Final Technical Report
TNW2008-02
Research Project Agreement No. T4118, Task 03

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

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and in cooperation with

U.S. Department of Transportation
Federal Highway Administration

February 2008

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
TNW2008-02		

4. TITLE AND SUBTITLE

QUANTIFYING INCIDENT-INDUCED TRAVEL DELAYS ON FREEWAYS USING TRAFFIC SENSOR DATA

5. REPORT DATE

February 2008

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Yinhai Wang, Mark Hallenbeck, and Patikhom Cheevarunothai

8. PERFORMING ORGANIZATION REPORT NO.

TNW2008-02

9. PERFORMING ORGANIZATION NAME AND ADDRESS

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Seattle, WA 98195-2700

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

DTRS99-G-0010

12. SPONSORING AGENCY NAME AND ADDRESS

Research Office
Washington State Department of Transportation
Transportation Building, MS 47372
Olympia, Washington 98504-7372
Doug Brodin, Project Manager, 360-705-7972

13. TYPE OF REPORT AND PERIOD COVERED

Final Research Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the University of Washington and the US Department of Transportation.

16. ABSTRACT

Traffic congestion is a major operational problem for freeways in Washington State. Recent studies have estimated that more than 50% 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.

This research project developed a new algorithm for quantifying travel delays induced by different incident categories using traffic data extracted from archived loop detector data and incident log data recorded by the WSDOT Incident Response (IR) team. The algorithm applies a modified deterministic queuing theory to estimate incident-induced delay using one-minute aggregated loop detector data. Incident-induced delay refers to the difference between the total delay and the recurring travel delay at the time and location associated with the impact of incident. The specialty of the delay calculation in this study is the use of a dynamic traffic-volume-based background profile, which is considered a more accurate representative of prevailing traffic conditions. According to the test results, the proposed algorithm can provide good incident-induced delay estimates and capture the evolution of freeway traffic flow during incident duration. Since the actual traffic data measured by loop detectors are used in this study to compute vehicle arrival and departure rates for delay calculations, the estimated incident-induced delay should be much closer to the reality than simulation based estimates. 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.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Traffic Congestion, Incident Delay, Freeway Travel Time, Loop Data, Queuing Theory.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	79	

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EXECUTIVE SUMMARY

Recent studies have identified traffic incidents as the main cause of more than 50% of the traffic congestion on freeways. With a good understanding of incident-induced congestion, the Washington State Department of Transportation (WSDOT) will be able to select effective countermeasures against freeway traffic congestion. Unfortunately, little work has been done to develop a tool or methodology for improving our understanding of congestion-inducing incidents in Washington State.

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

IID refers to the difference between the total delay and the recurring travel delay at the time and location associated with the impact of incident. The innovative aspect 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. Moreover, to reflect different traffic patterns on weekdays and weekends, two sets of traffic-volume-based background profiles were generated and used for IID calculation.

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. To verify the accuracy and validity of the algorithm, a microscopic simulation model for the Evergreen Point Bridge on SR 520 was developed using the VISSIM traffic simulation tool. The simulation model was calibrated using data from onsite loop detectors. Virtual loops were placed at exactly the same locations as the onsite loops in the simulation model. Traffic data collected from the virtual loops were used as the inputs to the algorithm and the simulation model measured delays were used as the ground-truth data to check the estimation accuracy. The validity test results demonstrated that the proposed algorithm can provide reasonable estimates of IID and capture the evolution of traffic flow during incident duration.

The ARIA system was applied to quantify the IIDs for all the 18 incidents that occurred in January 2003 on the eastbound SR 520 Evergreen Point Bridge and all the 147 incidents that occurred from January through March 2003 between MP 1.68-15.75 of the I-405 corridor. The IID estimates are valuable for us to understand the cost of incidents.

Principal findings of this research are as follows:

1) An injury collision typically results in a very long delay on freeways. Its delay could be longer than 274% of the delay caused by a non-injury collision and longer than 19 times the delay from a blocking disabled vehicle incident.

2) The frequency of non-injury collision increased significantly over the years. In 2005, there were over 5,500 non-injury collisions that occurred on the freeways. Considering 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 collisions are needed to reduce freeway delay.

3) 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.

While a number of researchers confirmed the appropriateness of using a deterministic queuing diagram for delay calculation, several previous studies 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 considering 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 78.5 percent in 1980-1992 and 23.3 percent in 1992-2004 (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 makes it an urgent task to mitigate 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 found that more than 50% 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 due to the fact that incident-induced congestion may be effectively alleviated by cost-effective solutions 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's duration 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 based on loop occupancy data from the existing loop detection systems (Hallenbeck et al., 2003). The loop occupancy profile extracted directly from loop detector data is compared with the background occupancy profile to identify the occurrence and to estimate the influence of an individual incident. The background occupancy profile was fabricated from the medians of loop occupancy values collected on the weekdays without incidents. This algorithm is straightforward to apply. However, test results showed that this algorithm may not be sensitive enough to capture all incidents. In a preliminary analysis, we found that about 50% 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 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 few slow moving vehicles passing over a loop or heavy traffic of 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 using the loop-occupancy-based algorithm

(a) Site one: 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. Based on the availability of the traffic and incident log data, the development of a new algorithm for quantifying the total travel delay associated with different types of incidents becomes feasible. This study emphasizes the development of such an algorithm. Some known problems associated with previous algorithms were mitigated or eliminated from the proposed algorithm to enhance the estimation accuracy of IID. The proposed algorithm was implemented in a database-driven computer system to automate all the computation processes. All data are stored in a Microsoft Structured Query Language (SQL) server database and can be queried when needed. The more accurate estimates of IID help WSDOT identify suitable countermeasures against incident-related traffic congestion on freeways.

1.2 RESEARCH OBJECTIVES

The objectives of this study are:

- 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 for quantifying incident-induced travel delays on freeways using traffic sensor data; and
- To build up 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 impacts of traffic incidents, researchers have spent enormous effort developing procedures for detecting the occurrence of incidents. Methods used for incident detection include artificial neural network (Ritchie and Cheu, 1993; and Ishak and Al-Deek, 1998), a loop-occupancy-based approach (Lin and Daganzo, 1997), and wavelet technique (Teng and Qi, 2003). Application of these methods helps shorten the time needed for incident detection and hence reduce incident response time that consequently lowers incident impacts on traffic flow.

However, those incident-detection procedures do not provide information on the impact of incidents on traffic congestion. This led to an interest in developing procedures for estimating IID. The existing procedures are based on either the deterministic queuing theory or the 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 the unit of vehicle-hours. Morales (1987) developed an analytical procedure for estimating incident-induced traffic delay based on the queuing diagram. 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) applied a queuing diagram to estimate IID and provided several interesting observations, such as 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 based on the arrival time at the incident site and the distribution of the incident duration. This delay model captured 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 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 due to 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 was also 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 into the queuing theory for estimating IID on freeways. Their delay estimation model provided reasonable estimates of the mean as well as the variance of IID.

Traffic flow contains some similar characteristics to fluid flow. Therefore, there have been several attempts to use the theory of kinematic waves to explain behaviors of traffic flow. These attempts led to the development and application of shock wave analysis to estimate IID. The shock wave analysis was initiated when Lighthill and

Whitham (1955) showed how to characterize traffic flow through an analogy with 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. Thus, the first shock-wave-based model has been called the Lighthill, Whitham, and Richards model (the LWR model).

Al-Deek et al. (1995) proposed a new method to calculate the total incident delay using loop data and incident data based on the shock wave analysis. 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 comparison between the delay estimates from the queuing theory and shock wave analysis were conducted by several researchers. Nam and Drew (1998) mentioned 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 the derived background occupancy profile that represents the typical traffic condition for incident-free days. The difference between the two profiles is used to calculate the delay caused by the incidents. However, the test results of the process showed that traffic congestion sometimes moves from upstream to downstream locations, which might be questionable. Nonetheless, this study has 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 occurr on freeway networks in the State of Washington each year. The collection of incident log data in Washington has been independently conducted by three unique 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, the TSMC incident database, and the Computer Aided Dispatch (CAD) database, respectively.

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. According to the consultation with the WSDOT personnel who manage incident log data, certain data attributes in the CAD database are confidential; therefore, obtaining a large amount of CAD data is restricted. Similarly, the TSMC data is limited to certain freeway sections and periods of time due to their procedures of incident data collection. As a result, the WITS data between 2002-2005 for the major freeways and state highways in the Puget Sound region were selected for our analysis.

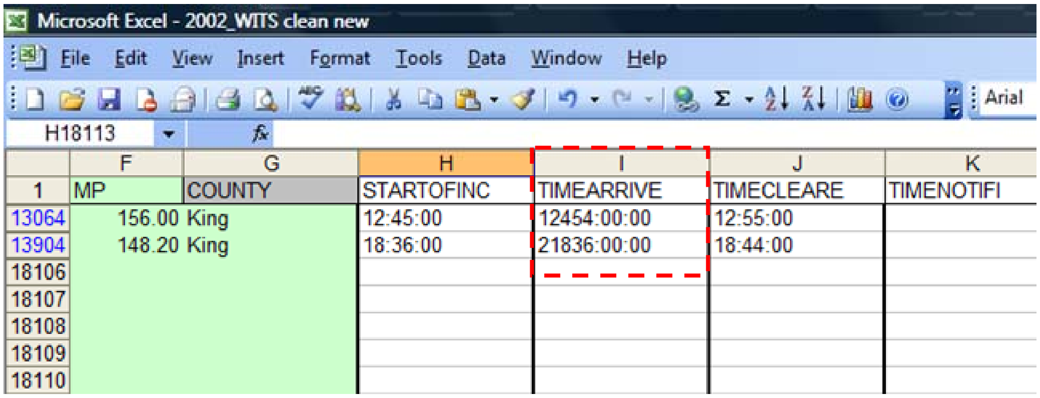
3.2 LOOP DATA COLLECTION

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 a one-minute level to reduce random data fluctuations caused by random traffic arrivals. This task was automatically completed by using a simple computer application the research team developed in C# language.

