabled Vehicle	21,335	4	67	11	60	1	-	-	-	-
Abandoned Vehicle	7,949	2	5	-	10	-	-	-	-	-
Debris Blocking Traffic	4,375	8	4	9	20	-	1	-	-	-
N/A	-	17	194	45	1,840	2	5	1	4	6

Table 4-4. Incident categories in 2004

	No SC	PD	Fire	HM	OC	PD,HM	F,OC	PD,F	HM,OC	PD,OC
Fatality	102	5	-	-	-	-	-	-	-	-
Injury Collision	1,402	61	12	4	8	3	-	2	-	1
Non-Injury Collision	4,367	121	14	11	8	4	-	1	-	-
Blocking Disabled	3,851	2	11		10	-	-	-	-	-
Disabled Vehicle	25,917	1	60	10	33	1	-	-	-	-
Abandoned Vehicle	9,149	2	1	2	6	-	-	-	-	-
Debris Blocking Traffic	5,099	11	1	6	16	-	-	-	-	-
N/A	-	19	163	48	1,901		3	1	4	1

Table 4-5. Incident categories in 2005

	No SC	PD	Fire	HM	OC	PD,HM	F,OC	PD,F	HM,OC	PD,OC
Fatality	129	9	-	-	2	-	-	1	1	-
Injury Collision	1,501	64	10	2	4	2	1	2	-	1
Non-Injury Collision	5,331	160	15	14	19	8	-	2	-	-
Blocking Disabled	4,319	5	15	2	7	-	-	-	-	1
Disabled Vehicle	27,864	4	71	14	54	-	-	-	2	-
Abandoned Vehicle	10,246	3	-	2	8	-	-	-	-	-
Debris Blocking Traffic	5,930	9	2	10	12	-	-	-	-	2
N/A	-	33	156	45	2,014	-	6	-	2	4

As expected, most of WSDOT property damages were mainly caused by non-injury collision and injury collision. The data also showed that every main incident category, even disabled vehicle (on shoulder), may be associated with certain WSDOT property damage.

These findings are useful in helping transportation management agencies select effective and economical countermeasures to alleviate traffic congestion. For instance, widening a freeway shoulder could directly minimize the impacts of disabled vehicles (on shoulder) on traffic movements, and a strict traffic enforcement plan could reduce the number of abandoned vehicles.

4.2 INCIDENT DURATION

Each recorded incident has four time stamps associated with it: Start, Notification, Arrival, and Clearance (SNAC) times. Start time refers to the time when an incident occurs. Notification time is the time when the incident response agent is informed of the incident’s occurrence. Arrival time corresponds to the moment when the incident response team arrives at the incident site. Clearance time records the instant when the incident has been cleared. The duration of an incident can be divided into three time intervals, as illustrated in Figure 4-1: (1) interval between the Start time and the Notification time (named the SN interval); (2) interval between the Notify time and the Arrival time (called the NA interval); and (3) interval between the Arrival time and the Clearance time (termed the AC interval).

Because the Notification time does not seem to matter much for IID research, the intervals considered in this study were the time interval starting from the Start time till the Arrival time (the SNA interval); the interval from the Start time to the Clearance time (the SNAC interval); and the time difference between the Arrival time and the Clearance time (the AC interval). The SNA interval measures the time needed for a traffic management agency to respond to the incident. The duration of an incident is quantified by the SNAC interval. The AC interval represents the time needed to clear an incident. This period typically corresponds to the time when freeway capacity is restricted. Statistics of the SNA, SNAC, and AC intervals were calculated for all incident categories and are described in the following three subsections.

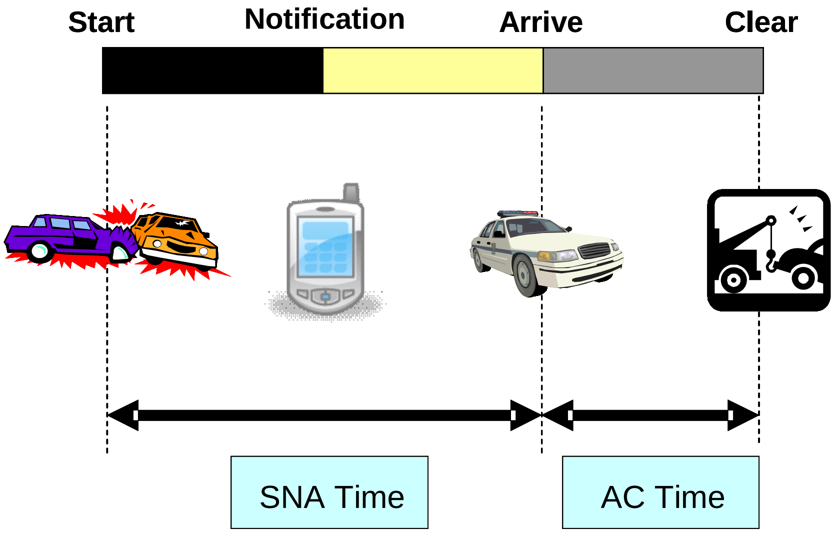


Figure 4-1. Start, Notification, Arrival, and Clearance (SNAC) times of incident

4.2.1 SNA Interval

The SNA (or response) interval indicates how quickly an incident response truck can arrive. It should be a function of incident location, response team size, and traffic condition. To allocate limited incident response resources, we need to know at what time of day the response time is the longest for a particular route. This information can help traffic management agencies identify the time of day and freeway sections that badly need resources for improving incident response.

Tables 4-6 and 4-7 display the SNA intervals for the main corridors in the greater Seattle area (i.e., I-5, I-405, I-90, and SR 520) from 2002 to 2005. On the basis of these two tables, the three longest median values of SNA intervals were 60 minutes, 28 minutes, and 15 minutes, corresponding to incidents that occurred in 2002 on northbound I-405, northbound I-5, and southbound I-405, respectively. These long SNA intervals were all in the hours between 19:00 and 6:00.

Surprisingly, even though attempts have been made to minimize traffic congestion by reducing an incident's SNA interval, the median value of SNA intervals has become longer every year. For instance, the median length of SNA intervals in the PM peak hours of the I-5 northbound direction from 2002 to 2005 were 0, 2, 4, and 5 minutes, respectively. This trend might be a result of significantly increased frequency of incidents handled by gradually increased numbers of incident response units as well as the increased travel time due to higher travel demand.

The two tables also show that the SNA intervals on SR 520 for both directions were typically longer than those of other corridors (based on the median lengths of the SNA intervals). Most of the SNA interval's median time lengths for I-405, I-90, and I-5 were below 5 minutes. In contrast, the SNA interval median time lengths of SR 520 incidents were normally longer than 5 minutes. This may be simply explained by the narrow shoulder of the SR 520 Bridge and higher traffic demand.

Table 4-6. SNA intervals in 2002-2003 (in minutes)

2002					**2003**				
I-5					**I-5**				
Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	0	0	0	28	Median	1	3	2	2
SD	11	9	9	65	SD	8	8	7	19
Maximum	132	105	105	295	Maximum	98	120	101	212
I-5					**I-5**				
Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	0	0	0	5	Median	1	2	1	4
SD	14	10	10	34	SD	7	9	8	18
Maximum	191	140	139	199	Maximum	125	195	192	145
I-405					**I-405**				
Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	3	0	0	60	Median	2	4	5	5
SD	8	13	7	123	SD	8	8	7	11
Maximum	45	184	55	300	Maximum	95	187	56	60
I-405					**I-405**				
Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	0	0	0	15	Median	5	4	4	4
SD	8	8	7	25	SD	7	6	7	13
Maximum	56	60	36	86	Maximum	63	62	60	96
I-90					**I-90**				
Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	0	0	0	0	Median	0	1	2	0
SD	7	10	6	19	SD	14	13	12	20
Maximum	60	116	30	108	Maximum	232	171	187	223
I-90					**I-90**				
Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	0	0	0	0	Median	0	3	3	0
SD	8	17	8	57	SD	13	12	10	42
Maximum	85	305	61	505	Maximum	205	171	86	453
SR 520					**SR 520**				
Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	6	6	5	10	Median	7	7	8	12
SD	8	7	7	6	SD	7	8	7	9
Maximum	61	53	55	24	Maximum	43	75	30	28
SR 520					**SR 520**				
Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	5	4	5	3	Median	5	6	8	4
SD	9	7	6	4	SD	8	7	9	4
Maximum	45	60	26	6	Maximum	40	40	59	12

Table 4-7. SNA intervals in 2004-2005 (in minutes)

2004					2005				
I-5					**I-5**				
Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	2	4	4	3	Median	3	5	5	5
SD	7	8	7	23	SD	8	9	8	20
Maximum	145	95	90	315	Maximum	212	236	225	245
I-5					**I-5**				
Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	2	4	3	5	Median	3	5	4	5
SD	8	9	7	28	SD	8	9	7	30
Maximum	135	272	86	480	Maximum	90	203	81	537
I-405					**I-405**				
Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Northbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	5	5	6	2	Median	4	6	7	4
SD	7	8	8	13	SD	7	10	8	13
Maximum	63	130	90	85	Maximum	63	244	65	144
I-405					**I-405**				
Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Southbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	5	5	6	3	Median	5	6	7	4
SD	7	7	9	19	SD	9	7	10	9
Maximum	60	55	89	132	Maximum	62	71	65	60
I-90					**I-90**				
Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	1	3	5	0	Median	3	3	4	0
SD	33	11	11	28	SD	13	15	13	12
Maximum	790	122	112	363	Maximum	249	341	189	75
I-90					**I-90**				
Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	2	4	5	5	Median	0	3	5	0
SD	12	12	13	32	SD	10	13	13	32
Maximum	137	155	191	453	Maximum	129	253	180	468
SR 520					**SR 520**				
Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Westbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	7	8	9	10	Median	5	8	7	9
SD	6	7	6	14	SD	6	7	5	9
Maximum	33	35	31	60	Maximum	47	52	27	29
SR 520					**SR 520**				
Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00	Eastbound	6:00-9:00	9:00-16:00	16:00-19:00	19:00-6:00
Median	7	6	8	7	Median	3	8	8	5
SD	6	6	6	8	SD	5	7	9	13
Maximum	33	55	27	29	Maximum	26	57	75	42

However, if we consider the possible maximum value of SNA intervals, all major freeways except SR 520 could have very long maximum SNA intervals (e.g., the maximum SNA interval during PM peak hours (16:00-19:00) on the northbound direction of I-5 in 2005 was almost 4 hours). One possible explanation is that because I-5, I-405, and I-90 cover longer corridors and have more lanes than SR 520, the SNA interval can become very long if an incident location is distant from incident response units. The ratio of incident response teams per freeway mile on I-5, I-405, and I-90 may be insufficient. Information about the median and maximum of SNA intervals is essential for identifying effective incident response strategies. For example, to improve incident response for SR 520 would require reducing the SNA for general incidents, while on I-5, I-405, and I-90 improvements would be more effective if efforts were focused on severe incidents, during which abnormally long SNA times have been observed.

4.2.2 SNAC Interval

The SNAC interval shows the time when the freeway is experiencing the impacts of an incident. Depending on the incident category, the SNAC interval may vary significantly. Some incident categories may take much longer to remove than other categories. The medians of SNAC intervals for different incident categories are shown in Table 4-8. It is typical that a fatality collision needs more time to be cleared because police officers need to collect more information about involved drivers and/or passengers, and the reason for the fatalities. It is interesting to see that even though the total percentage of the high frequency incident categories (excluding Injury Collision) was about 90 percent, their SNAC intervals were normally short. Specifically, the median time lengths for the SNAC intervals of disabled vehicle (at shoulder) and abandoned vehicle incidents were only 11 and 3 minutes, respectively.

Table 4-8. SNAC intervals (in minutes) by incident categories

	2002	**2003**	**2004**	**2005**
Fatality	233	220	217	245
Injury Collision	57	48	48	48
Non-Injury Collision	25	22	21	22
Blocking Disabled	16	15	15	15
Disabled Vehicle	10	11	11	12
Abandoned Vehicle	4	3	3	3
Debris Blocking Traffic	6	7	8	8

4.2.3 AC Interval

The AC interval is strongly related to actions taken by the incident response crew to clear the incident. The AC interval lengths of incidents associated with different clearance actions were analyzed. Table 4-9 shows the median values of the AC intervals from 2002 through 2005. Because some actions cannot be used to clear certain types of incidents, the most appropriate actions are typically selected by the incident response team. The calculated median values of AC intervals can provide a reasonable approximation of the typical amount of time that an incident response team would need to remove an incident of a certain type after its arrival.

Table 4-9. Actions taken vs. AC intervals for incidents (in minutes)

Action Taken	AC Intervals			
	2002	2003	2004	2005
Changed Flat Tire	14	15	17	16
Cleared Debris	6	5	5	4
Minor Repair	10	12	12	9
Provided Fuel	10	9	10	10
Push	13	13	15	14
Tow	13	25	24	25
Traffic Control	23	37	32	37

CHAPTER 5 RESEARCH APPROACH

5.1 ALGORITHM DESIGN FOR QUANTIFYING INCIDENT-INDUCED DELAY

In this study, we designed an algorithm for quantifying IID on the basis of a modified deterministic queuing theory. This algorithm uses loop detector measured traffic data (e.g., vehicle counts and lane occupancies) from loop stations immediate upstream and downstream of the incident location. To represent a real-world traffic condition associated with the duration of an incident, a background traffic profile (BTP) extracted directly from single-loop measurements is used. Similar to the algorithm developed by Hallenbeck et al. (2003), the proposed algorithm employs a BTP to characterize the delay in relation to the prevailing traffic conditions at the roadway section of the incident. However, this algorithm uses a volume-based BTP rather than a time-based BTP. The proposed algorithm searches for the most suitable background traffic profiles in the historical data sets on the basis of the arrival volume sequence, termed the arrival traffic profile, or ATP, detected by the immediate upstream loop station uninfluenced by the incident. Such an approach is adaptive to the actual travel demand during an incident. Delay calculated from the upstream and downstream sensor measurements for the period identified by the BTP corresponds to the recurrent delay under the specific traffic condition. IID can be calculated as the difference between the total travel delay and the recurrent delay. The following two sections describe the procedure for generating the background traffic profile and the details of each step in the algorithm to calculate the IID.

5.2 DERIVATION OF DYNAMIC TRAFFIC BACKGROUND PROFILE

The BTP was derived from on-site loop detector data. WSDOT loop detector data are aggregated into 20-second intervals and archived in a database system maintained by the Intelligent Transportation Systems (ITS) Program at the University of Washington. To reduce random fluctuations of traffic arrivals in short time (20-second) intervals while keeping the incident's Start and Clearance times at a reasonable level of accuracy, loop data were aggregated into 1-minute intervals in this study.

As mentioned earlier, the BTP represents the prevailing traffic condition typical for the location at a specific traffic volume level. Therefore, only traffic data from incident-free days should be used in the derivation of BTPs. However, with the incident records accounted for, it was difficult to find enough loop data measured on incident-free days to generate an acceptable BTP. We found that most of the days of our study period had at least one incident near a loop station. This made it difficult to obtain high quality BTPs. The IID calculated by using these inappropriate BTPs could be severely misleading. To solve this problem, we expanded the size of our data samples by allowing the usage of a portion of loop data on an incident day. Of course, the loop data have to be extracted from time periods without incident impacts. The criteria used for selecting loop data for BTP generation were as follows:

(1) Data should be extracted from time periods that are free of incident impacts and at least 5 minutes away from the next incident's Start time; and

(2) Data should not be extracted during the period starting 5 minutes before an incident's Start time through a period that is four times the incident duration following the incident's Clearance time.

For example, on January 21, 2004, there was only one incident on SR 520; it started at 12:32 PM and was cleared at 12:47 PM. Thus, the incident duration was 15 minutes. Given the criteria, the loop data that should be included to derive background traffic profiles are the measurements between 12:00 AM and 12:27 PM and the data from 13:47 PM to 23:59 PM.

After loop data have been obtained for the times and days without incident impacts, volume-based BTPs can be identified. The most suitable BTPs are principally formulated on the basis of the actual ATP measured at the immediate upstream loop station free of incident impacts during the incident interval (i.e., the SNAC interval). The ATP for an incident is extracted from the incident occurrence time to the identified dissipation time of the incident's impacts. The traffic arrival sequence at a specific location over the past three months is employed as the historical database for finding the BTPs. Such a sequence can be regarded as a long series of 1-minute volume counts. The extracted ATP is compared with this historical sequence for identifying the best three matches. As demonstrated in Figure 5-1, a sequential search is conducted to calculate the degree of match between the ATP and each historical volume count sub-sequences. The sum of square errors of the matching 1-minute counts in the sequences is employed to reflect how close the two sequences are. For example, assume that the impact of the incident in Figure 5-1 lasts for *n* minutes. Then the ATP contains *n* 1-minute counts. The match calculation employs a pointer that points at the head of the subsequence for comparison with the ATP. The initial value of the pointer is 1, indicating that the calculation should start from the first 1-minute count of the historical data. In Figure 5-1, "Try 1" compares the ATP with the first *n* 1-minute counts in the historical sequence. The sum of square errors for "Try 1" is calculated and recorded before the pointer is incremented by 1. Then "Try 2" is conducted to compare the ATP with the subsequence from the second 1-minute count through the $(n+1)^{th}$ 1-minute count in the historical data. This process continues until the end of historical data stored in the IS database is reached. Then the three subsequences with the smallest sum-of-square-error values are identified as the top three matches. In Figure 5-1, the "Try 5" profile is assumed to be one of the three best matches. Figure 5-2 shows the steps for identifying the BTPs.

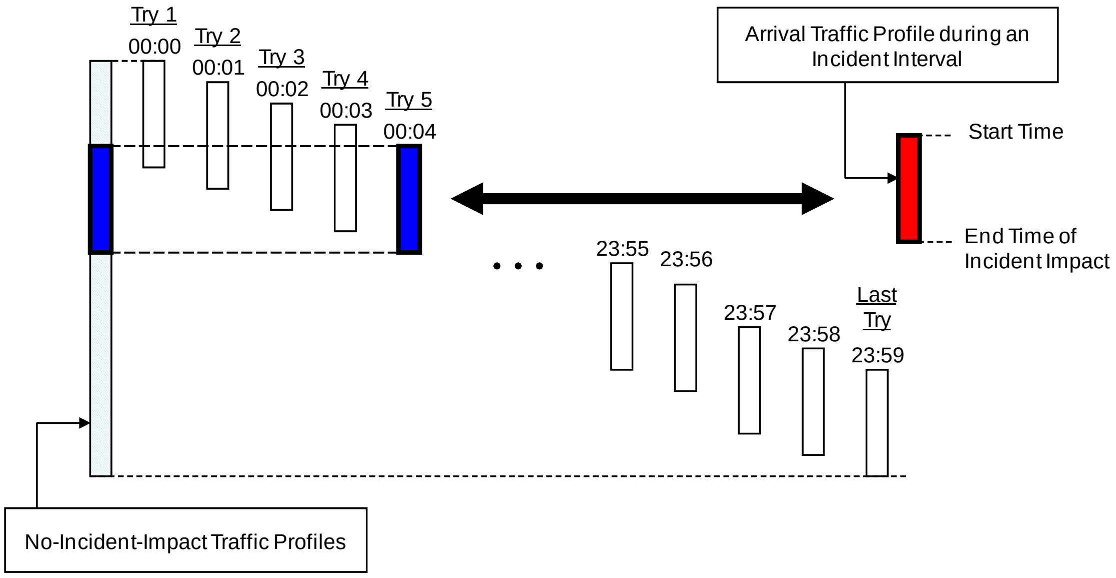


Figure 5-1. Search for suitable background traffic profiles

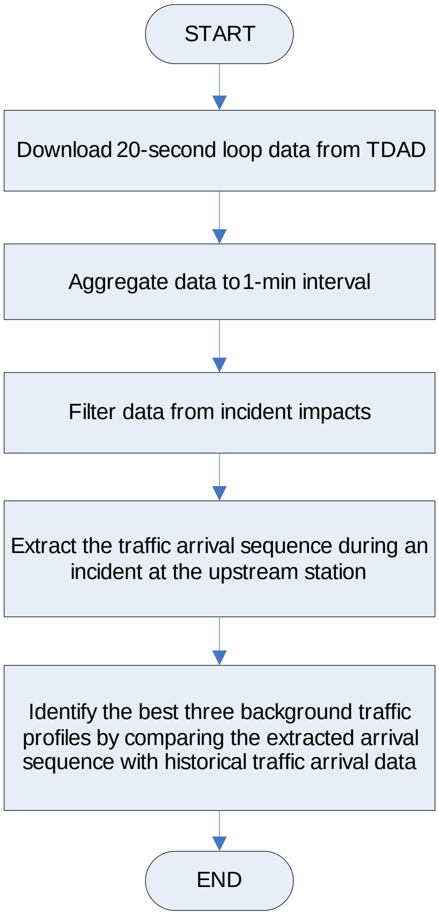


Figure 5-2. Derivation of the background traffic profiles

Figure 5-3 displays an example of the identified BTP. We can see that this BTP (represented by the dynamic volume-based (DVB) Profile line in the figure) is very similar to the actual ATP at the upstream station. This implies that the BTP can mimic the traffic arrival reasonably well during the impact time of an incident.

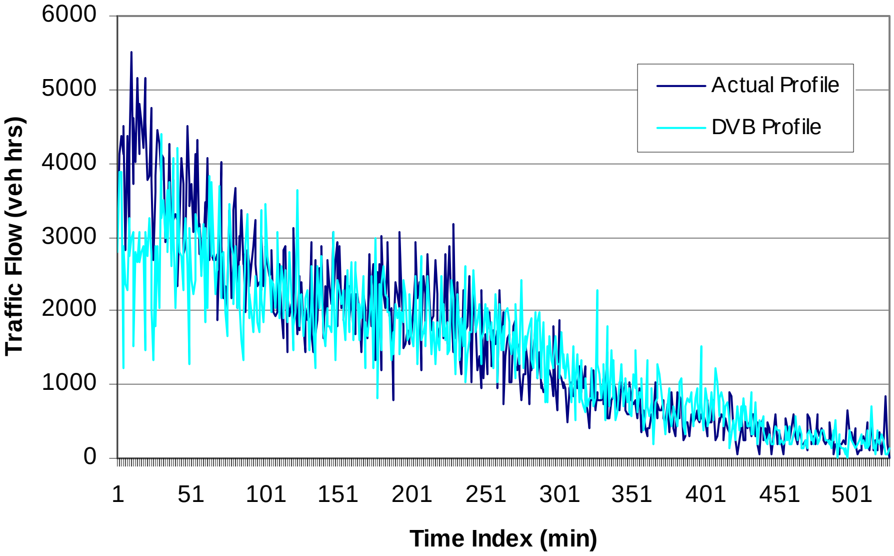


Figure 5-3. Illustration of the DVB background profile

5.3 CALCULATION OF INCIDENT-INDUCED DELAY

Figure 5-4 shows the flow chart of the proposed algorithm for IID estimation. This algorithm is based on the modified deterministic queuing theory. It begins by obtaining the information for an individual incident from the IS database. Then the algorithm requires the Start time and the exact location (in MP) of the incident as inputs. After the incident location is known, the upstream and downstream loop stations of the incident (illustrated in Figure 5-5) will be identified. Traffic data observed at those loop stations are used to build a queuing diagram for the freeway segment. The boundaries of freeway segments are the locations of the loop stations.