In addition to the aggregated one-minute loop data, a portion of high-resolution loop event data (60 Hz) collected in the previous project entitled "Improving Dual-Loop Truck (and Speed) Data: Quick Detection of Malfunctioning Loops and Calculation of Required Adjustments" (Nihan et al., 2006) was used in this study for 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 based on 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 are mainly data input errors, such as data storing in wrong columns, manual typing mistakes, and duplicated inputs. Figures 3-1 and 3-2 show examples of typical errors found in incident data. Cleaned incident data were then stored in a database table specifically designed for this study.

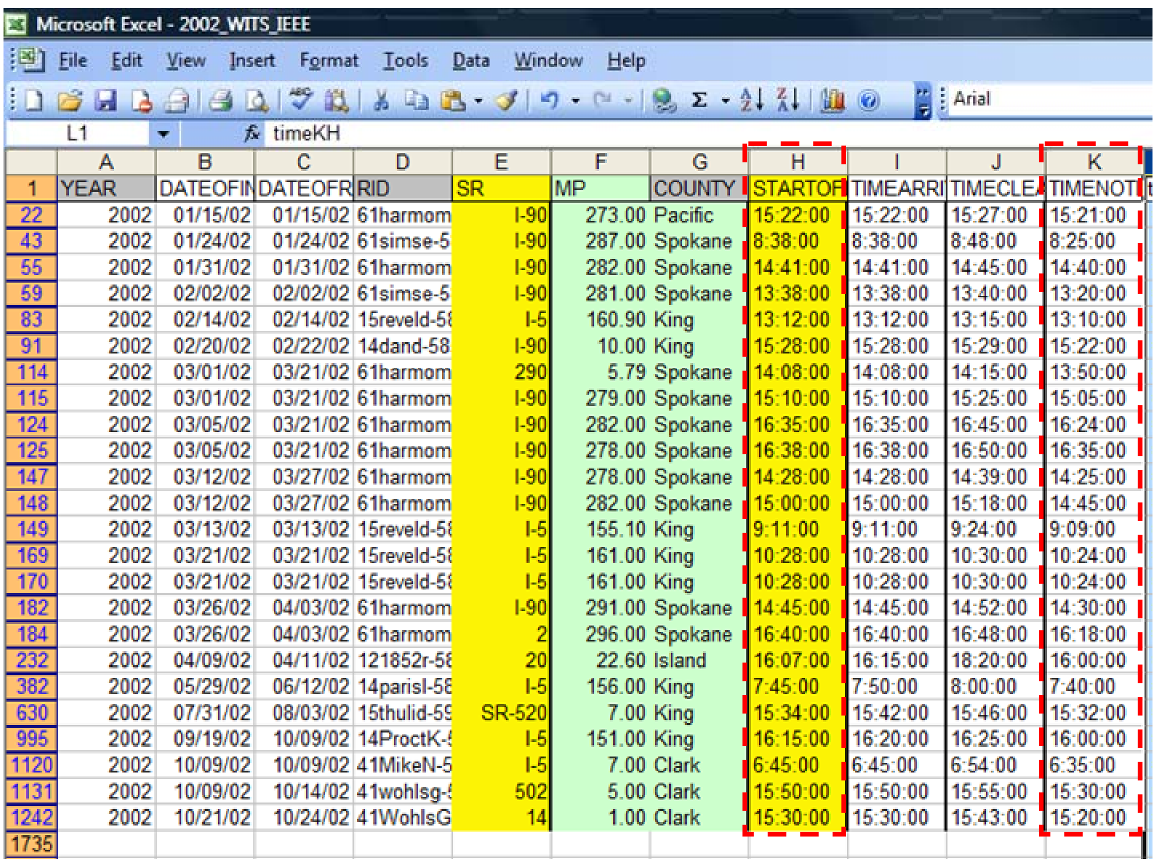


Microsoft Excel - 2002_WITS clean new

H18113

	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)



Microsoft Excel - 2002_WITS_IEEE

L1 timeKH

	A	B	C	D	E	F	G	H	I	J	K
1	YEAR	DATEOFIN	DATEOFR	RID	SR	MP	COUNTY	STARTOF	TIMEARRI	TIMECLEA	TIMENOTI
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 occurred after notify time (columns H and K)

Loop data were also checked for errors 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 are 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 is principally based on the available incident log and loop data. The approach used was to apply an Entity/Relationship (E/R) diagram (Garcia-Molina et al., 2002). Based on the 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 the diamond symbols. Each entity set has its own primary key for efficiently querying and manipulating data management. 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.

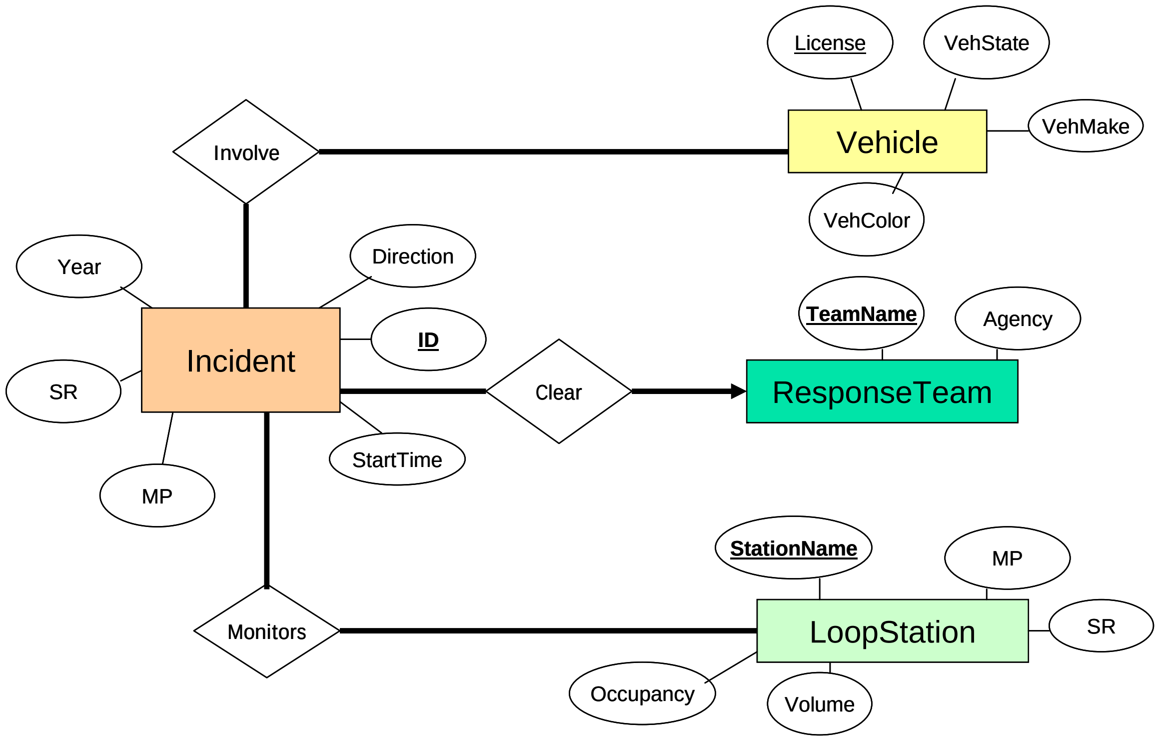


Figure 3-3. E/R diagram design of the incident study database

In Figure 3-3, "ID" stands for incident report ID, "SR" represents State Route number, and "MP" means Mile Post. The E/R diagram design can be converted to the following relational schemas:

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

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 is linked to the computer system application that implements the algorithm. The incident and loop data in the SQL database can be easily queried and used 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 as follows: 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 are disabled vehicle (at shoulder), abandoned vehicle, blocking disabled vehicle, non-injury collision, and debris blocking traffic. Among them a disabled vehicle incident is the most frequent category accounting for about 50% for all years. Being the second most frequent incident category, abandoned vehicle represents 13% to 18% over the four-year period. Fortunately, these two major incident types are not lane-blocking, although they do impact freeway capacity.

Additionally, there are four supplemental categories 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 Incident Tracking System, 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. Some incidents may not have supplemental categories, which is optional (denoted by the "No SC" column). Even though main incident category information is required, the research team found several incidents without this information (denoted by the "N/A" row).

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 show that every main incident category, even disabled vehicle (on shoulder), may be associated with certain WSDOT property damage.

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

4.2 INCIDENT DURATION

Each recorded incident has four timestamps associated with it: Start, Notify, Arrival, and Clearance (SNAC) times. Start time refers to the time when an incident occurs. Notify time is the time when the incident response agent notices the occurrence of the incident. Arrival time corresponds to the moment when the incident response team arrives at the incident site. Clearance time records the instant when the incident is 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 Notify 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).

However, the Notify time does not seem to matter much for IID research. Therefore, the intervals considered in this study are 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 incident. 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 to its incomplete recovery. Statistics of the SNA, SNAC, and AC intervals were calculated for all incident categories and are described in the following three subsections.

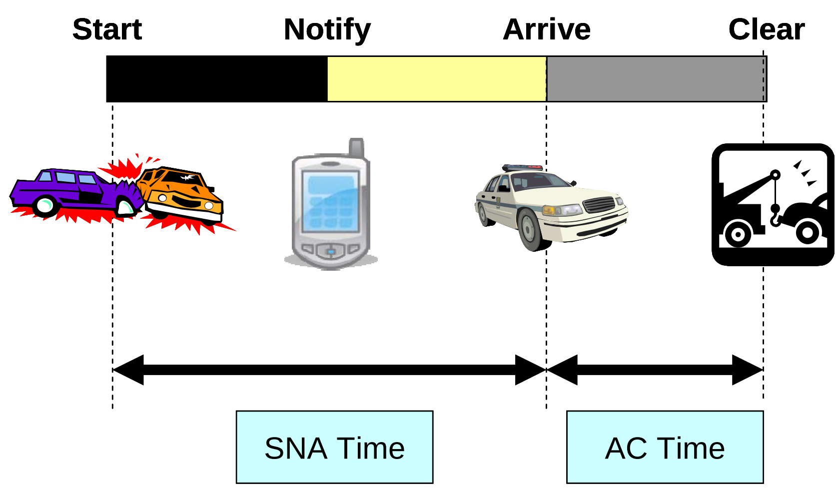


Figure 4-1. Start, Notify, Arrival, and Clearance (SNAC) times of incident

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 the 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. Based on these two tables, the three longest SNA intervals correspond to incidents that occurred on the northbound direction of I-405 in 2002, the northbound direction of I-5 in 2002, and the southbound direction of I-405 in 2002, (the median lengths of their SNA intervals are 60, 28, and 15 minutes, respectively). These long SNA intervals are 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 SNA interval 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 are zero, two, four, and five minutes, respectively. This trend might be a result of significantly increased frequency of incidents handled by gradually increased numbers of incident response units.