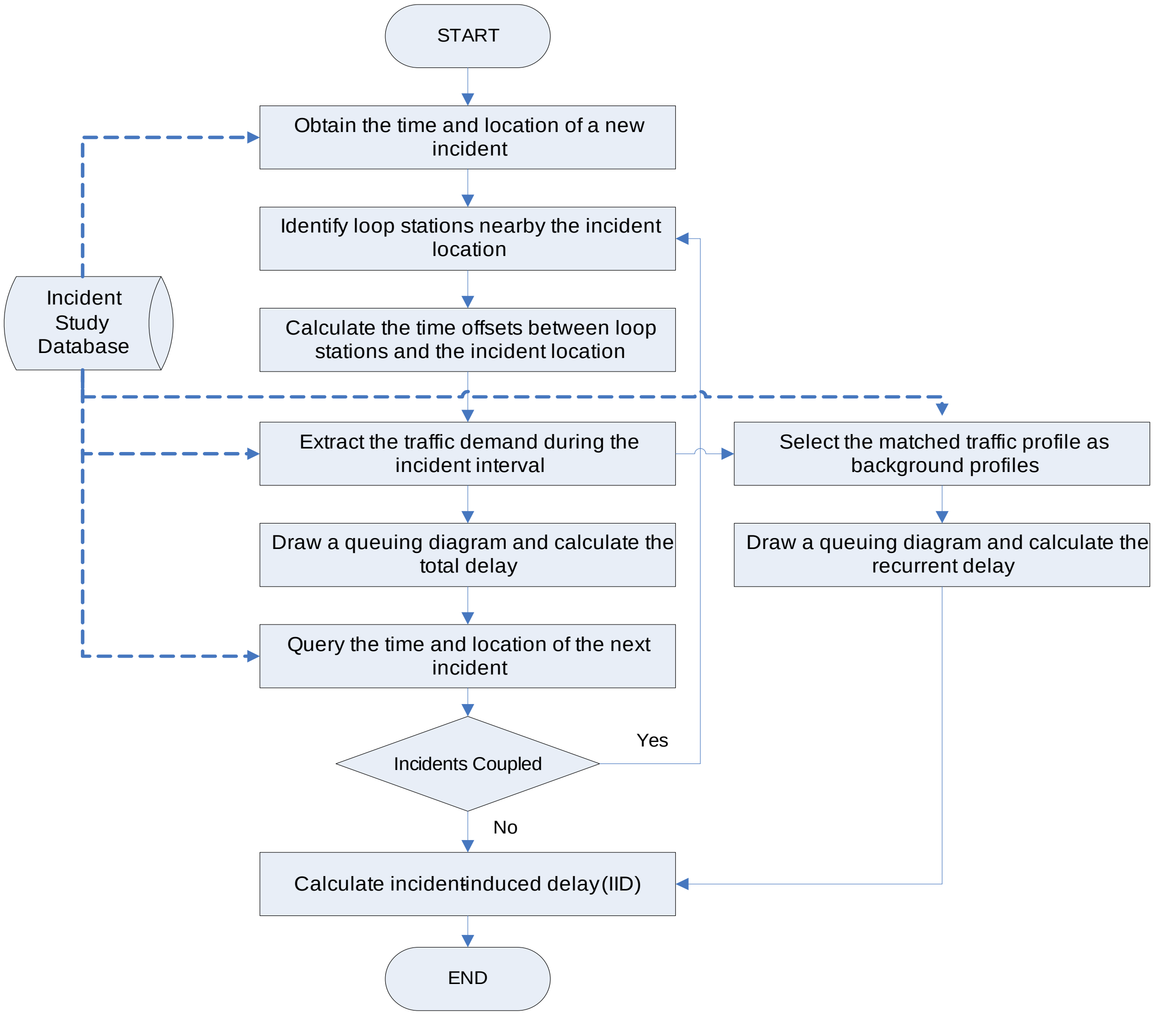


Figure 5-4. Flow chart for calculating IID on freeways

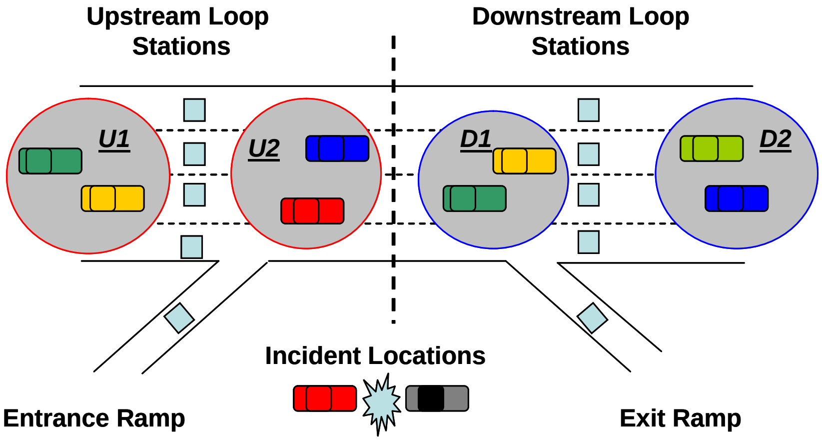


Figure 5-5. Loop stations upstream and downstream of an incident

A deterministic queuing diagram, as shown in Figure 5-6, is formed with cumulative arrival and departure curves. The cumulative arrival curve is determined by vehicle counts at the un-occupied upstream loop station. If the closest upstream loop station is occupied by queued vehicles, the immediate upstream loop station beyond the end of vehicle queue is used. These vehicle counts are from both mainstream lane loop detectors and entrance ramp loop detectors (see Figure 5-5). Similarly, vehicle counts at the immediate downstream station of the incident are used to draw the cumulative departure curve. A downstream station may contain loop detectors on both mainstream lanes and exit ramps.

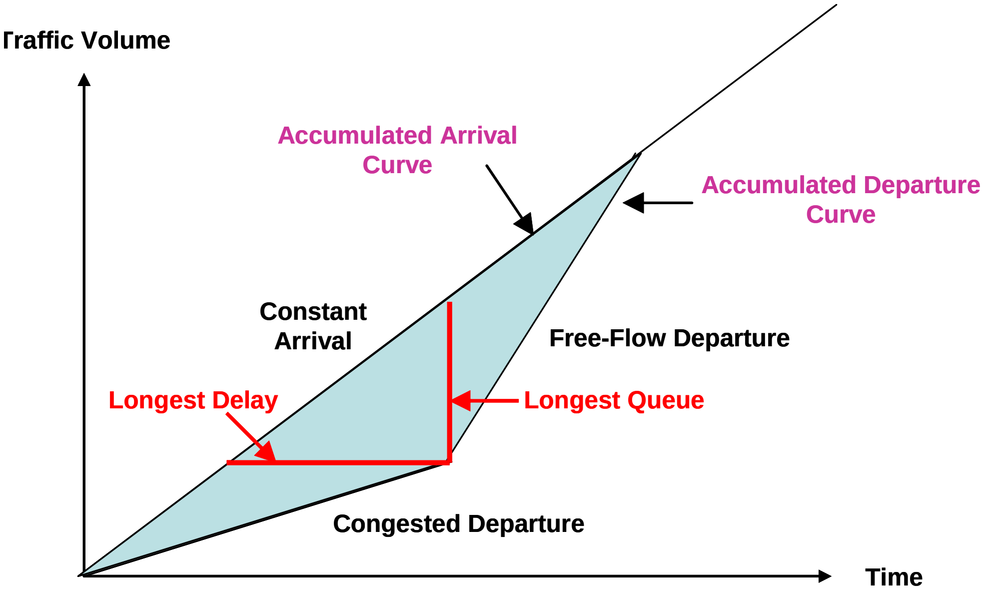


Figure 5-6. Deterministic queuing diagram

Because the deterministic queuing diagram assumes a point queue (i.e., a vehicle's physical length is zero) and the cumulative arrival and departure curves are directly measured at the incident site, measurements from the upstream and downstream loop stations must be properly adjusted to fit the deterministic queuing diagram requirements. The distance between the upstream and downstream loop stations in Washington State is typically half a mile or longer. An incident may occur at any position between the two loop stations. Therefore, the mean time offset between the upstream station and the incident location ($Offset_{UI}$), and the mean time offset between the incident location and the downstream station ($Offset_{DI}$) need to be calculated and utilized in the queuing analysis. Equations (5-1) and (5-2) are used to calculate the time offsets.

$$Offset_{UI} = \frac{Dist_{UI}}{Speed_{U}} \tag{5-1}$$

$$Offset_{DI} = \frac{Dist_{DI}}{Speed_{D}} \tag{5-2}$$

where $Dist_{UI}$ and $Dist_{DI}$ denote the distances from the incident location to the upstream and downstream loop stations, respectively. Similarly, $Speed_{U}$ and $Speed_{D}$ stand for the mean vehicle speeds measured at the upstream and downstream stations, respectively. The main reasons for using these time offsets are to include all vehicles affected by an incident in the analysis and to exclude vehicles that passed the incident location before the incident occurrence. In Figure 5-5, vehicle groups *U1* (traveling to the upstream loop station when an incident occurs) and *U2* (traveling between the upstream loops and the incident location when an incident starts) must be included in the queuing analysis because they are delayed by an incident. On the other hand, vehicle groups *D1* (traveling away from the incident location but before reaching the downstream loop station) and *D2* (already traversed the loops at the downstream station) have to be excluded because they are not affected by the incident.

If the queuing analysis starts exactly at the incident's Start time, the vehicle group *U1* is automatically included and the vehicle group *D2* is not counted. To include group

U2, the $Offset_{UI}$ time needs to be subtracted from the incident's Start time at the upstream loop station to make the analysis start early. Similarly, the $Offset_{DI}$ time must be considered to ignore vehicle group *D1* from the queuing analysis. At the downstream loop, $Offset_{DI}$ should be added to the incident's Start time to delay the beginning time of the downstream loop data analysis. By making these adjustments, measurements at the upstream and downstream loops are virtually moved to the incident location. The accumulated numbers of arrival and departure vehicles on a freeway segment can be expressed by equations (5-3) and (5-4).

$$Accumulated\ Arrival = \sum_{t=t_i-Offset_{UI}} Arrival \tag{5-3}$$

$$Accumulated\ Departure = \sum_{t=t_i+Offset_{DI}} Departure \tag{5-4}$$

The aggregated 1-minute vehicle arrival and departure data can be queried from the IS database and used for generating the arrival and departure curves. Then a deterministic queuing diagram, such as the one shown in Figure 5-6, can be formed. This queuing diagram contains many important pieces of information for queuing analysis, including the number of vehicles that have experienced delay, the total vehicle delay, and longest individual vehicle delay. The vertical line between the accumulated arrival and departure curves in Figure 5-6 represents the number of delayed vehicles at a given time interval. The horizontal line between the two curves implies the delay for the vehicle arrived at a particular interval. The shaded area between the two curves signifies the total delay.

As mentioned earlier, the total vehicle delay may include delay caused by recurrent congestion at a freeway section. To separate IID from recurrent congestion-caused delay, another queuing diagram using data from an appropriate BTP for the same freeway section is needed. The ATP at the upstream station during the incident is used for finding the three most suitable volume-based BTPs. Because a BTP represents a typical traffic condition free of incident impacts, any travel delay at this site should be caused by recurrent congestion. To reduce possible errors associated with the randomness in BTP selection, recurrent delay for each of the three identified BTPs is calculated. The mean of the three calculated recurrent delays is employed for IID calculation. If the total vehicle delay associated with an incident is longer than the recurrent delay calculated from the BTPs, the difference should be IID, as illustrated in Figure 5-7, in which the number of delayed vehicles within each time interval is plotted.