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

However, if we consider the possible maximum value of SNA intervals, all major freeways except SR 520 could have a very long maximum SNA interval (e.g., the maximum SNA interval during PM peak hours (16:00-19:00) on the northbound direction of I-5 in 2005 is almost four hours). One explanation is that since I-5, I-405, and I-90 cover wider area 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. The information about the median and maximum of SNA intervals might imply that a better strategy for taking care of SR 520 incidents may be needed to lower the typical SNA interval and more attention should be paid to an incident response on I-5, I-405, and I-90, where more incident response resources or enhanced response strategy may be warranted to reduce the maximum possible SNA interval.

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

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

Figure 4-7. SNA intervals in 2004-2005 (in minute)

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

4.2.2 SNAC Interval

The SNAC interval shows the time when the freeway is under the impact of an incident. Depending on the incident category, the SNAC interval may vary significantly. Some incident categories may take much longer time 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 the driver 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) is about 90%, their SNAC intervals are normally short. Specifically, the median time lengths for the SNAC intervals of disabled vehicle (at shoulder) and abandoned vehicle incidents are only eleven and three minutes, respectively.

Table 4-8. SNAC intervals (in minute) 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. Since some actions cannot be used to clear certain types of incident, the most appropriate actions are typically selected by the incident response team. The calculated median values of AC intervals can provide a reasonable approximation to the typical time length an incident response team would need to remove an incident after its arrival.

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

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 based on a modified deterministic queuing theory. This algorithm applies loop-detector measured traffic data (e.g., vehicle counts and lane occupancies) from immediately upstream and downstream loop stations of the incident location as inputs. To represent a real-world traffic condition associated with the duration of an incident, an actual traffic profile extracted directly from single-loop measurements is used. Similar to the algorithm developed by Hallenbeck et al. (2003), the proposed algorithm employs a background traffic profile to characterize the prevailing traffic condition at the roadway section of the incident. However, this algorithm uses an adaptive volume-based background traffic profile rather than a constant background loop-occupancy profile. The proposed algorithm compares the actual traffic profile of a time interval with the corresponding background traffic profile to differentiate incident-induced congestion from recurring travel delay at the prevailing traffic condition. Since the background traffic profile is used to characterize prevailing traffic conditions including recurrent traffic congestion, the appropriate background profile derivation is vital to the accuracy and performance of this algorithm. 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 background traffic profile is derived from onsite loop detector data. WSDOT loop detector data are aggregated into 20-second interval measurements and archived in a database system maintained by the Intelligent Transportation Systems (ITS) Program at University of Washington. To reduce negative impacts from random fluctuations of traffic arrivals in short (20-second) time intervals, loop data were aggregated into one-minute intervals in this study. Since the distributions of traffic flow on weekdays and weekends are dissimilar, the background profile for weekdays should be different from that of weekends. Therefore, two different patterns of background traffic profile were generated, one for weekdays and the other for weekends.

As mentioned earlier, a background profile represents a 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 background traffic profiles. After choosing the days without incidents, vehicle counts at each loop station from the selected days are sorted from low to high values. The median value of vehicle counts in a specific time interval at each loop station is taken as the representative vehicle counts of that loop station in the corresponding time interval. For instance, assume that the one-minute vehicle counts between 15:00-15:01pm on Monday through Friday at a loop station are five, six, five, three, and seven, respectively; the median of vehicle counts would be five. Thus, five should be the representative number of vehicles passing the loop station between 15:00-15:01pm on the prevailing traffic condition for weekdays.

Nonetheless, with the incident records accounted for, it is difficult to find enough loop data of incident-free days to generate an acceptable background profile. We found that most of the days of our study period have at least one incident near a loop station. This makes it difficult to obtain high quality profiles of background traffic because the median of a small sample of days may not accurately represent a prevailing traffic condition. The IID calculated by using these inappropriate background profiles could be severely misleading. To solve this problem, we expanded the size of our data samples by allowing a portion of loop data on an incident day to be used. Of course, the loop data must be extracted from time periods without incident impacts. Criteria used to select loop data for background traffic profile generation are as follows: (1) Data should be extracted from time periods that are free of incident impacts and at least five minutes away from the next incident's start time; and (2) Data should not be extracted from time periods starting five minutes before an incident's start time through four times the incident duration following its Clearance time. For example, on January 21, 2004, there was only one incident on State Route (SR) 520 that started at 12:32pm and was cleared at 12:47pm. The incident duration is 15 minutes. Based on the criteria, the loop data that should be included to derive background traffic profiles are the measurements between 12:00am and 12:27pm and the data from 13:47pm to 23:59pm. Figure 5-1 illustrates the steps for deriving background traffic profiles.

Figure 5-1. Derivation of the background traffic profiles

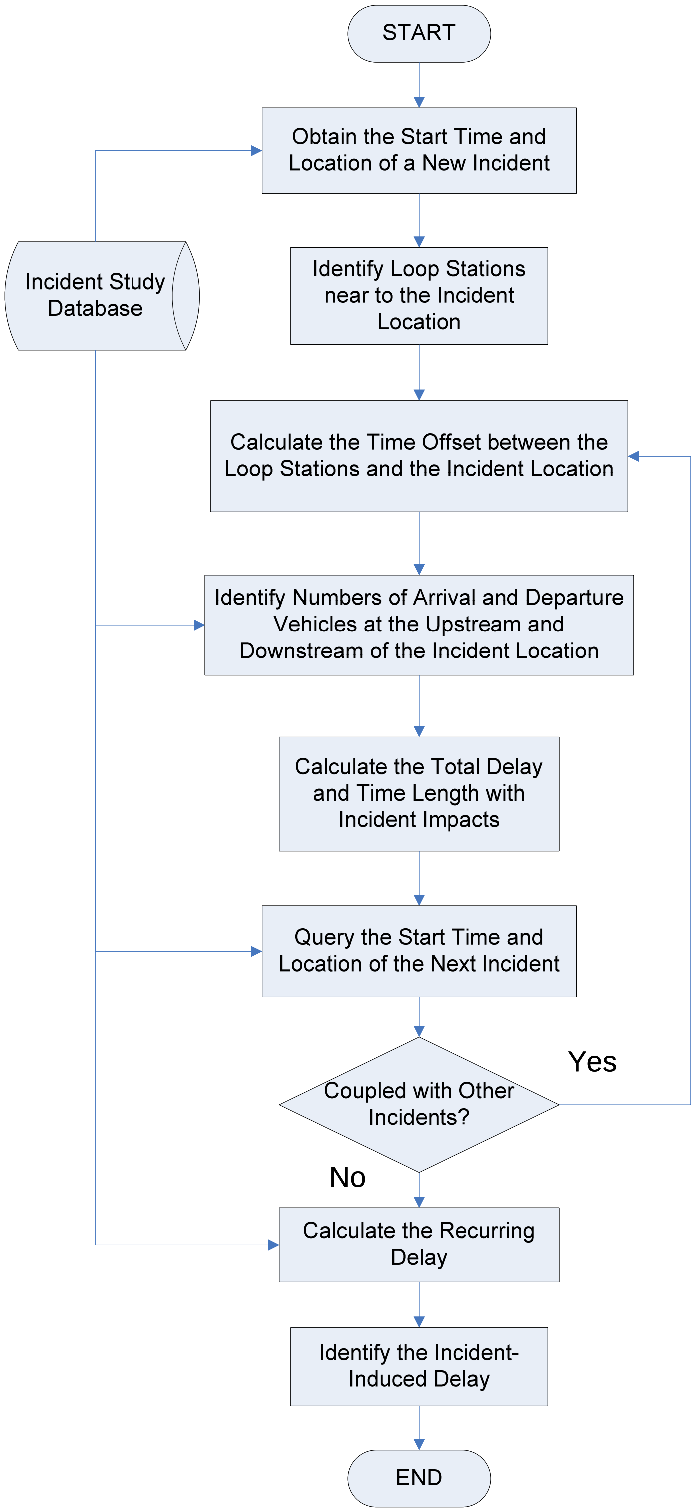


Figure 5-2. Flow chart for calculating IID on freeways

5.3 CALCULATION OF INCIDENT-INDUCED DELAY

Figure 5-2 illustrates all important steps of the proposed algorithm for IID estimation. This algorithm is based on the modified deterministic queuing theory. It begins by obtaining the information of an individual incident from the incident 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 5-3) 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.

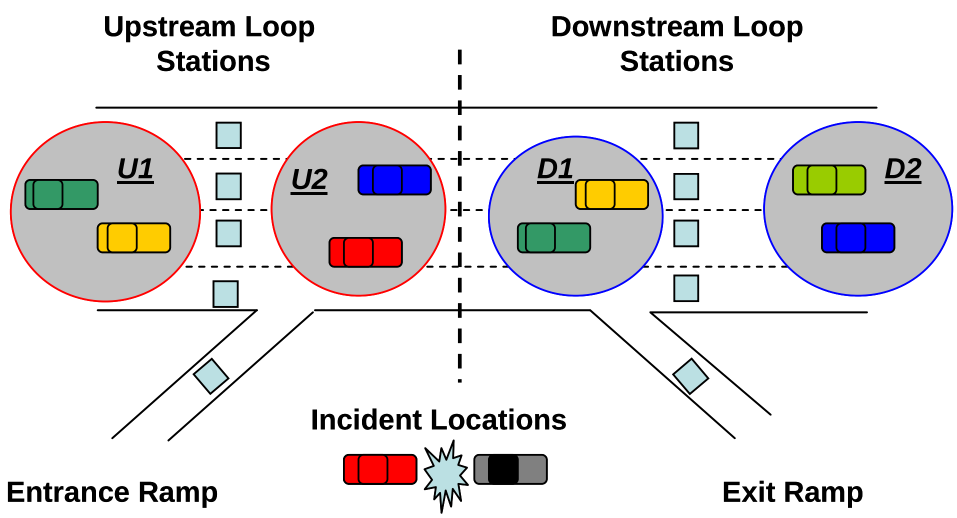


Figure 5-3. Upstream and downstream loop stations of an incident

A deterministic queuing diagram, as shown in Figure 5-4, is formed by 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 5-3). 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.