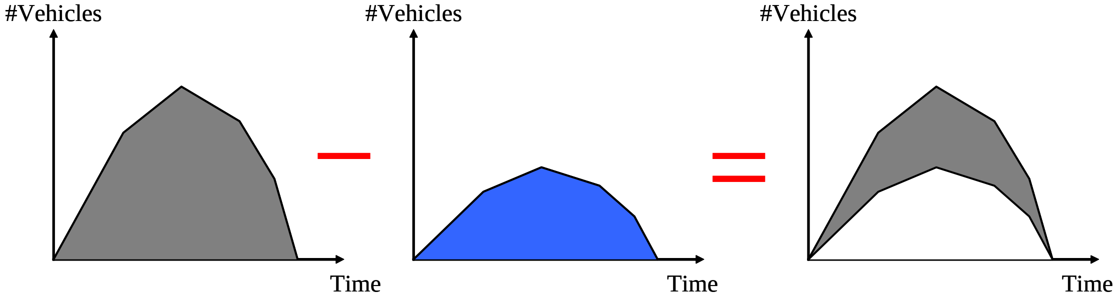
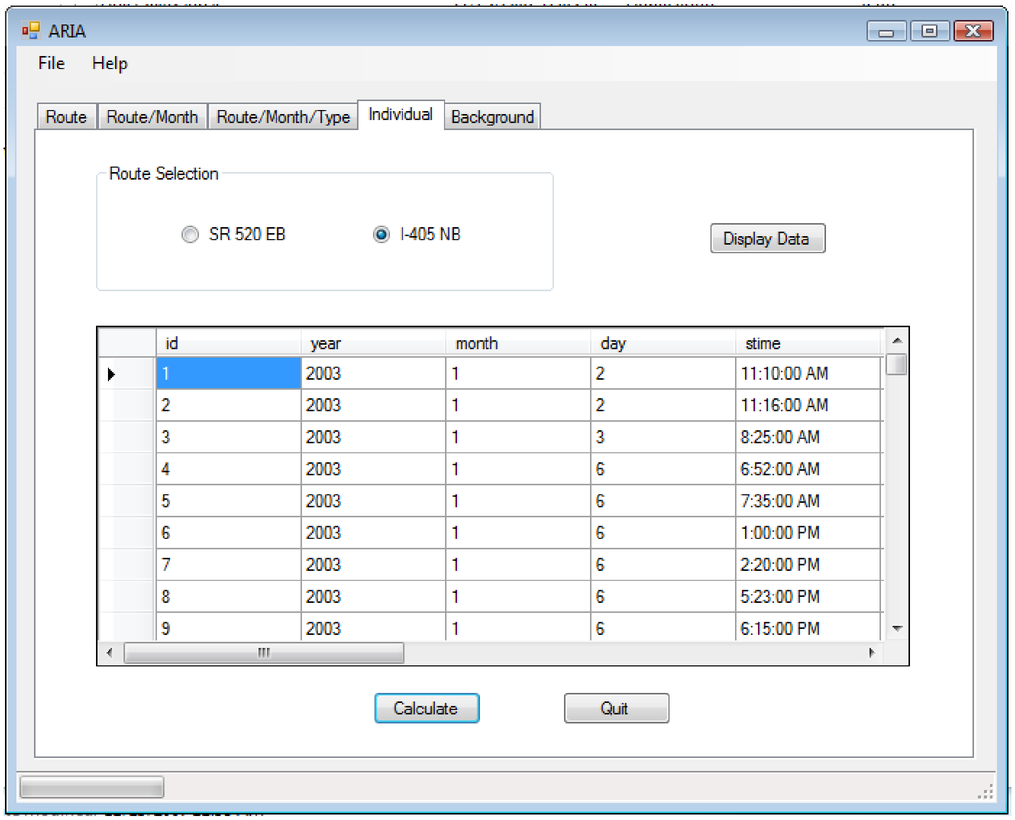


Figure 5-7. Positive incident-induced delay

It is important to remember that if the queue extends into one or more upstream segments, all the extended segments need to be combined into the original segment. Traffic data from the upstream and downstream loop stations defining the combined segment should be used for calculation. In this study, loop occupancy data measured at the upstream loop stations were used as indicators of queue extension. If the occupancy from an immediate upstream loop at the queue end is larger than 35 percent, then the vehicle queue has occupied the current upstream loop and extended into the upstream freeway segment. This 35 percent occupancy threshold is consistent with that used by WSDOT for separating heavily congested traffic conditions from stop and go conditions on the Seattle area traveler information website (WSDOT 2008).

5.4 ALGORITHM IMPLEMENTATION

The proposed algorithm was implemented in a computer system, named the Advanced Roadway Incident Analyzer (ARIA). A snapshot of its user interface is shown in Figure 5-8. The system is capable of calculating travel delays caused by different categories of incidents that occur on freeways. To use ARIA to obtain an average IID over multiple incidents on freeway networks, the freeway’s route, direction, MP, and incident categories must be selected. Similarly, to calculate the delay induced by a specific incident, additional information on the exact date and time of the incident occurrence is also required.



○ SR 520 EB ● I-405 NB

id	year	month	day	stime
1	2003	1	2	11:10:00 AM
2	2003	1	2	11:16:00 AM
3	2003	1	3	8:25:00 AM
4	2003	1	6	6:52:00 AM
5	2003	1	6	7:35:00 AM
6	2003	1	6	1:00:00 PM
7	2003	1	6	2:20:00 PM
8	2003	1	6	5:23:00 PM
9	2003	1	6	6:15:00 PM

Figure 5-8. User interface of the ARIA system

CHAPTER 6 VALIDATION OF THE ALGORITHM

6.1 SIMULATION MODEL DEVELOPMENT

To evaluate the performance of the proposed algorithm, travel delays calculated with the algorithm needed to be compared with the actual travel delays experienced by freeway users. However, data on actual travel delays are typically unavailable because of the difficulties in collecting such data. Although truck travel time data for some commercial fleets can be extracted from their global positioning systems (GPS) devices, the sample size would be too small to validate the proposed IID estimation algorithm. Therefore, we had to rely on traffic simulation data to evaluate the performance of the proposed algorithm. In this study, traffic simulation data produced by the VISSIM traffic simulation software (PTV 2001) were applied.

VISSIM is a microscopic traffic simulation tool that is capable of modeling integrated roadway networks and tracking individual vehicle movements (PTV 2001). In VISSIM, traffic detectors can be placed at desired locations to collect traffic volume and occupancy data, just like inductance loop detectors do for real-world traffic operations. With travel time data collection zones defined on a roadway network, each vehicle’s travel time and delay data can be collected. Such data were applied to validate the new algorithm proposed in this study for calculating IID.

The eastbound SR 520 Evergreen Point Floating Bridge was chosen as the algorithm validation site. The reason for choosing this site was its relatively simple highway geometry—two on-ramps and no off-ramp over a 3-mile freeway section. There are two travel lanes on eastbound SR 520 at the Evergreen Point Floating Bridge. A

VISSIM simulation model was specifically developed for this site. Figure 6-1 shows a snapshot of the simulation site. Virtual loops were placed in the simulation model at exactly the same locations as the traffic monitoring loops. After proper calibration of the simulation model, traffic volume and lane occupancy measured by the virtual loops were collected from the simulation model and compared to ground-truth data observed by the real-world loop detectors.

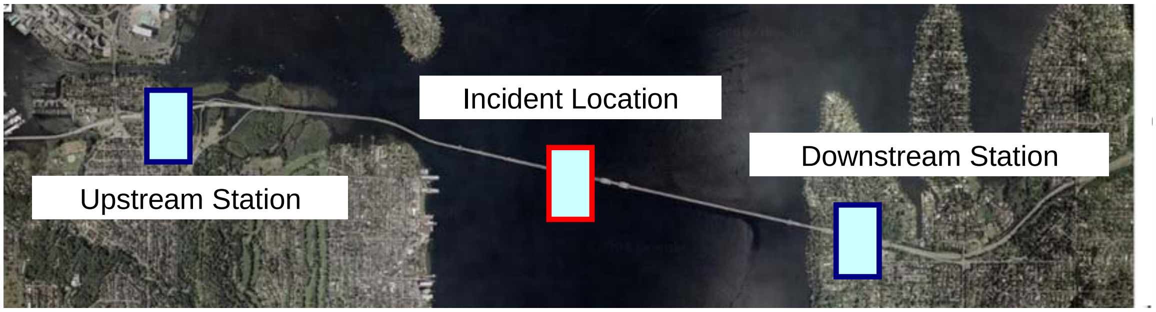


Figure 6-1. Snapshot of the SR 520 Floating Bridge

There is no standard way to simulate freeway incidents in VISSIM. After trying multiple ways, such as placing a bus stop, adding a signal head, etc., the research team decided to use the one-car parking lot method demonstrated in a VISSIM 4.2 training example. Readers are referred to the manual (PTV 2007) for details of this method.

6.2 CALIBRATION OF THE SIMULATION MODEL

Calibration is a critical step in ensuring that a simulation model produces reliable outputs. Results from improperly calibrated simulation models can be misleading and must be avoided. Ground-truth traffic volume and occupancy data observed by on-site loop detectors were used to calibrate the simulation model. The calibration process followed an approach similar to that proposed by Gomes et al. (2004). Vehicle volume data at the virtual loop detector locations were carefully compared with those observed by the on-site loop detectors. These detector locations served as check points for the calibration. Several parameters (e.g., lane changing gap and minimum headway) related to car following and lane changing behaviors were adjusted until the simulation model produced data close enough to the ground-truth data at the check points.

Eighteen incidents that occurred on the eastbound lanes of the SR 520 Floating Bridge in January 2003 were used to validate the proposed algorithm. Loop detector measurements in the time periods during these 18 incidents were applied to calibrate the simulation model. Table 6-1 shows an example of the comparison of the ground-truth traffic flow data and the simulated traffic flow data for the time period of 13:50 to 13:58 PM on January 2nd after the calibration. As required by the algorithm, travel time had to be collected for both the current traffic condition and the prevailing traffic condition (represented by the background traffic profile). Hence, the simulation model of one incident needed to be configured twice, once for simulating the current traffic condition with the incident and once for modeling the prevailing traffic condition free of the incident.

Table 6-1. Comparison of traffic volume data from the on-site loops and the virtual loops of the simulation model for the period of 13:50-13:58 on January 2, 2003

	Upstream Station		**Downstream Station**	
	Loop	**Simulation**	**Loop**	***Simulation***
current traffic condition with incident	342	358	207	230
prevailing traffic condition free of incident	385	402	392	405

6.3 ALGORITHM VALIDATION

Delays caused by the 18 incidents that occurred in the eastbound direction of SR 520 on the Evergreen Point Floating Bridge in January 2003 were calculated to evaluate the performance of the algorithm. To reduce the randomness of traffic simulation results, nine pairs of simulation runs were conducted for each incident. Each pair of simulation runs comprised one simulation run for the prevailing traffic condition and the other for the actual traffic condition when an incident occurred. A different random seed was used for each pair of simulation runs.

Figure 6-2 shows a comparison of the IID for all of the 18 incidents. The comparison illustrates that most of the IID estimated by the algorithm were smaller than the average IID directly measured from the simulation models (the simulation models' random seed numbers varied from 20 to 70 for each incident, as shown in Table 6-2). The mean of relative difference between the algorithm's IID and the simulation models' IID for the 18 incidents was 20 percent. However, because the relative error was not too big, and the trend of the algorithm's IID was very similar to that of the IID from the simulation runs, we concluded that the algorithm can provide relatively close estimates of IID.

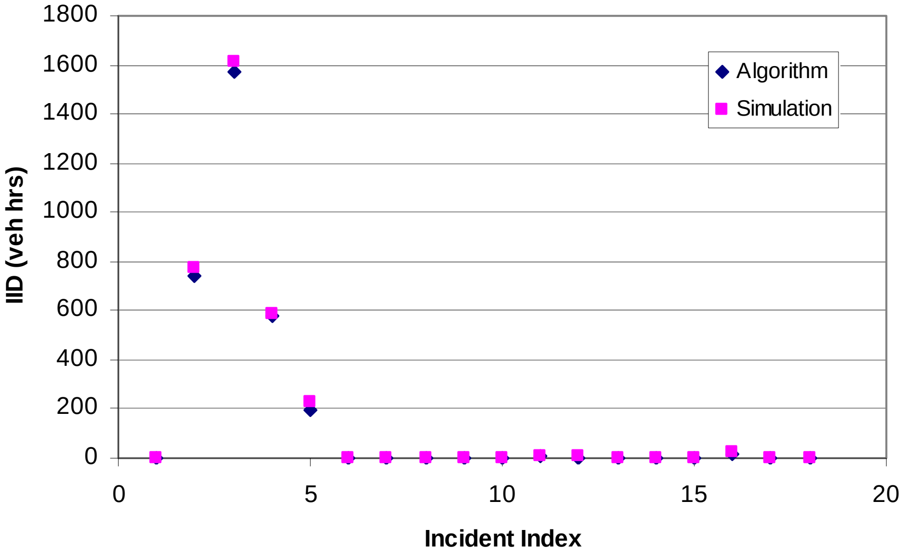


Figure 6-2. Comparison of the IID from the algorithm and the simulation model

Table 6-2 illustrates the IID, total delays, and recurrent delays in vehicle-hours from the nine pairs of simulation runs, each with a different random seed number, for the incidents that occurred between 13:50 and 15:58 on January 2, 2003. The 95 percent confidence interval (CI) of the IID measurements was between 0.0 and 0.16 vehicle-hours. The algorithm had 0.0 vehicle-hours as the calculated IID using the proposed algorithm. The calculated IID fell within the 95 percent CI for this incident. However, after the calculated IID from the proposed algorithm was compared with the 95 percent CI of the simulation models' IID for all 18 incidents, the algorithm's IID for 12 of the 18 incidents fell within the 95 percent CI. These 12 incidents are indicated "Yes" in the "Within 95% CI" column of Table 6-3. Therefore, further research is needed to determine the specific error range with the proposed algorithm.