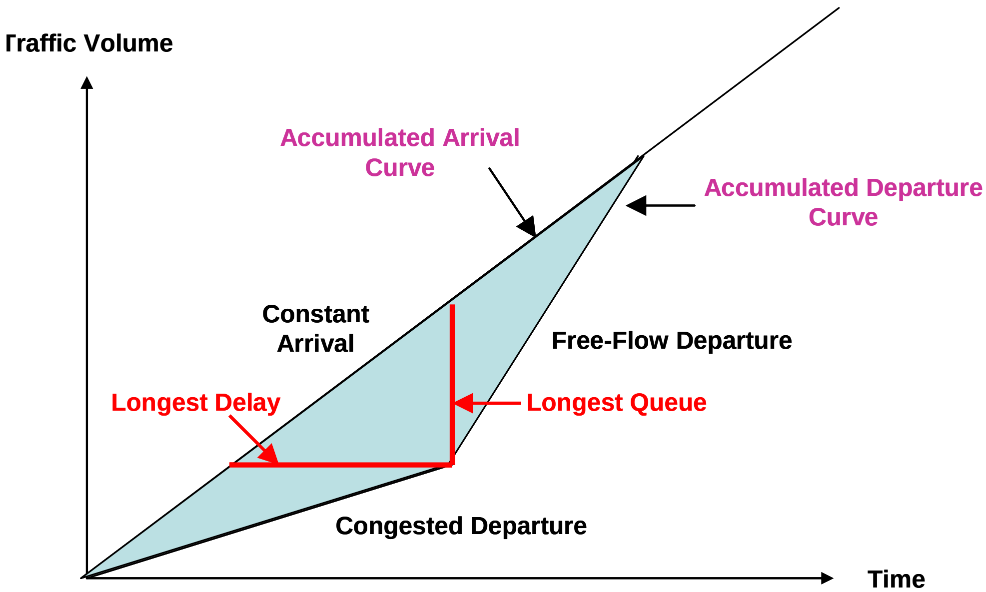


Figure 5-4. Deterministic queuing diagram

Since the deterministic queuing diagram assumes 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 down stream loop stations must be properly adjusted to fit the deterministic queuing diagram requirements. The distance between the upstream and downstream loop stations 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 reason for using these time offsets is to include all vehicles impacted by an incident in the analysis and exclude vehicles that passed the incident location before the incident occurrence. In Figure 5-3, 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 contrary, 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 one-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 5-4, can be formed. The queuing diagram contains many important pieces of information for queuing analysis including the number of vehicles that experienced delay, the total vehicle delay, and longest individual vehicle delay. A vertical line between the accumulated arrival and departure curves in Figure 5-4 represents the number of delayed vehicles at a given time interval. A 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.

However, 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 background profile for the same freeway section is needed. Since the background profile represents a typical traffic condition free of incident, any travel delay at this site should be caused by recurrent congestion. If the total vehicle delay associated with an incident is longer than the background travel delay calculated from the background traffic profile, the difference should be IID, as illustrated in Figure 5-5(a), in which the number of delayed vehicles within each time interval is plotted.

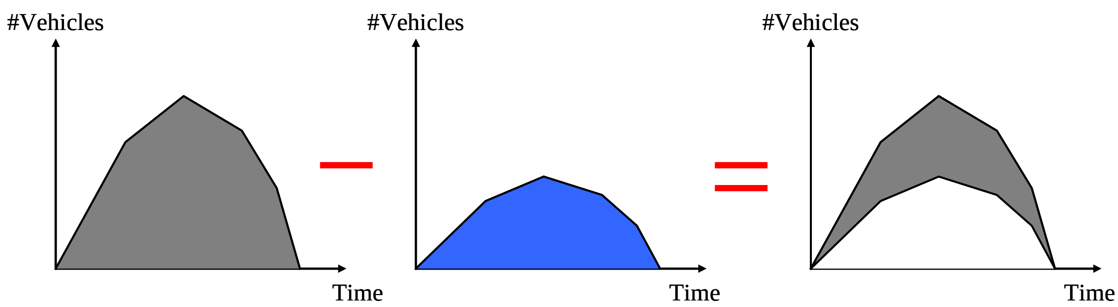


Figure 5-5(a). Positive incident-induced delay

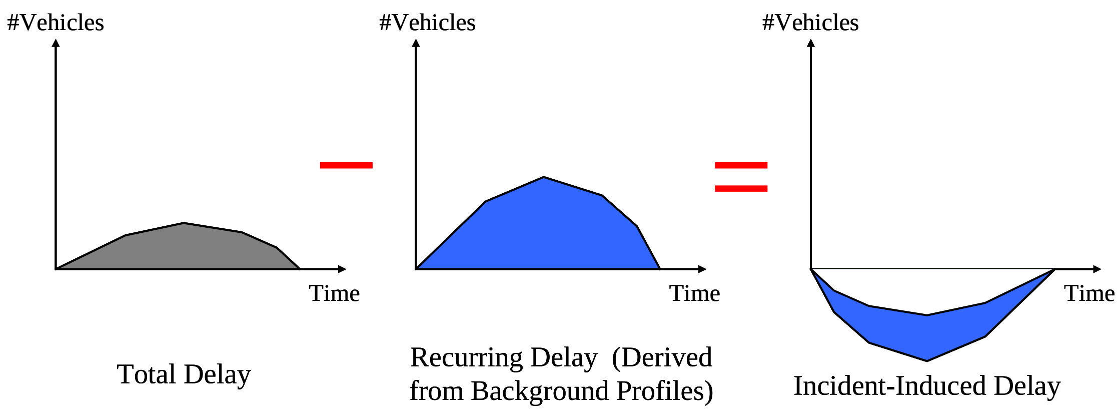


Figure 5-5(b). Negative incident-induced delay

In this study, we assume that the recurring delay resulting from regular traffic conditions can be precisely evaluated from the background traffic profile using a deterministic queuing diagram. However, it was found that the total delay may be less than the recurring delay in certain traffic conditions if the background traffic profile is selected based on time of day. This could result in an unrealistic negative value of IID as illustrated Figure 5-5(b). The reason for this problem lies in the way of selecting the background traffic profile. Even for a freeway section with recurrent congestion at peak hours, it may not be congested at the same time for a specific day when an incident occurred in its upstream section and severely reduces its arrival rate. In this case, even when an incident occurs at this section, its total delay may still be lower then its background travel delay because its current traffic volume is much lower than usual. This indicates that the time-based selection for background traffic profile is unsuitable for special traffic flow conditions.

To eliminate this problem, an adaptive background traffic profile is used instead of the constant one that is based on incident occurrence time. The main idea is to select the most suitable background traffic profile for each traffic condition (e.g., free-flow and congested). We believe that it is more reasonable to use a volume-based selection method for the background traffic profile. Hence, a volume classification test is conducted to identify the traffic flow level that should be used as the threshold to differentiate traffic conditions. The concept of Level of Service (LOS) is employed to help achieve this purpose in the test. Through the test, we found that it is appropriate to have three traffic flow levels - light, moderate, and heavy - each corresponding to one unique background traffic profile. The first traffic flow threshold (the “LOS C” column in Table 5-1) separates the light flow level (LOS A, B, and C) from the moderate flow level (LOS D and E). The second traffic flow threshold (the “LOS E” column in Table 5-1) differentiates the moderate flow level (i.e., LOS D and E) from the heavy flow level (i.e., LOS F). Figure 5-6 shows an example of how a background traffic profile is selected based on the traffic condition of LOS D or E. Note that the values of the two thresholds vary depending on the freeway's free-flow speeds (FFS) as displayed in Table 5-1 (TRB, 2000).

Table 5-1. Traffic flow thresholds for the adaptive background traffic profile

FFS (mph)	LOS C (pc/h/ln)	LOS E (pc/h/ln)
75	1830	2400
70	1770	2400
65	1680	2350
60	1560	2300
55	1430	2250

Note: pc/h/ln = passenger car per hour per lane

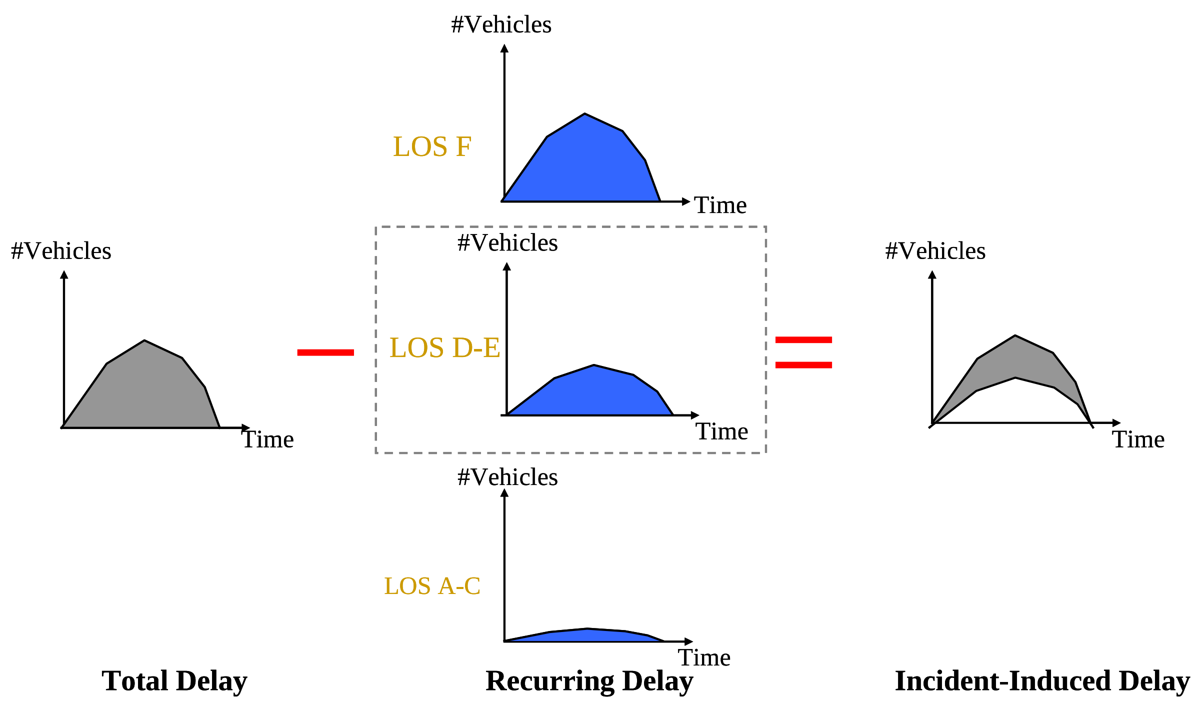


Figure 5-6. Selection of a background traffic profile

In the case that 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 are used as indicators of queue extension. If the occupancy from an immediate upstream loop at the queue end is larger than 50% (based on the congestion speed of 16 mph (Coifman, 2002) and the minimum headway of 0.63 second (Al-Ghamdi, 2001)), the queue will have occupied the current upstream loop and extended into the upstream freeway segment.

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 5-7. The system is capable of calculating travel delays caused by different categories of incidents that occurred on freeways. To obtain an average IID over multiple incidents on freeway networks using ARIA, 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 when the incident happened needs to be provided.

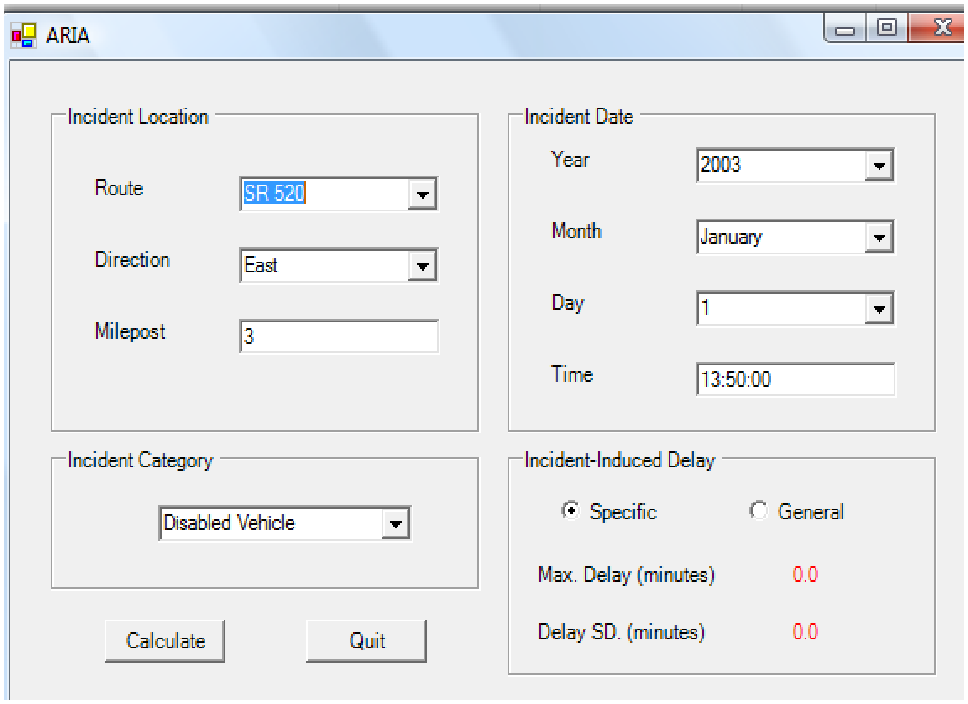


Figure 5-7. User interface of the ARIA system

CHAPTER 6 VALIDATION OF THE ALGORITHM

6.1 SIMULATION MODEL DEVELOMENT

To evaluate the performance of the proposed algorithm, travel delays calculated by the algorithm need to be compared with the actual travel delay experienced by freeway users. However, data on actual travel delays are typically unavailable due to the difficulties in collecting such data. Although truck travel time data for some commercial fleets can be extracted from the equipped Global Positioning Systems (GPS) devices, the sample size is too small to validate the proposed IID estimation algorithm. Therefore, we have 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) are 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 for collecting traffic volume and occupancy data, just like inductance loop detectors do for real-world traffic operations. Through defining travel time data collection zones on a roadway network, each vehicle's travel time and delay data can be collected. Such data can be applied to validate the new algorithm proposed in this study for calculating IID.

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

VISSIM simulation model was specifically developed for this site. Figure 6-1 shows a snapshot of the simulation site. Virtual loops are 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 can be 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 (PTV, 2007) for details of this method.

6.2 CALIBRATION OF SIMULATION MODEL

Calibration is a critical step for a simulation model to produce 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 are used for calibrating the simulation model. The calibration process follows an approach similar to that proposed by Gomes et al. (2004). Vehicle volume data at the virtual loop detector locations are carefully compared with those observed by the on-site loop detectors. These detector locations serve as check points for the calibration. Several parameters (e.g., lane changing gap and minimum headway) related to car following and lane changing behaviors are adjusted until the simulation model produces data close enough to the ground-truth data at the check points.

Eighteen incidents that occurred on the eastbound 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 eighteen incidents were applied to calibrate the simulation model. Tables 6-1 and 6-2 show samples of the comparison of the ground-truth traffic flow data and the simulated traffic flow data for the time periods of 13:50-13:58pm on January 2 and 17:51-18:30 on January 23 after the calibration. As required by the algorithm, travel time must 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 needs to be configured twice, one for simulating the current traffic condition with the incident and the other for modeling the prevailing traffic condition free of the incident.

Table 6-1. Comparison of traffic volume data from the onsite 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	416	407	447	415

Table 6-2. Comparison of traffic volume data from the onsite loops and the virtual loops of the simulation model for the period of 17:51-18:30 on January 23, 2003

	Upstream Station		Downstream Station	
	Loop	**Simulation**	**Loop**	***Simulation***
current traffic condition with incident	1771	1677	1726	1662
prevailing traffic condition free of incident	1963	1967	2253	2139

6.3 ALGORITHM VALIDATION

Delay caused by the eighteen incidents that occurred in the eastbound direction of SR 520 at the Evergreen Point Bridge in January 2003 can be calculated to evaluate the performance of the algorithm. Figure 6-2 shows the comparison of the IID for all of the eighteen incidents. Even though most of the estimated IID by the algorithm are smaller than the IID from the simulation models, they are reasonably close with the average percent difference of 15.3%. Therefore, our simulation tests indicate that the algorithm can provide relatively close estimates of IID.

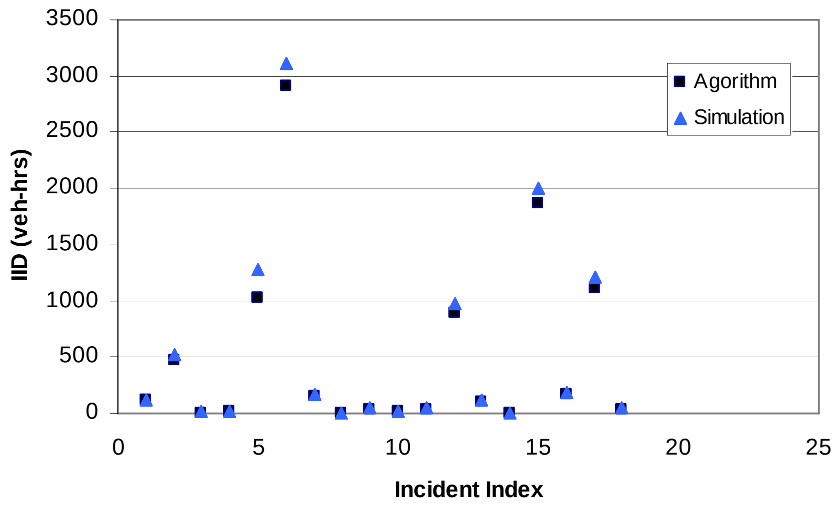


Figure 6-2. Comparison of the IID from the algorithm and the simulation model

Additionally, the impact of the simulation models' random seed number on the delay estimates was considered in this study. Tables 6-3 and 6-4 illustrate IID, total delays, and recurring delays in vehicle-hours of the two incidents that occurred between 13:50-15:58 on January 2, 2003 and between 17:51-18:30 on January 23, 2003, respectively. The 95% confidence interval of the IID for the incident between 13:50-15:58 on Jan 2, 2003 is between 115 and 122 vehicle-hours. The algorithm has 116 vehicle-hours as the resulting IID. The calculated IID by the proposed algorithm falls within the confidence interval. However, for the incident that occurred between 17:51-18:30 on January 23, 2003, the estimated IID is 893.14 vehicle-hours which is out of the 95% confidence interval (between 1,003-1,075 vehicle-hours) of the IID collected from the simulation runs. In summary, to find out the specific error range with the proposed algorithm, further research is needed.