Table 6-2. Delays from the simulation models for the period of 13:50-13:58 on January 2, 2003

Random Seed Number	Total Delay	Recurrent Delay	Incident Delay
20	95.84	95.84	0.00
25	97.65	97.52	0.13
30	98.46	98.11	0.35
35	100.46	100.34	0.12
42 (Default)	99.76	99.76	0.00
50	97.32	97.20	0.12
55	98.71	98.71	0.00
60	97.28	97.24	0.04
70	97.19	97.19	0.00

Table 6-3. Confidence intervals of the IID from the simulation runs

ID	Date	Start Time	MP	IID (veh hrs)	IID (veh mins per veh)	Simulation Delay (veh mins per veh)		Within 95% CI
						Min	Max	
S1	1/2/2003	1:50:00 PM	3	0	0.00	0.00	0.03	Yes
S2	1/4/2003	10:53:00 AM	2.7	742.78	129.55	127.43	129.69	Yes
S3	1/4/2003	11:06:00 AM	2.7	1573.13	319.96	317.87	321.75	Yes
S4	1/4/2003	12:03:00 PM	2.7	578.23	87.83	87.13	88.11	Yes
S5	1/6/2003	8:45:00 AM	4	191.67	5.25	5.85	6.02	No
S6	1/6/2003	1:10:00 PM	3	0.46	0.02	0.00	0.04	Yes
S7	1/6/2003	2:30:00 PM	4	0	0.00	0.00	0.04	Yes
S8	1/9/2003	4:53:00 PM	1.6	0	0.00	0.10	0.17	No
S9	1/10/2003	4:30:00 PM	4	0	0.00	0.00	0.05	Yes
S10	1/13/2003	12:07:00 PM	3	0	0.00	0.11	0.15	No
S11	1/22/2003	7:21:00 AM	1.6	10.68	0.34	0.29	0.40	Yes
S12	1/22/2003	3:10:00 PM	2	4.06	0.43	0.48	0.68	No
S13	1/28/2003	8:00:00 AM	4	0	0.00	0.03	0.11	No
S14	1/28/2003	6:20:00 PM	4	0	0.00	0.00	0.21	Yes
S15	1/29/2003	5:02:00 PM	3	0.13	0.01	0.00	0.10	Yes
S16	1/30/2003	8:00:00 AM	2	15.2	1.53	1.28	1.81	Yes
S17	1/30/2003	1:53:00 PM	2.1	0	0.00	0.00	0.18	Yes
S18	1/30/2003	3:23:00 PM	1.6	0	0.00	0.14	0.28	No

CHAPTER 7 DISCUSSION OF ALGORITHM RESULTS

7.1 ALGORITHM APPLICATION

As mentioned earlier, the proposed algorithm was implemented in the ARIA system. ARIA could automatically calculate IID if supporting BTPs could be found in the IS database. Although the calculation for each incident takes seconds to complete, the preparation of historical traffic data is time consuming. Because of the time constraints of this project, the proposed algorithm was applied to only two sample corridors: the eastbound lanes of SR 520 on the Evergreen Point Floating Bridge and northbound I-405 between MP 1.68 and MP 15.75. The results for the two corridors are summarized in the following two sections.

7.2 SR 520 EVERGREEN POINT FLOATING BRIDGE

Fifty-four incidents occurred in the eastbound lanes of the SR 520 Evergreen Point Floating Bridge between November 1, 2002, and January 31, 2003. These included five non-injury collisions, four abandoned vehicle incidents, 12 disabled vehicle incidents, 21 blocking disabled vehicle incidents, six debris blocking traffic incidents, one injury collision, and five unknown category incidents. Table 7-1 shows a breakdown of incident categories during this time period.

Table 7-1. Incident occurrence frequency on SR 520 over the three-month period

Description	Nov-02	Dec-02	Jan-03	Total
Abandoned Vehicle	1	1	2	4
Blocking Disabled	11	5	5	21
Debris Blocking Traffic	3	2	1	6
Disabled Vehicle	4	1	7	12
Injury Collision	0	0	1	1
Non-Injury Collision	4	0	1	5
N/A	0	4	1	5
Total	23	13	18	54

Because the SR 520 Evergreen Point Floating Bridge has very narrow shoulders (1 foot on each side) for both travel directions, any incident that occurs at this site will somehow block traffic movements and therefore result in travel delay when traffic demand exceeds the reduced capacity. Therefore, disabled vehicle (on shoulder) incidents can be considered blocking disabled incidents on the SR 520 Bridge. This implies that the impacts of each incident category on traffic flow at this site are distinctive from other freeway corridors with wider shoulders. For this reason, the research team expected higher average delays caused by incidents at this roadway section. Delays caused by each of these 54 incidents were calculated, and the results are summarized in tables 7-2 through 7-4. The "N/A" symbol indicates that IID of the incident could not be calculated because traffic data at the upstream and/or downstream stations during the incident were erroneous or missing (e.g., the data were not collected by loop detectors).

Table 7-2. Incident delay on the eastbound SR 520 Floating Bridge in November 2002

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	IID (veh hrs)
Q1	BK	Sun	2002-11-03	13:17:00	13:30:00	3.7	Blocking Disabled	0.92
Q2	BK	Mon	2002-11-04	09:08:00	09:17:00	3	Blocking Disabled	N/A
Q3	BK	Mon	2002-11-04	09:35:00	09:41:00	1.6	Blocking Disabled	N/A
Q4	BK	Mon	2002-11-04	09:49:00	09:59:00	3	Blocking Disabled	N/A
Q5	BK	Tue	2002-11-05	09:18:00	09:30:00	3.8	Non-Injury Collision	N/A
Q6	SH	Wed	2002-11-06	07:25:00	07:38:00	4	Disabled Vehicle	0.05
Q7	BK	Wed	2002-11-06	17:07:00	17:15:00	3.7	Blocking Disabled	0.03
Q8	BK	Thu	2002-11-07	13:35:00	13:45:00	2.6	Non-Injury Collision	4.48
Q9	BK	Fri	2002-11-08	15:10:00	15:23:00	3.5	Debris Blocking Traffic	4.44
Q10	BK	Sun	2002-11-10	12:58:00	13:04:00	2.7	Blocking Disabled	0
Q11	BK	Tue	2002-11-12	17:55:00	18:06:00	3	Blocking Disabled	0.16
Q12	SH	Fri	2002-11-15	16:49:00	17:15:00	3	Disabled Vehicle	4.48
Q13	SH	Mon	2002-11-18	06:35:00	06:57:00	4	Disabled Vehicle	0.02
Q14	BK	Mon	2002-11-18	08:33:00	08:43:00	3	Blocking Disabled	204.15
Q15	BK	Mon	2002-11-18	15:23:00	15:32:00	3	Debris Blocking Traffic	0.07
Q16	BK	Tue	2002-11-19	15:40:00	15:52:00	1.6	Non-Injury Collision	0
Q17	BK	Tue	2002-11-19	17:27:00	17:47:00	3	Non-Injury Collision	0.4
Q18	BK	Wed	2002-11-20	08:05:00	08:18:00	3.7	Blocking Disabled	N/A
Q19	SH	Thu	2002-11-21	14:09:00	14:42:00	1.6	Disabled Vehicle	2.67
Q20	SH	Fri	2002-11-22	06:30:00	06:55:00	4	Abandoned Vehicle	0
Q21	BK	Mon	2002-11-25	10:20:00	10:40:00	3	Blocking Disabled	N/A
Q22	BK	Mon	2002-11-25	12:40:00	12:57:00	3	Debris Blocking Traffic	N/A
Q23	BK	Fri	2002-11-29	10:10:00	10:27:00	3.2	Blocking Disabled	0.45

Note: veh hrs = vehicle-hours

Table 7-3. Incident delay on the eastbound SR 520 Floating Bridge in December 2002

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	IID (veh hrs)
R1	BK	Thu	2002-12-05	08:43:00	08:50:00	3	Blocking Disabled	N/A
R2	BK	Sat	2002-12-07	09:38:00	09:46:00	3.7	Blocking Disabled	N/A
R3	BK	Sat	2002-12-07	15:44:00	16:05:00	1.6	Other Contact	N/A
R4	BK	Sat	2002-12-07	15:45:00	16:10:00	1.7	Other Contact	N/A
R5	BK	Sun	2002-12-08	18:23:00	19:48:00	3.8	Blocking Disabled	0
R6	SH	Sun	2002-12-08	19:15:00	19:48:00	3.8	Disabled Vehicle	0
R7	BK	Fri	2002-12-13	09:18:00	09:29:00	3	Other Contact	N/A
R8	BK	Tue	2002-12-17	14:00:00	15:03:00	4	Abandoned Vehicle	N/A
R9	BK	Fri	2002-12-20	14:30:00	15:02:00	2.3	Debris Blocking Traffic	0.06
R10	BK	Fri	2002-12-20	14:50:00	15:03:00	1.6	Blocking Disabled	44.35
R11	BK	Fri	2002-12-27	08:40:00	09:00:00	4	Debris Blocking Traffic	N/A
R12	SH	Fri	2002-12-27	14:20:00	14:31:00	3.7	Other Contact	N/A
R13	BK	Sat	2002-12-28	08:07:00	08:20:00	3	Blocking Disabled	N/A

Table 7-4. Incident delay on the eastbound SR 520 Floating Bridge in January 2003

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	IID (veh hrs)
S1	BK	Thu	1/2/2003	1:50:00 PM	2:02:00 PM	3	Non-Injury Collision	0
S2	BK	Sat	1/4/2003	10:53:00 AM	11:05:00 AM	2.7	Blocking Disabled	742.78
S3	BK	Sat	1/4/2003	11:06:00 AM	11:13:00 AM	2.7	Blocking Disabled	1573.13
S4	BK	Sat	1/4/2003	12:03:00 PM	12:12:00 PM	2.7	Blocking Disabled	578.23
S5	SH	Mon	1/6/2003	8:45:00 AM	9:21:00 AM	4	Abandoned Vehicle	191.67
S6	SH	Mon	1/6/2003	1:10:00 PM	1:45:00 PM	3	Other Contact	0.46
S7	SH	Mon	1/6/2003	2:30:00 PM	2:48:00 PM	4	Disabled Vehicle	0
S8	SH	Thu	1/9/2003	4:53:00 PM	5:22:00 PM	1.6	Disabled Vehicle	0
S9	SH	Fri	1/10/2003	4:30:00 PM	4:52:00 PM	4	Disabled Vehicle	0
S10	SH	Mon	1/13/2003	12:07:00 PM	12:17:00 PM	3	Disabled Vehicle	0
S11	BK	Wed	1/22/2003	7:21:00 AM	7:54:00 AM	1.6	Blocking Disabled	10.68
S12	BK	Wed	1/22/2003	3:10:00 PM	3:20:00 PM	2	Debris Blocking Traffic	4.06
S13	SH	Tue	1/28/2003	8:00:00 AM	8:22:00 AM	4	Disabled Vehicle	0
S14	SH	Tue	1/28/2003	6:20:00 PM	6:35:00 PM	4	Disabled Vehicle	0
S15	SH	Wed	1/29/2003	5:02:00 PM	5:30:00 PM	3	Abandoned Vehicle	0.13
S16	BK	Thu	1/30/2003	8:00:00 AM	8:10:00 AM	2	Blocking Disabled	15.2
S17	BK	Thu	1/30/2003	1:53:00 PM	3:05:00 PM	2.1	Injury Collision	0
S18	SH	Thu	1/30/2003	3:23:00 PM	3:37:00 PM	1.6	Disabled Vehicle	0

According to the calculated IID, a blocking disabled incident always resulted in delay on the eastbound SR 520 Evergreen Point Floating Bridge. In the three-month period from November 2002 to January 2003, the three longest IID were caused by the three blocking disabled incidents that occurred on January 4, 2003 (i.e., the S2, S3, and S4 incidents in Table 7-4). Their IID values were 742.74, 1573.13, and 578.23 vehicle-hours, respectively. Note that given their Start times, the S3 incident might have been caused by the S2 incident.