Table 6-3. Delays from the simulation models for the period of 13:50-13:58 on Jan. 2

Random Seed Number	Incident Delay	Total Delay	Recurring Delay
20	120.03	441.53	321.49
25	127.14	448.59	321.45
30	120.88	442.33	321.45
35	115.54	437.04	321.5
42 (Default)	114.47	436.29	321.81
50	121.12	442.36	321.24
55	116.85	438.14	321.29
60	120.96	442.75	321.79
70	110.38	432.37	321.99

Table 6-4. Delays from the simulation models for the period of 17:51-18:30 on Jan. 23

Random Seed Number	Incident Delay	Total Delay	Recurring Delay
20	1,052.93	2,475.63	1,422.71
25	894.46	2,318.25	1,423.79
30	1,059.77	2,482.52	1,422.75
35	1,054.24	2,466.71	1,412.47
42 (Default)	1,049.16	2,468.80	1,419.64
50	1,068.36	2,482.96	1,414.59
55	1,062.56	2,473.38	1,410.82
60	1,055.53	2,465.43	1,409.90
70	1,057.31	2,468.50	1,411.19

CHAPTER 7 DISCUSSION OF ALGORITHM RESULTS

7.1 ALGORITHM APPLICATION

As mentioned earlier, the proposed algorithm was implemented in the ARIA system. Incident induced delay can be automatically calculated by ARIA if supporting background traffic profile data are available in the IS database. Although the calculation for each incident takes seconds to complete, the preparation of historical traffic data is time consuming. Due to the time constraints of this project, the proposed algorithm was applied to only two sample corridors: the eastbound section of SR 520 Evergreen Point Bridge and the I-405 northbound section between MP 1.68 and MP 15.75. Results for the two corridors are summarized in the following two sections.

7.2 SR 520 EVERGREEN POINT BRIDGE

Fifty four incidents occurred on the eastbound SR 520 Evergreen Point Bridge between November 1st, 2002 and January 31st, 2003. These included 6 non-injury collisions, 4 abandoned vehicle incidents, 10 disabled vehicle incidents, 20 blocking disabled vehicle incidents, 6 debris blocking traffic incident, 1 injury collision, and 7 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

Description	**Nov-02**	**Dec-02**	**Jan-03**	**Total**
Abandoned Vehicle	1	1	2	4
Blocking Disabled	11	5	4	20
Debris Blocking Traffic	3	2	1	6
Disabled Vehicle	4	1	5	10
Injury Collision	0	0	1	1
Non-Injury Collision	4	0	2	6
N/A	0	4	3	7
Total	23	13	18	54

Since the SR 520 Evergreen Point Bridge has very narrow shoulders (one foot) on both left and right sides in both travel directions, any incident that occurs at this site would somehow block traffic movements and therefore result in travel delay when traffic demand exceeds a certain level. Notice that we may consider a disabled vehicle (on shoulder) incident as a blocking disabled incident on the SR 520 Bridge. This implies that the impact of each incident category on traffic flow at this site is distinctive from other freeway corridors with wider shoulders. By this reason, the research team expects 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.

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

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Delay (veh hr)
Q1	BK	Sun	2002-11-03	13:17:00	13:30:00	3.7	Blocking Disabled	20.92
Q2	BK	Mon	2002-11-04	09:08:00	09:17:00	3	Blocking Disabled	0.07
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	5.00
Q7	BK	Wed	2002-11-06	17:07:00	17:15:00	3.7	Blocking Disabled	4.47
Q8	BK	Thu	2002-11-07	13:35:00	13:45:00	2.6	Non-Injury Collision	0.02
Q9	BK	Fri	2002-11-08	15:10:00	15:23:00	3.5	Debris Blocking Traffic	23.28
Q10	BK	Sun	2002-11-10	12:58:00	13:04:00	2.7	Blocking Disabled	0.00
Q11	BK	Tue	2002-11-12	17:55:00	18:06:00	3	Blocking Disabled	0.05
Q12	SH	Fri	2002-11-15	16:49:00	17:15:00	3	Disabled Vehicle	0.00
Q13	SH	Mon	2002-11-18	06:35:00	06:57:00	4	Disabled Vehicle	0.00
Q14	BK	Mon	2002-11-18	08:33:00	08:43:00	3	Blocking Disabled	5.00
Q15	BK	Mon	2002-11-18	15:23:00	15:32:00	3	Debris Blocking Traffic	0.80
Q16	BK	Tue	2002-11-19	15:40:00	15:52:00	1.6	Non-Injury Collision	0.03
Q17	BK	Tue	2002-11-19	17:27:00	17:47:00	3	Non-Injury Collision	2.48
Q18	BK	Wed	2002-11-20	08:05:00	08:18:00	3.7	Blocking Disabled	14.38
Q19	SH	Thu	2002-11-21	14:09:00	14:42:00	1.6	Disabled Vehicle	0.00
Q20	SH	Fri	2002-11-22	06:30:00	06:55:00	4	Abandoned Vehicle	0.00
Q21	BK	Mon	2002-11-25	10:20:00	10:40:00	3	Blocking Disabled	85.13
Q22	BK	Mon	2002-11-25	12:40:00	12:57:00	3	Debris Blocking Traffic	0.52
Q23	BK	Fri	2002-11-29	10:10:00	10:27:00	3.2	Blocking Disabled	0.22

Note: veh hrs = vehicle-hours

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

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Delay (veh hr)
R1	BK	Thu	2002-12-05	08:43:00	08:50:00	3	Blocking Disabled	6200.08
R2	BK	Sat	2002-12-07	09:38:00	09:46:00	3.7	Blocking Disabled	256.2
R3	BK	Sat	2002-12-07	15:44:00	16:05:00	1.6	Other Contact	5472.53
R4	BK	Sat	2002-12-07	15:45:00	16:10:00	1.7	Other Contact	5467.88
R5	BK	Sun	2002-12-08	18:23:00	19:48:00	3.8	Blocking Disabled	2.00
R6	SH	Sun	2002-12-08	19:15:00	19:48:00	3.8	Disabled Vehicle	0.00
R7	BK	Fri	2002-12-13	09:18:00	09:29:00	3	Other Contact	118.50
R8	BK	Tue	2002-12-17	14:00:00	15:03:00	4	Abandoned Vehicle	2650.93
R9	BK	Fri	2002-12-20	14:30:00	15:02:00	2.3	Debris Blocking Traffic	1.00
R10	BK	Fri	2002-12-20	14:50:00	15:03:00	1.6	Blocking Disabled	2.00
R11	BK	Fri	2002-12-27	08:40:00	09:00:00	4	Debris Blocking Traffic	1.18
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	24.00

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

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Delay (veh hrs)
S1	BK	Thu	2003/01/02	13:50:00	15:58:00	3	Non-Injury Collision	116.12
S2	BK	Mon	2003/01/06	8:45:00	9:21:00	4	Abandoned Vehicle	468.67
S3	SH	Mon	2003/01/06	13:10:00	13:45:00	3	N/A	5.57
S4	SH	Mon	2003/01/06	14:30:00	14:48:00	4	Disabled Vehicle	17.86

S5	BK	Wed	2003/01/08	14:48:00	14:56:00	2.5	N/A	1,019.13
S6	BK	Fri	2003/01/10	10:21:00	10:32:00	3	N/A	2,910.86
S7	SH	Fri	2003/01/10	16:30:00	16:52:00	4	Disabled Vehicle	144.87
S8	SH	Tue	2003/01/14	5:33:00	5:45:00	3.5	Blocking Disabled	4.82
S9	BK	Thu	2003/01/16	17:14:00	17:33:00	1.8	Non-Injury Collision	33.87
S10	BK	Wed	2003/01/22	7:21:00	7:54:00	1.6	Blocking Disabled	8.96
S11	BK	Wed	2003/01/22	15:10:00	15:20:00	2	Debris Blocking Traffic	34.90
S12	BK	Thu	2003/01/23	17:51:00	18:30:00	3	Blocking Disabled	893.14
S13	SH	Tue	2003/01/28	8:00:00	8:22:00	4	Disabled Vehicle	94.88
S14	SH	Tue	2003/01/28	18:20:00	18:35:00	4	Disabled Vehicle	1.83
S15	BK	Wed	2003/01/29	17:02:00	17:30:00	3	Abandoned Vehicle	1,865.20
S16	BK	Thu	2003/01/30	7:57:00	8:10:00	2	Blocking Disabled	165.82
S17	BK	Thu	2003/01/30	13:53:00	15:05:00	2.1	Injury Collision	1,108.96
S18	SH	Thu	2003/01/30	15:23:00	15:37:00	1.6	Disabled Vehicle	37.56

Apart from the unknown category incidents, four out of five incidents with the longest IID (890 vehicle-hours or more) occurred in the afternoon. These incidents lasted for at least 7 minutes before being cleared from freeway traffic lanes. One interesting finding is that longer incident duration does not necessarily lead to longer incident delay. For instance, an abandoned vehicle incident that occurred between 17:02:00 and 17:30:00 (lasted for 28 minutes) had the incident delay of 1,865 vehicle-hours, but the IID of an injury-collision incident existed from 13:53:00 to 15:05:00 (lasted for 1 hours and 12 minutes) was only 1,109 vehicle-hours. Another point worth mentioning is that, unlike afternoon incidents, morning incidents normally have smaller impacts on traffic flow (most of incidents caused less than 100 vehicle-hour delay) possibly due to the unbalanced demands between morning and afternoon travels at this site. The afternoon peak volume is higher than the morning peak volume over weekdays.

In this study, we also applied the proposed algorithm to check the accuracy of the incident's Start and Clearance times. According to the incident log data (please see the S1 incident in Table 7-4), the incident occurred between 13:50-15:58pm on January 2, 2003.

That is the incident was cleared at 15:58pm. However, the accuracy of this incident's Clearance time is questionable because a non-injury collision incident rarely lasts for over two hours. Thus, the algorithm was applied to check the accuracy of this incident's Start and Clearance times.

Figure 7-1 graphically displays how traffic flow was influenced by the incident. According to the IID curve, freeway users started to experience IID at about 13:47pm, which indicates that the actual occurrence time for this incident should be three minutes earlier than the recorded Start time. Since an incident may not be immediately reported or detected, the recorded Start time often contains error in several minutes range.

In Figure 7-1, we can see that the number of delayed vehicles reached its maximum at 13:58pm, which should be the time when the incident was cleared. The recorded clearance time of 15:38pm was probably mistyped for 13:58pm. After 13:58pm, the number of queued vehicles decreased and the queue was completely discharged at 14:15pm. This implies that the impact of this incident took about 17 minutes to fade away after it was cleared.

Based on the results of the incident delay analysis, the incident duration should be between 13:47pm and 13:58pm, not from 13:50pm to 15:58pm. The incident duration was further checked with loop detector data. The number of entering and exiting traffic for the freeway segment with this incident shows no sign of traffic congestion after 14:15pm. Therefore, the algorithm is also capable of checking the incident's SNAC time interval for certain conditions. However, verification of this use is still needed and will be included in future research.

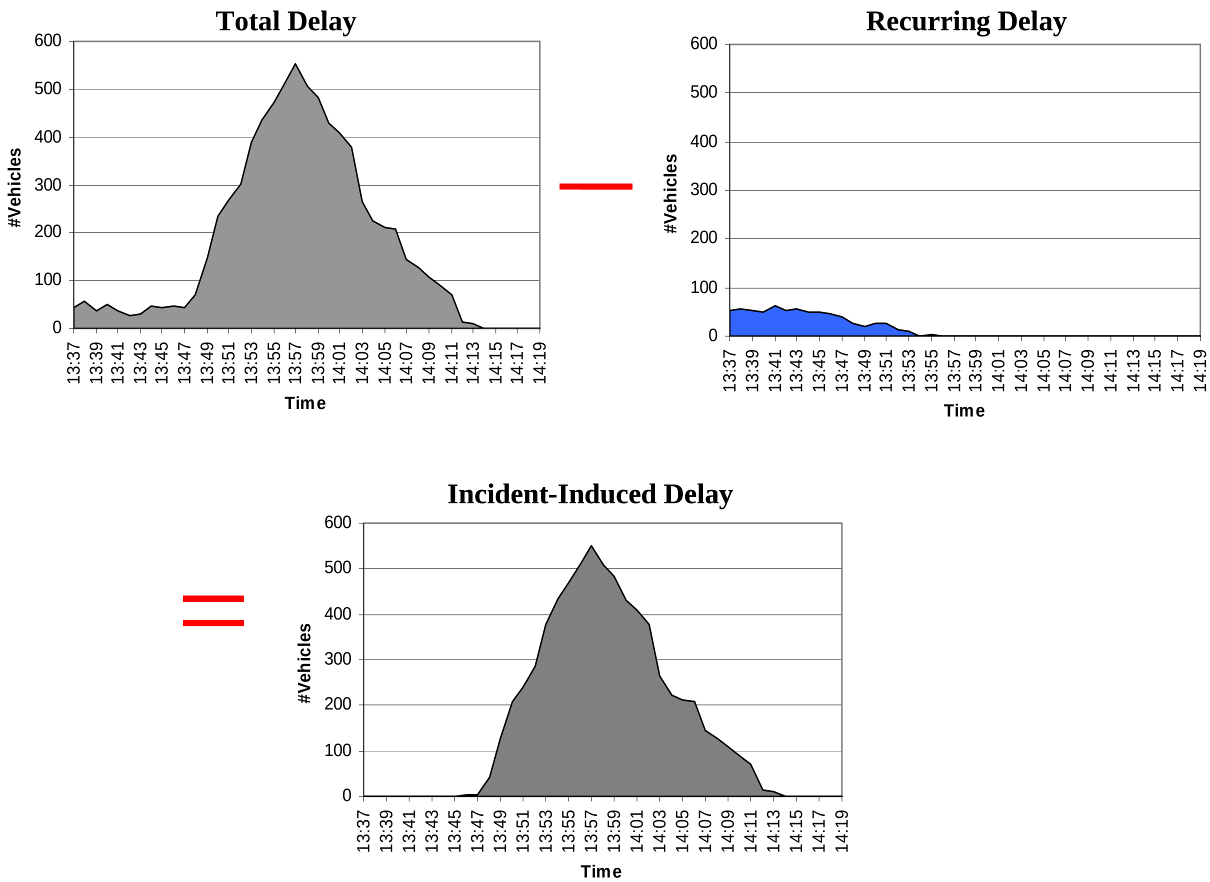


Figure 7-1. Incident –induced delay on the SR 520 Bridge occurred at 13:50pm on January 2, 2003

7.2 I-405 CORRIDOR

There were 147 incidents between MP 1.68-15.75 in the northbound direction of I-405 between January and March of 2003. Table 7-5 shows a breakdown of incident categories during this time 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 of certain incidents could not be calculated because of missing and/or bad loop data. The “N/A” sign represents that delay information of an incident is not available.

Table 7-5. Incident occurrence frequency on I-405

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 analyzing the loop data from 41 loop stations on this I-405 section, 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 month of January and February in 2003. The loops recorded zero traffic counts for several whole days over the two months. However, the data became normal in March 2003.

Delay induced by each incident can be 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 is zero. This could be simply explained by the low number of traveling vehicles during the time interval when such an incident occurred. If traffic demand is lower than the remaining freeway capacity during incident duration, there should not be any IID.

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

ID	Code	Day	Date	Start Time	End Time	Mile Post	Description	Recurring 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	869
I2	BK	Thu	2003/01/02	11:16:00	11:18:00	13.5	Blocking Disabled	0	448
I3	SH	Fri	2003/01/03	8:25:00	8:45:00	7	Disabled Vehicle	0	47
I4	SH	Mon	2003/01/06	6:52:00	6:54:00	11	Abandoned Vehicle	0	187
I5	SH	Mon	2003/01/06	7:35:00	7:38:00	11	Disabled Vehicle	0	977
I6	BK	Mon	2003/01/06	13:00:00	13:45:00	4	Blocking Disabled	0	762
I7	SH	Mon	2003/01/06	14:20:00	14:47:00	7	Disabled Vehicle	0	307
I8	SH	Mon	2003/01/06	17:23:00	17:40:00	2.9	Disabled Vehicle	0	0
I9	BK	Mon	2003/01/06	18:15:00	18:35:00	13.8	N/A	0	6,524
I10	BK	Tue	2003/01/07	9:16:00	9:20:00	11.2	N/A	0	0
I11	BK	Wed	2003/01/08	9:05:00	9:30:00	5.5	Non-Injury Collision	99	215
I12	SH	Wed	2003/01/08	12:50:00	12:56:00	4	Disabled Vehicle	897.5	6,176
I13	BK	Wed	2003/01/08	15:01:00	15:28:00	9.3	N/A	0	0
I14	SH	Wed	2003/01/08	15:35:00	15:40:00	14	Disabled Vehicle	0	114
I15	BK	Thu	2003/01/09	10:15:00	10:40:00	11	Non-Injury Collision	0	13,228
I16	BK	Thu	2003/01/09	11:00:00	11:15:00	5	Blocking Disabled	0	148
I17	BK	Fri	2003/01/10	6:48:00	6:57:00	11.5	Blocking Disabled	0	0
I18	BK	Fri	2003/01/10	6:50:00	8:30:00	5.4	Blocking Disabled	0	349
I19	SH	Fri	2003/01/10	13:40:00	13:50:00	11.2	Disabled Vehicle	0	0
I20	BK	Mon	2003/01/13	6:45:00	7:06:00	13.5	Non-Injury Collision	0	9,361
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	0
I23	BK	Tue	2003/01/14	7:30:00	7:37:00	11.2	N/A	0	0
I24	SH	Tue	2003/01/14	13:30:00	13:43:00	11.2	Disabled Vehicle	17	0
I25	SH	Tue	2003/01/14	14:25:00	14:39:00	11.2	Disabled Vehicle	0	0
I26	SH	Tue	2003/01/14	15:20:00	15:25:00	10.3	Disabled Vehicle	0	0
I27	SH	Tue	2003/01/14	15:32:00	15:35:00	13.7	Disabled Vehicle	0	0
I28	BK	Tue	2003/01/14	16:04:00	16:06:00	13.8	N/A	0	486
I29	SH	Tue	2003/01/14	17:02:00	17:14:00	13.1	Disabled Vehicle	0	3,243
I30	BK	Wed	2003/01/15	16:04:00	16:06:00	13.8	N/A	0	94
I31	SH	Wed	2003/01/15	17:58:00	18:01:00	10.5	Disabled Vehicle	0	0
I32	BK	Thu	2003/01/16	7:12:00	7:29:00	4.7	N/A	N/A	N/A
I33	BK	Thu	2003/01/16	12:30:00	12:40:00	3	Blocking Disabled	18	0
I34	BK	Fri	2003/01/17	6:45:00	7:26:00	9	Injury Collision	0	3,439
I35	BK	Fri	2003/01/17	9:30:00	9:39:00	10	Blocking Disabled	0	579
I36	SH	Fri	2003/01/17	16:58:00	17:00:00	10.2	Abandoned Vehicle	0	0
I37	SH	Mon	2003/01/20	10:08:00	10:10:00	9	Abandoned Vehicle	0	0
I38	SH	Mon	2003/01/20	17:43:00	17:51:00	11	Disabled Vehicle	0	2,143
I39	SH	Tue	2003/01/21	8:54:00	8:59:00	10	Disabled Vehicle	0	198

I40	SH	Tue	2003/01/21	9:30:00	9:52:00	4	Blocking Disabled	N/A	N/A
I41	BK	Tue	2003/01/21	13:11:00	13:49:00	4	N/A	N/A	N/A
I42	SH	Tue	2003/01/21	13:45:00	13:47:00	12.6	Abandoned Vehicle	0	215
I43	SH	Wed	2003/01/22	6:20:00	6:23:00	12.5	Disabled Vehicle	0	252
I44	SH	Thu	2003/01/23	7:35:00	7:48:00	11.1	Disabled Vehicle	0	5,619
I45	BK	Fri	2003/01/24	13:47:00	13:57:00	13.5	Non-Injury Collision	0	2,777
I46	SH	Fri	2003/01/24	16:10:00	16:12:00	12.7	Abandoned Vehicle	0	238
I47	SH	Mon	2003/01/27	6:33:00	6:49:00	10	Disabled Vehicle	0	1,452
I48	SH	Wed	2003/01/29	13:00:00	13:05:00	2	Disabled Vehicle	N/A	N/A
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	N/A	N/A
I52	BK	Fri	2003/01/31	13:33:00	13:56:00	2	N/A	N/A	N/A