Another interesting finding was that longer incident duration did not necessarily lead to longer incident delay. For instance, the abandoned vehicle incident that occurred between 17:02:00 and 17:30:00 (lasted for 28 minutes) on January 29, 2003, had an incident delay of 0.13 vehicle-hours, but the debris blocking traffic incident that occurred between 15:10:00 and 15:20:00 (lasted for 10 minutes) on January 22, 2003, was 4.06 vehicle-hours. Therefore, the severity of an incident should not be evaluated simply by the incident duration.

7.3 I-405 CORRIDOR

Between MP 1.68 and 15.75 on northbound I-405, 147 incidents occurred in January through March of 2003. Table 7-5 shows a breakdown of incident categories during this period. Within the three-month period, this freeway section had 16 abandoned vehicle, 16 blocking disabled, four debris blocking traffic, 66 disabled vehicle (on shoulder), six injury collision, 18 non-injury collision, and 21 unknown category incidents. Note that IID values of certain incidents could not be calculated because of missing and/or bad loop data. Again, the "N/A" symbol denotes that the IID of the incident could not be estimated because traffic data during the incident were erroneous or missing.

Table 7-5. Incident occurrence frequency on I-405 over the three-month period

Description	January	February	March	Total
Abandoned Vehicle	5	2	9	16
Blocking Disabled	10	4	2	16
Debris Blocking Traffic	0	3	1	4
Disabled Vehicle	19	16	31	66
Injury Collision	1	3	2	6
Non-Injury Collision	5	6	7	18
N/A	12	6	3	21
Total	52	40	55	147

After the loop data from 41 loop stations on this I-405 section had been analyzed, the research team identified ES-621D (located at MP 2.00), ES-626D (located at MP

2.46), and ES-634R (located at MP 4.11) as bad loop stations for the months of January and February 2003. The loops recorded zero traffic counts for several whole days over the two months. However, the detectors began working again in March 2003.

Delay induced by each incident was easily estimated by the ARIA system implementing the proposed algorithm. Tables 7-6, 7-7, and 7-8 display the IID for January, February, and March 2003, respectively. Several incidents did not cause any extra delay, as the calculated IID was zero. This could be explained by the low number of vehicles traveling during the time interval when the incident occurred. If traffic demand is lower than the remaining freeway capacity during the incident duration, there should not be any IID.

Table 7-6. Incident delay on northbound I-405 in January 2003

ID	Code	Day	Date	Start Time	End Time	Mile Post	Description	Recurrent Delay (veh hrs)	Incident Delay (veh hrs)
I1	BK	Thu	2003/01/02	11:10:00	11:48:00	13.8	Non-Injury Collision	0.21	1.07
I2	BK	Thu	2003/01/02	11:16:00	11:18:00	13.5	Blocking Disabled	1770.63	1533.09
I3	SH	Fri	2003/01/03	8:25:00	8:45:00	7	Disabled Vehicle	0	0
I4	SH	Mon	2003/01/06	6:52:00	6:54:00	11	Abandoned Vehicle	0.84	0
I5	SH	Mon	2003/01/06	7:35:00	7:38:00	11	Disabled Vehicle	0.64	225.82
I6	BK	Mon	2003/01/06	13:00:00	13:45:00	4	Blocking Disabled	1.6	0
I7	SH	Mon	2003/01/06	14:20:00	14:47:00	7	Disabled Vehicle	0.04	0.14
I8	SH	Mon	2003/01/06	17:23:00	17:40:00	2.9	Disabled Vehicle	N/A	N/A
I9	BK	Mon	2003/01/06	18:15:00	18:35:00	13.8	N/A	0.19	0.46
I10	BK	Tue	2003/01/07	9:16:00	9:20:00	11.2	N/A	N/A	N/A
I11	BK	Wed	2003/01/08	9:05:00	9:30:00	5.5	Non-Injury Collision	1.65	3716.5
I12	SH	Wed	2003/01/08	12:50:00	12:56:00	4	Disabled Vehicle	N/A	N/A
I13	BK	Wed	2003/01/08	15:01:00	15:28:00	9.3	N/A	0.19	0
I14	SH	Wed	2003/01/08	15:35:00	15:40:00	14	Disabled Vehicle	N/A	N/A
I15	BK	Thu	2003/01/09	10:15:00	10:40:00	11	Non-Injury Collision	N/A	N/A
I16	BK	Thu	2003/01/09	11:00:00	11:15:00	5	Blocking Disabled	N/A	N/A
I17	BK	Fri	2003/01/10	6:48:00	6:57:00	11.5	Blocking Disabled	1.07	8376.15
I18	BK	Fri	2003/01/10	6:50:00	8:30:00	5.4	Blocking Disabled	0.15	0
I19	SH	Fri	2003/01/10	13:40:00	13:50:00	11.2	Disabled Vehicle	N/A	N/A
I20	BK	Mon	2003/01/13	6:45:00	7:06:00	13.5	Non-Injury Collision	N/A	N/A

I21	BK	Mon	2003/01/13	7:36:00	7:40:00	4.7	N/A	N/A	N/A
I22	BK	Tue	2003/01/14	7:00:00	8:06:00	13	Blocking Disabled	0.07	0
I23	BK	Tue	2003/01/14	7:30:00	7:37:00	11.2	N/A	0.38	3753.09
I24	SH	Tue	2003/01/14	13:30:00	13:43:00	11.2	Disabled Vehicle	0.08	0
I25	SH	Tue	2003/01/14	14:25:00	14:39:00	11.2	Disabled Vehicle	4.68	0
I26	SH	Tue	2003/01/14	15:20:00	15:25:00	10.3	Disabled Vehicle	4065.63	5070.44
I27	SH	Tue	2003/01/14	15:32:00	15:35:00	13.7	Disabled Vehicle	2.15	0
I28	BK	Tue	2003/01/14	16:04:00	16:06:00	13.8	N/A	0.83	0
I29	SH	Tue	2003/01/14	17:02:00	17:14:00	13.1	Disabled Vehicle	1810.05	4541.1
I30	BK	Wed	2003/01/15	16:04:00	16:06:00	13.8	N/A	0.09	0.07
I31	SH	Wed	2003/01/15	17:58:00	18:01:00	10.5	Disabled Vehicle	3421.57	0
I32	BK	Thu	2003/01/16	7:12:00	7:29:00	4.7	N/A	0	0
I33	BK	Thu	2003/01/16	12:30:00	12:40:00	3	Blocking Disabled	0.02	3152.21
I34	BK	Fri	2003/01/17	6:45:00	7:26:00	9	Injury Collision	902.89	0
I35	BK	Fri	2003/01/17	9:30:00	9:39:00	10	Blocking Disabled	N/A	N/A
I36	SH	Fri	2003/01/17	16:58:00	17:00:00	10.2	Abandoned Vehicle	N/A	N/A
I37	SH	Mon	2003/01/20	10:08:00	10:10:00	9	Abandoned Vehicle	0.34	0
I38	SH	Mon	2003/01/20	17:43:00	17:51:00	11	Disabled Vehicle	0.26	471.95
I39	SH	Tue	2003/01/21	8:54:00	8:59:00	10	Disabled Vehicle	1839.53	0
I40	SH	Tue	2003/01/21	9:30:00	9:52:00	4	Blocking Disabled	0	0
I41	BK	Tue	2003/01/21	13:11:00	13:49:00	4	N/A	0	0.02
I42	SH	Tue	2003/01/21	13:45:00	13:47:00	12.6	Abandoned Vehicle	154.28	0
I43	SH	Wed	2003/01/22	6:20:00	6:23:00	12.5	Disabled Vehicle	0.82	0
I44	SH	Thu	2003/01/23	7:35:00	7:48:00	11.1	Disabled Vehicle	0.39	165.17
I45	BK	Fri	2003/01/24	13:47:00	13:57:00	13.5	Non-Injury Collision	2502.05	838.75
I46	SH	Fri	2003/01/24	16:10:00	16:12:00	12.7	Abandoned Vehicle	1.47	0
I47	SH	Mon	2003/01/27	6:33:00	6:49:00	10	Disabled Vehicle	1042.04	0
I48	SH	Wed	2003/01/29	13:00:00	13:05:00	2	Disabled Vehicle	0.59	0
I49	BK	Thu	2003/01/30	9:37:00	10:30:00	5.4	N/A	0	0
I50	BK	Thu	2003/01/30	13:38:00	14:20:00	12.9	N/A	0	0
I51	BK	Fri	2003/01/31	12:50:00	13:14:00	2.5	Blocking Disabled	0.73	0
I52	BK	Fri	2003/01/31	13:33:00	13:56:00	2	N/A	3.83	0

Table 7-7. Incident delay on northbound I-405 in February 2003

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Recurrent Delay (veh hrs)	Incident Delay (veh hrs)
J1	SH	Mon	2003/02/03	9:01:00	9:02:00	11	Disabled Vehicle	0.64	1.62
J2	BK	Tue	2003/02/04	9:41:00	9:59:00	10.5	N/A	0.88	0
J3	SH	Tue	2003/02/04	11:00:00	11:09:00	13.6	Disabled Vehicle	0.38	1401.81
J4	SH	Wed	2003/02/05	17:55:00	17:58:00	12.6	Abandoned Vehicle	0.35	4054.81
J5	BK	Thu	2003/02/06	9:58:00	10:01:00	13	Debris Blocking Traffic	N/A	N/A
J6	BK	Thu	2003/02/06	17:08:00	17:41:00	13.6	Blocking Disabled	0.09	327.93
J7	BK	Fri	2003/02/07	7:15:00	7:17:00	7.5	N/A	0	0.8
J8	SH	Fri	2003/02/07	8:53:00	9:03:00	12.8	Disabled Vehicle	0.95	2115.06
J9	BK	Mon	2003/02/10	7:28:00	7:55:00	9.5	Non-Injury Collision	0.32	0
J10	SH	Mon	2003/02/10	8:06:00	8:11:00	3	Disabled Vehicle	0.64	0
J11	BK	Mon	2003/02/10	13:10:00	15:30:00	10	Blocking Disabled	2.04	281.48
J12	SH	Tue	2003/02/11	9:38:00	9:56:00	11.1	Disabled Vehicle	0.73	1.92
J13	BK	Tue	2003/02/11	10:16:00	10:23:00	13.8	N/A	0.85	1712.51
J14	BK	Wed	2003/02/12	8:50:00	9:10:00	9	Non-Injury Collision	N/A	N/A
J15	BK	Thu	2003/02/13	10:45:00	11:15:00	2.5	Debris Blocking Traffic	0.03	0
J16	BK	Thu	2003/02/13	10:58:00	10:59:00	10.55	N/A	5537.04	0
J17	SH	Fri	2003/02/14	17:20:00	17:34:00	13.4	Disabled Vehicle	2528.54	0
J18	SH	Mon	2003/02/17	6:38:00	6:49:00	9	Disabled Vehicle	411.78	0
J19	SH	Mon	2003/02/17	7:32:00	8:26:00	12	Disabled Vehicle	8.79	0
J20	BK	Mon	2003/02/17	11:41:00	12:06:00	12.5	N/A	0.31	2503.84
J21	BK	Tue	2003/02/18	9:45:00	10:33:00	12.9	Injury Collision	N/A	N/A
J22	BK	Tue	2003/02/18	14:05:00	14:09:00	11.5	Debris Blocking Traffic	5.47	0
J23	BK	Wed	2003/02/19	10:13:00	13:45:00	7	Non-Injury Collision	209.03	0
J24	SH	Wed	2003/02/19	14:05:00	14:09:00	10.1	Abandoned Vehicle	247.33	0
J25	BK	Wed	2003/02/19	17:46:00	17:51:00	9.3	Blocking Disabled	6.23	0
J26	BK	Thu	2003/02/20	6:45:00	7:10:00	9	Non-Injury Collision	456.72	0
J27	SH	Thu	2003/02/20	9:24:00	9:34:00	12	Disabled Vehicle	0.04	0.22
J28	BK	Thu	2003/02/20	9:54:00	10:30:00	10	Non-Injury Collision	N/A	N/A
J29	SH	Fri	2003/02/21	8:47:00	8:49:00	10	Disabled Vehicle	6515.14	0
J30	SH	Fri	2003/02/21	16:10:00	16:24:00	14	Disabled Vehicle	633.78	2311.5
J31	BK	Mon	2003/02/24	8:55:00	10:15:00	5	Injury Collision	0.07	0
J32	BK	Mon	2003/02/24	17:38:00	17:51:00	10	Blocking Disabled	1321.81	0
J33	BK	Tue	2003/02/25	9:02:00	10:11:00	6.5	N/A	N/A	N/A
J34	SH	Tue	2003/02/25	17:48:00	18:30:00	10	Disabled Vehicle	0	0
J35	SH	Tue	2003/02/25	17:55:00	18:08:00	10	Disabled Vehicle	0	0
J36	BK	Wed	2003/02/26	8:24:00	8:45:00	9	Non-Injury Collision	N/A	N/A
J37	SH	Wed	2003/02/26	16:37:00	16:40:00	13.8	Disabled Vehicle	N/A	N/A
J38	SH	Thu	2003/02/27	17:55:00	18:19:00	13.8	Disabled Vehicle	2.24	570.02
J39	SH	Fri	2003/02/28	12:05:00	12:07:00	12	Disabled Vehicle	1.42	0
J40	BK	Fri	2003/02/28	16:05:00	16:20:00	10	Injury Collision	N/A	N/A

Table 7-8. Incident-induced delay on northbound I-405 in March 2003

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Recurrent Delay (veh hrs)	Incident Delay (veh hrs)
K1	SH	Sun	3/2/2003	9:05:00	9:08:00	14.9	Abandoned Vehicle	N/A	N/A
K2	SH	Mon	3/3/2003	14:00:00	14:20:00	14.9	Disabled Vehicle	1823.88	0
K3	SH	Tue	3/4/2003	13:31:00	13:34:00	12.4	N/A	0.97	0
K4	SH	Tue	3/4/2003	14:05:00	14:08:00	14.9	Abandoned Vehicle	1753.56	0
K5	SH	Tue	3/4/2003	14:38:00	14:49:00	6.0	Disabled Vehicle	0.12	0.16
K6	SH	Wed	3/5/2003	6:25:00	6:29:00	15.0	Disabled Vehicle	1753.56	1140.34
K7	SH	Wed	3/5/2003	7:58:00	8:07:00	15.0	Disabled Vehicle	0.01	312.61
K8	SH	Wed	3/5/2003	13:15:00	13:22:00	15.3	N/A	1809.01	0
K9	SH	Wed	3/5/2003	15:40:00	16:01:00	10.3	Disabled Vehicle	6420.77	0
K10	SH	Wed	3/5/2003	16:07:00	16:14:00	15.0	Disabled Vehicle	899.66	0
K11	SH	Wed	3/5/2003	16:10:00	16:40:00	7.0	Disabled Vehicle	204.73	0
K12	BK	Thu	3/6/2003	8:49:00	9:02:00	15.0	Non-Injury Collision	1199.98	0
K13	SH	Fri	3/7/2003	16:59:00	17:04:00	2.2	Disabled Vehicle	N/A	N/A
K14	SH	Sun	3/9/2003	14:00:00	14:30:00	9.3	Disabled Vehicle	0.07	0
K15	BK	Mon	3/10/2003	8:10:00	8:44:00	14.0	Blocking Disabled	6.2	0
K16	SH	Mon	3/10/2003	11:34:00	11:35:00	10.0	Disabled Vehicle	1528.87	0
K17	SH	Mon	3/10/2003	16:52:00	16:54:00	10.0	Abandoned Vehicle	7679.65	0
K18	SH	Mon	3/10/2003	16:58:00	17:09:00	15.1	Disabled Vehicle	899.71	0
K19	SH	Tue	3/11/2003	12:40:00	12:48:00	4.5	Disabled Vehicle	409.66	0
K20	BK	Wed	3/12/2003	12:20:00	12:47:00	5.0	Non-Injury Collision	0.13	0
K21	SH	Wed	3/12/2003	12:45:00	12:56:00	14.0	Disabled Vehicle	634.05	193.22
K22	SH	Wed	3/12/2003	18:14:00	19:31:00	15.5	Disabled Vehicle	0.92	0
K23	SH	Thu	3/13/2003	18:10:00	18:30:00	12.3	Disabled Vehicle	292.35	0
K24	SH	Fri	3/14/2003	8:45:00	8:53:00	15.0	Disabled Vehicle	2117.38	0
K25	SH	Fri	3/14/2003	12:31:00	12:34:00	15.0	Abandoned Vehicle	854.55	0
K26	SH	Fri	3/14/2003	13:20:00	13:39:00	9.0	Abandoned Vehicle	446.24	0
K27	SH	Fri	3/14/2003	16:55:00	17:05:00	14.9	Disabled Vehicle	0.12	0
K28	SH	Mon	3/17/2003	6:44:00	6:48:00	9.0	Disabled Vehicle	0.05	0
K29	SH	Mon	3/17/2003	12:03:00	12:25:00	11.0	Disabled Vehicle	0.52	0
K30	SH	Mon	3/17/2003	14:50:00	14:59:00	10.4	Disabled Vehicle	3260.1	0
K31	SH	Mon	3/17/2003	15:04:00	15:06:00	14.5	Abandoned Vehicle	0.18	0
K32	SH	Mon	3/17/2003	15:24:00	15:31:00	2.7	Non-Injury Collision	N/A	N/A
K33	SH	Tue	3/18/2003	15:00:00	15:17:00	5.4	Non-Injury Collision	0.42	5
K34	SH	Tue	3/18/2003	15:50:00	16:15:00	15.3	Disabled Vehicle	909.52	0
K35	SH	Thu	3/20/2003	15:15:00	15:35:00	14.9	Disabled Vehicle	N/A	N/A
K36	SH	Fri	3/21/2003	5:46:00	5:54:00	15.1	Abandoned Vehicle	0.08	0
K37	SH	Sat	3/22/2003	13:56:00	14:03:00	15.3	Disabled Vehicle	0.01	2714.38
K38	BK	Sat	3/22/2003	15:32:00	15:49:00	8.0	N/A	5044.02	0
K39	SH	Sun	3/23/2003	16:47:00	16:50:00	11.1	Abandoned Vehicle	N/A	N/A
K40	SH	Mon	3/24/2003	8:58:00	9:00:00	15.0	Disabled Vehicle	0.06	0
K41	SH	Mon	3/24/2003	9:15:00	9:18:00	9.0	Disabled Vehicle	721.28	0
K42	BK	Mon	3/24/2003	14:35:00	15:12:00	5.4	Debris Blocking Traffic	0.02	0
K43	SH	Mon	3/24/2003	14:42:00	15:01:00	15.3	Blocking Disabled	0	2355.22

K44	N/A	Mon	3/24/2003	17:47:00	17:54:00	5.4	Disabled Vehicle	316.5	47.94
K45	SH	Tue	3/25/2003	9:08:00	9:16:00	15.0	Non-Injury Collision	318.52	6067.59
K46	SH	Tue	3/25/2003	11:35:00	11:48:00	15.3	Disabled Vehicle	1817.06	6432.31
K47	SH	Tue	3/25/2003	16:19:00	16:23:00	14.9	Abandoned Vehicle	N/A	N/A
K48	BK	Tue	3/25/2003	16:45:00	17:10:00	5.0	Non-Injury Collision	N/A	N/A
K49	BK	Tue	3/25/2003	16:48:00	17:19:00	6.9	Injury Collision	N/A	N/A
K50	BK	Tue	3/25/2003	17:10:00	17:30:00	5.0	Injury Collision	N/A	N/A
K51	SH	Tue	3/25/2003	17:30:00	17:40:00	3.0	Disabled Vehicle	N/A	N/A
K52	SH	Tue	3/25/2003	18:15:00	18:30:00	14.9	Disabled Vehicle	N/A	N/A
K53	SH	Thu	3/27/2003	11:04:00	11:08:00	13.0	Disabled Vehicle	N/A	N/A
K54	SH	Sun	3/30/2003	14:00:00	14:04:00	14.8	Disabled Vehicle	853.99	0
K55	SH	Mon	3/31/2003	10:07:00	10:20:00	13.0	Non-Injury Collision	0.12	2270.64

Statistics for IID by incident category are summarized in Table 7-9. At this study site, no fatal accidents occurred during the three-month study period. Although two injury accidents were observed, both of them occurred during off-peak periods and did not cause any delay. With the absence of fatal accidents and the sparse data on injury collision over the three-month study period, the calculated statistics showed that non-injury collision was the incident category with the most noticeable impacts on freeway traffic flow. The median value of IID introduced by a non-injury collision was 1.07 vehicle-hours, while the medians of IID values for other observed incident types were 0.0. The 0.0 or small median for IID does not mean that there were no impacts of this incident type on freeway traffic. For example, the maximum calculated IID of blocking disabled vehicle incidents was over 8,000 vehicle-hours, the highest among all the observed incidents over the three-month study period. However, the 0.0 median value of a specific type of incident does imply that most incidents of this type were efficiently handled by the existing incident response teams or occurred when traffic demand was sufficiently low. Note that because of the small sample numbers in the selected three-month period, the statistics for IID for debris blocking traffic and injury collision incidents may not be meaningful and should be ignored.

Table 7-9. Statistics of incident-induced delays (in vehicle-hours)

Description	Frequency	Median	SD	Max
Abandoned Vehicle	12	0	1,124	4,054
Blocking Disabled	14	0	2,317	8,376
Debris Blocking Traffic	3	0	0	0
Disabled Vehicle	56	0	1,315	6,432
Injury Collision	2	0	0	0
Non-Injury Collision	11	1.07	2,034	6,068

Although there were no fatality collisions and not enough injury collisions observed within the analysis time period along the studied corridor, the delay caused by fatality and injury collisions is expected to be much higher than that produced by a non-injury collision because the average AC interval for fatality and injury collisions is longer than 3 hours (Incident Response Quarterly Update 2006).

As mentioned earlier, the incident category with the longest median was non-injury collision. The number of non-injury collisions increased remarkably every year, and in 2005 the frequency of occurrence rose to over 5,500 incidents per year in Washington State. Therefore, delays caused by these incidents are tremendous. WSDOT may want to develop a specific strategy to deal with non-injury collisions. It is worth mentioning that the variation of incident delay in this category is high, and this may correspond to the different numbers of involved vehicles, collision severity, and the types of damaged vehicles.

For the rest of incident categories, similar to the eastbound SR 520 Floating Bridge, the longest IID along northbound I-405 was caused by a blocking disabled vehicle incident. Interestingly, during the study, the research team found that certain disabled vehicle incidents can cause very high incident delays. We suspect that these long delays may be associated with multiple incidents that are not properly recorded. Anyway, this finding was unexpected and may warrant further study. Note that even though the disabled vehicle incident is not highly ranked by median delay, its frequency of occurrence is very high (about 50 percent of all incidents).

It is worth mentioning that the severity of incident impacts on freeway traffic, though difficult to evaluate accurately, may depend on two main factors: (1) traffic demand during the incident and (2) remaining freeway capacity, which is related to the number of blocked traffic lanes. However, because information on remaining capacity is difficult to obtain (the number of blocked lanes varies from incident to incident and changes with the process of incident clearance), our analysis could not incorporate such information precisely in the simulation experiments. Furthermore, because of the limited size of incident data in this study, only the disabled vehicle incident category had enough incident samples in different traffic flow levels. Therefore, the average of non-zero IID in each traffic demand level was calculated only for disabled vehicle incidents, and the results are shown in Table 7-10. It is obvious that the incident impact is highly related to traffic flow level. The impacts of incidents tend to be longer with higher traffic demand. This implies that the early detection of incidents and the early control of traffic demand (e.g., ramp meter control) should play an important role in mitigating the impacts of incidents.

Table 7-10. Incident-induced delay of disabled vehicles (in vehicle-hours)

Flow	Average IID
500-1,000	0
1,001-1,500	825
1,501-2,000	1,742
>2,000	2,395

Finally, we want to mention that the proposed algorithm has its limitations. It is based on the deterministic queuing diagram, which assumes that both vehicle arrival and departure rates can be measured at the incident location and that vehicles’ physical lengths are negligible. However, freeway traffic sensors are discrete observation points that are normally away from incident locations. Also, vehicle queues are not point queues. Given the differences between reality and the assumptions, the proposed algorithm may produce noticeable errors, at least under certain conditions. The accuracy of the proposed algorithm depends largely on the quality of the BTPs and the quality of loop detector measurements. With newer traffic sensing technologies, high-resolution vehicle data have become available. These new data may be applied in future studies to improve the quality of IID estimates.

CHAPTER 8   CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

In this study, a new algorithm, based on a modified deterministic queuing theory, was developed for quantifying incident-induced delay (IID) on freeways. IID refers to the difference between the total delay and the recurrent travel delay, if any, at the time and location influenced by an incident. The innovative aspect of the delay calculation in this study is the use of a dynamic traffic volume-based background traffic profile (BTP), which is considered a more accurate representation of prevailing traffic conditions, for recurrent delay calculations. The BTP is selected on the basis of the actual arrival traffic profile (ATP) at the upstream station of the incident location and is specific to the traffic condition associated with each incident. By using the traffic volume-based BTPs, the calculated delays should be much more accurate than using a constant background profile determined by time of day.

This algorithm was implemented in a database-driven computerized system called ARIA to automate all the computational processes. To verify the accuracy and validity of the algorithm, a microscopic simulation model for the Evergreen Point Floating Bridge on SR 520 was developed with the VISSIM traffic simulation tool. The simulation model was calibrated by using on-site loop-observed data. Virtual loops were placed at exactly the same locations as the on-site loops in the simulation model. Traffic data collected from the virtual loops were used as inputs to the algorithm, and the simulation model-measured delays were used as the ground-truth data to check estimation accuracy. Results from the validity tests demonstrated that the proposed algorithm can provide reasonable estimates of IID.

The proposed algorithm for estimating IID over a freeway section can be extended for network-wide IID calculations as well. The ARIA system was applied to quantify the IIDs for all the 54 incidents that occurred from November 2002 till January 2003 on the eastbound SR 520 Evergreen Point Floating Bridge and all of the 147 incidents that occurred from January through March 2003 between MP 1.68 and 15.75 on northbound I-405. The IID estimates are valuable in helping us to better understand the costs of incidents. These estimation results may also help WSDOT improve its understanding of congestion-inducing incidents and select more effective countermeasures against incident-related traffic congestion on freeways.

The principal findings of this research are as follows:

1) The frequency of non-injury collisions increased significantly over the years. In 2005, over 5,500 non-injury collisions occurred on WSDOT freeways. Given that non-injury collisions cause longer delays than most incident types except injury collisions and fatal collisions, effective measures for reducing the number of non-injury collision are needed to reduce freeway delay.
2) The proposed algorithm and the ARIA system developed in this study demonstrated their effectiveness in calculating IID. ARIA has the potential to become an analytical tool for quantifying freeway delays and monitoring the impacts of operational changes.

8.2 RECOMMENDATIONS FOR FUTURE STUDY

While a number of researchers have confirmed the appropriateness of using a deterministic queuing diagram for delay calculation, several previous studies have also found that certain assumptions of the deterministic queuing theory are not appropriate and therefore may generate errors in travel delay estimates. Field collected vehicle delay data are needed to verify the proposed algorithm. Meanwhile, new algorithms, such as those that consider shock wave movements in traffic flow, need to be investigated in future research.

Additionally, a method for identifying the best traffic volume-based BTPs should be further improved and tested by using data from other freeway corridors. Also, because high-resolution traffic sensor data have become available, more accurate estimates of vehicle arrival and departure times and speeds at upstream and downstream sensor stations are feasible. Such detailed vehicle movement data will be helpful to improve the accuracy of IID estimates.

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GLOSSARY OF ACRONYMS

AC	Time interval from the Arrival Time to the Clearance Time of an incident
ARIA	Advanced Roadway Incident Analyzer System
ATP	Arrival Traffic Profile
BTP	Background Traffic Profile
CAD	Computer Aided Dispatch
CI	Confidence Interval
DTS	Data Transformation Services
DVB	Dynamic Volume Based
E/R	Entity-Relationship
F	Fire
FHWA	Federal Highway Administration
GPS	Global Positioning Systems
HM	Haz-Mat
IID	Incident-Induced Delay
IS	Incident Study
ITS	Intelligent Transportation System
LOS	Level of Service
MP	Milepost
NA	Time interval from the Notified Time to the Arrival Time of an incident

OC	Other Contact
PD	Property Damage
PSRC	Puget Sound Regional Council
SC	Supplementary Category
SN	Time interval from the Start Time to the Notified Time of an incident
SNA	Time interval from the Start Time to the Arrival Time of an incident
SNAC	Time interval from the Start Time to the Clearance Time of an incident
SR	State Route
SQL	Structured Query Language
STAR Lab	Smart Transportation Applications and Research Laboratory
TDAD	Traffic Data Acquisition and Distribution
TSMC	Traffic Systems Management Center
TRAC	Washington State Transportation Center
TRB	Transportation Research Board
VMT	Vehicle Miles Traveled
WITS	Washington Incident Tracking System
WSDOT	Washington State Department of Transportation
WSP	Washington State Patrol

REFERENCES

Al-Deek, H. M., A. Garib, and A.E. Radwan (1995). New Method for Estimating Freeway Incident Congestion. *Transportation Research Record 1494*. 30-39. Transportation Research Board. Washington D.C.

Cheevarunothai, P., Y. Wang, and N. L. Nihan (2007). Using Dual-Loop Event Data to Enhance Truck Data Accuracy. Transportation Research Record. *Transportation Research Record,* No. 1993. 131-137, Transportation Research Board, Washington, D.C.

Chien, S. I. J., and S. M. Chowdhury (2000). Simulation-Based Estimates of Delays at Freeway Work Zones. Transportation Research Board 80th Annual Meeting, Washington D.C., CD-ROM.

Cohen, H. and F. Southworth (1999). On the Measurement and Valuation of Travel Time Variability Due to Incidents on Freeways. *Journal of Transportation and Statistics*, Vol. 2 (2). 123-131.

Dutzik, T., and R. Pregulman (2003). “More Roads, More Traffic: Why Highway Constructions Won’t Solve Traffic Congestion in Washington.” WashPIRG Foundation.

Fu, L., and L.R. Rilett (1997). Real-Time Estimation of Incident Delay in Dynamic and Stochastic Networks. *Transportation Research Recoard 1603*, pp. 99-105. Transportation Research Board. Washington D.C.

Fu, L., and B. Hellinga (1997). Real-Time, Adaptive Prediction of Incident Delay for Advanced Traffic Management Systems. *Proceedings of the Annual Conference of the Canadian Institute of Transportation Engineers*, May 12-15, 2002 in Ottawa, Canada.

Garcia-Molina, H., J.D. Ullman, and J. Widom (2002). *Database Systems: The Complete Book*. Prentice-Hall, Inc. Upper Saddle River, New Jersey.

Gomes, G., A. May, and R. Horowitz (2004). Congested Freeway Microsimulation Model Using VISSIM. *Transportation Research Record 1876*. 71-81. Washington D.C.

Gupta, A. K., and V. K. Katiyar (2005). Analyses of Shock Waves and Jams in Traffic Flow. *Journal of Physics: Mathematical and General.* Volume 38. pp. 4069-4083.

Hallenbeck, M.E., J.M. Ishimaru, and J. Nee (2003). Measurement of Recurring versus Non-Recurring Congestion: Technical Report. Research report for Washington State Department of Transportation. WA-RD 568.1. Seattle.

Hurdle, V. F., and B. Son (2001). Shock Wave and Cumulative Arrival and Departure Models: Partners Without Conflict. *Transportation Research Record 1776*. 159-166. Transportation Research Board. Washington D.C.

Incident Response Quarterly Update. (2006). Washington State Department of Transportation.

Ishak, S.S. and H.M. Al-Deek (1998). “Fuzzy ART Neural Network Model for Automated Detection of Freeway Incidents.” *Transportation Research Record 1634*. 56-63. Transportation Research Board. Washington D.C.

Li, J., C. J. Lan, and X. Gu (2006). Estimation on Incident Delay and Its Uncertainty on Freeway Networks. Transportation Research Board 85th Annual Meeting, Washington D.C., CD-ROM.

Lighthill, M. J., and G. B. Whitham (1955). On Kimematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, Vol. 229, No. 1778, pp. 317-345.

Lin, W. H., and F. Daganzo (1997). “A Simple Detection Scheme for Delay-Inducing Freeway Incidents.” *Transportation Research, Part A*. Vol. 31(2). 141-155.

Lindley, J. A. (1987). A Methodology for Quantifying Urban Freeway Congestion. *Transportation Research Record 1132*. 1-7. Transportation Research Board. Washington D.C.

Mongeot, H., and J.B. Lesort (2000). Analytical expressions of incident-induced flow dynamic perturbations using the macroscopic theory and an extension of the lighthill and whitham theory. *Transpn. Res. Record*, 1710.

Morales, M. J. (1987). Analytical Procedures for Estimating Freeway Congestion. *ITE Journal*, Vol. 57 (1). 45-49.

Nam, D. H., and D. R. Drew (1996). Analyzing Freeway Traffic Under Congestion: Traffic Dynamics Approach. *Journal of Transportation Engineering*, Vol. 124 (3). pp. 208-212.

Nihan, L.N., Y. Wang, and P. Cheevarunothai (2006). “Improving Dual-Loop Truck (and Speed) Data: Quick Detection of Malfunctioning Loops and Calculation of Required Adjustments.” Research Report Washington State Department of Transportation (WSDOT), Agreement T2695, Task 57.

Olmstead, T. (1999). Pitfall to Avoid When Estimating Incident-Induced Delay by Using Deterministic Queuing Models. *Transportation Research Record 1683*, pp. 38-46. Transportation Research Board. Washington D.C.

PTV (2001). VISSIM User Manual – Version 4.10. PTV Planung Transport Verkehr AG, Karlsruhe, Germany.

PTV (2007). Incident Simulation Example, VISSIM 4.2 training folder with the installation CD-Rom, Germany.

Puget Sound Regional Council (PSRC) (2005). Growth in Traffic and Vehicle Miles Traveled. http://www.psrc.org/datapubs/pubs/trends/t2aug05.pdf. Accessed on July 5, 2006.

Rakha, H., and W. Zhang (2005). Consistency of Shock-Wave and Queuing Theory Procedures for Analysis of Roadway Bottlenecks. Transportation Research Board 84th Annual Meeting, Washington D.C., CD-ROM, Paper 05-1763.

Richards, P. I. (1956). Shock Waves on the Highway. *Operations Research*, Vol. 4, No. 1, pp. 42-51.

Ritchie, S. G. and R. L. Cheu (1993). "Simulations of Freeway Incident Detection Using Artificial Neural Networks." *Transportation Research C*, Vol. 1(3): 203-217.

Skabardonis, A., K. Petty, H. Noeimi, D. Rydzewski, and P. P. Varaiya (1996). I-880 Field Experiment: Data-Base Development and Incident Delay Estimation Procedures. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1554*, TRB, National Research Council, Washington, D.C., pp. 204-212.

Sullivan, E. C. (1997). New Model for Predicting Freeway Incidents and Incident Delays. *Journal of Transportation Engineering*, Vol. 123 (4), pp. 267-275.

Teng, H and Y. Qi. (2003). Application of Wavelet Technique for Freeway Incident Detection. *Transportation Research C*, Vol. 11, No. 3: 289-308.

Transportation Research Board. (2000). *Highway Capacity Manual*. National Research Council. Washington D.C.

WSDOT (2003). *Definitions and Instructions for WSDOT Incident Tracking System*. Internal document, Olympia, Washington.

WSDOT (2008). *Seattle Traffic Questions - Frequently Asked Questions*. Accessed online at http://www.wsdot.wa.gov/traffic/seattle/questions/ on May 22, 2008.