Table 7-7. 1 Incident delay on the northbound of I-405 in February 2003

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Recurring Delay (veh hrs)	Incident Delay (veh hrs)
J1	SH	Mon	2003/02/03	9:01:00	9:02:00	11	Disabled Vehicle	0	0
J2	BK	Tue	2003/02/04	9:41:00	9:59:00	10.5	N/A	0	0
J3	SH	Tue	2003/02/04	11:00:00	11:09:00	13.6	Disabled Vehicle	0	152
J4	SH	Wed	2003/02/05	17:55:00	17:58:00	12.6	Abandoned Vehicle	0	280
J5	BK	Thu	2003/02/06	9:58:00	10:01:00	13	Debris Blocking Traffic	0	131
J6	BK	Thu	2003/02/06	17:08:00	17:41:00	13.6	Blocking Disabled	0	60
J7	BK	Fri	2003/02/07	7:15:00	7:17:00	7.5	N/A	78	0
J8	SH	Fri	2003/02/07	8:53:00	9:03:00	12.8	Disabled Vehicle	96	0
J9	BK	Mon	2003/02/10	7:28:00	7:55:00	9.5	Non-Injury Collision	0	1,208
J10	SH	Mon	2003/02/10	8:06:00	8:11:00	3	Disabled Vehicle	45	231
J11	BK	Mon	2003/02/10	13:10:00	15:30:00	10	Blocking Disabled	0	269
J12	SH	Tue	2003/02/11	9:38:00	9:56:00	11.1	Disabled Vehicle	0	128
J13	BK	Tue	2003/02/11	10:16:00	10:23:00	13.8	N/A	0	25
J14	BK	Wed	2003/02/12	8:50:00	9:10:00	9	Non-Injury Collision	0	550
J15	BK	Thu	2003/02/13	10:45:00	11:15:00	2.5	Debris Blocking Traffic	10	54
J16	BK	Thu	2003/02/13	10:58:00	10:59:00	10.55	N/A	0	0
J17	SH	Fri	2003/02/14	17:20:00	17:34:00	13.4	Disabled Vehicle	0	437
J18	SH	Mon	2003/02/17	6:38:00	6:49:00	9	Disabled Vehicle	0	0
J19	SH	Mon	2003/02/17	7:32:00	8:26:00	12	Disabled Vehicle	0	552
J20	BK	Mon	2003/02/17	11:41:00	12:06:00	12.5	N/A	0	32
J21	BK	Tue	2003/02/18	9:45:00	10:33:00	12.9	Injury Collision	0	3,546
J22	BK	Tue	2003/02/18	14:05:00	14:09:00	11.5	Debris Blocking Traffic	0	35
J23	BK	Wed	2003/02/19	10:13:00	13:45:00	7	Non-Injury Collision	0	8,990
J24	SH	Wed	2003/02/19	14:05:00	14:09:00	10.1	Abandoned Vehicle	0	105
J25	BK	Wed	2003/02/19	17:46:00	17:51:00	9.3	Blocking Disabled	0	308
J26	BK	Thu	2003/02/20	6:45:00	7:10:00	9	Non-Injury Collision	0	980
J27	SH	Thu	2003/02/20	9:24:00	9:34:00	12	Disabled Vehicle	0	28

J28	BK	Thu	2003/02/20	9:54:00	10:30:00	10	Non-Injury Collision	0	2,000
J29	SH	Fri	2003/02/21	8:47:00	8:49:00	10	Disabled Vehicle	0	0
J30	SH	Fri	2003/02/21	16:10:00	16:24:00	14	Disabled Vehicle	0	0
J31	BK	Mon	2003/02/24	8:55:00	10:15:00	5	Injury Collision	0	2,309
J32	BK	Mon	2003/02/24	17:38:00	17:51:00	10	Blocking Disabled	0	126
J33	BK	Tue	2003/02/25	9:02:00	10:11:00	6.5	N/A	0	0
J34	SH	Tue	2003/02/25	17:48:00	18:30:00	10	Disabled Vehicle	0	126
J35	SH	Tue	2003/02/25	17:55:00	18:08:00	10	Disabled Vehicle	0	19
J36	BK	Wed	2003/02/26	8:24:00	8:45:00	9	Non-Injury Collision	0	845
J37	SH	Wed	2003/02/26	16:37:00	16:40:00	13.8	Disabled Vehicle	0	55
J38	SH	Thu	2003/02/27	17:55:00	18:19:00	13.8	Disabled Vehicle	0	98
J39	SH	Fri	2003/02/28	12:05:00	12:07:00	12	Disabled Vehicle	0	12
J40	BK	Fri	2003/02/28	16:05:00	16:20:00	10	Injury Collision	25	1,080

Table 7-8. Incident-Induced Delay on the northbound of I-405 in March 2003

ID	Code	Day	Date	Start Time	Clearance Time	MP	Description	Recurring Delay (veh hrs)	Incident Delay (veh hrs)
K1	SH	Sun	3/2/2003	9:05:00	9:08:00	14.9	Abandoned Vehicle	0	0
K2	SH	Mon	3/3/2003	14:00:00	14:20:00	14.9	Disabled Vehicle	0	58
K3	SH	Tue	3/4/2003	13:31:00	13:34:00	12.4	N/A	0	0
K4	SH	Tue	3/4/2003	14:05:00	14:08:00	14.9	Abandoned Vehicle	0	0
K5	SH	Tue	3/4/2003	14:38:00	14:49:00	6.0	Disabled Vehicle	0	0
K6	SH	Wed	3/5/2003	6:25:00	6:29:00	15.0	Disabled Vehicle	0	0
K7	SH	Wed	3/5/2003	7:58:00	8:07:00	15.0	Disabled Vehicle	0	204
K8	SH	Wed	3/5/2003	13:15:00	13:22:00	15.3	N/A	0	0
K9	SH	Wed	3/5/2003	15:40:00	16:01:00	10.3	Disabled Vehicle	0	27
K10	SH	Wed	3/5/2003	16:07:00	16:14:00	15.0	Disabled Vehicle	0	560
K11	SH	Wed	3/5/2003	16:10:00	16:40:00	7.0	Disabled Vehicle	0	449
K12	BK	Thu	3/6/2003	8:49:00	9:02:00	15.0	Non-Injury Collision	0	245
K13	SH	Fri	3/7/2003	16:59:00	17:04:00	2.2	Disabled Vehicle	0	45
K14	SH	Sun	3/9/2003	14:00:00	14:30:00	9.3	Disabled Vehicle	0	1,408
K15	BK	Mon	3/10/2003	8:10:00	8:44:00	14.0	Blocking Disabled	0	237
K16	SH	Mon	3/10/2003	11:34:00	11:35:00	10.0	Disabled Vehicle	0	0
K17	SH	Mon	3/10/2003	16:52:00	16:54:00	10.0	Abandoned Vehicle	0	25
K18	SH	Mon	3/10/2003	16:58:00	17:09:00	15.1	Disabled Vehicle	0	205
K19	SH	Tue	3/11/2003	12:40:00	12:48:00	4.5	Disabled Vehicle	8	52
K20	BK	Wed	3/12/2003	12:20:00	12:47:00	5.0	Non-Injury Collision	0	2,847
K21	SH	Wed	3/12/2003	12:45:00	12:56:00	14.0	Disabled Vehicle	0	28
K22	SH	Wed	3/12/2003	18:14:00	19:31:00	15.5	Disabled Vehicle	0	4,008
K23	SH	Thu	3/13/2003	18:10:00	18:30:00	12.3	Disabled Vehicle	0	1,702
K24	SH	Fri	3/14/2003	8:45:00	8:53:00	15.0	Disabled Vehicle	0	0
K25	SH	Fri	3/14/2003	12:31:00	12:34:00	15.0	Abandoned Vehicle	0	0
K26	SH	Fri	3/14/2003	13:20:00	13:39:00	9.0	Abandoned Vehicle	0	128
K27	SH	Fri	3/14/2003	16:55:00	17:05:00	14.9	Disabled Vehicle	0	256

K28	SH	Mon	3/17/2003	6:44:00	6:48:00	9.0	Disabled Vehicle	0	0
K29	SH	Mon	3/17/2003	12:03:00	12:25:00	11.0	Disabled Vehicle	0	0
K30	SH	Mon	3/17/2003	14:50:00	14:59:00	10.4	Disabled Vehicle	0	0
K31	SH	Mon	3/17/2003	15:04:00	15:06:00	14.5	Abandoned Vehicle	0	9
K32	SH	Mon	3/17/2003	15:24:00	15:31:00	2.7	Non-Injury Collision	21	397
K33	SH	Tue	3/18/2003	15:00:00	15:17:00	5.4	Non-Injury Collision	10	1,038
K34	SH	Tue	3/18/2003	15:50:00	16:15:00	15.3	Disabled Vehicle	0	15
K35	SH	Thu	3/20/2003	15:15:00	15:35:00	14.9	Disabled Vehicle	0	0
K36	SH	Fri	3/21/2003	5:46:00	5:54:00	15.1	Abandoned Vehicle	0	18
K37	SH	Sat	3/22/2003	13:56:00	14:03:00	15.3	Disabled Vehicle	0	0
K38	BK	Sat	3/22/2003	15:32:00	15:49:00	8.0	N/A	0	23
K39	SH	Sun	3/23/2003	16:47:00	16:50:00	11.1	Abandoned Vehicle	0	7
K40	SH	Mon	3/24/2003	8:58:00	9:00:00	15.0	Disabled Vehicle	0	0
K41	SH	Mon	3/24/2003	9:15:00	9:18:00	9.0	Disabled Vehicle	0	0
K42	BK	Mon	3/24/2003	14:35:00	15:12:00	5.4	Debris Blocking Traffic	0	25
K43	SH	Mon	3/24/2003	14:42:00	15:01:00	15.3	Blocking Disabled	0	450
K44	N/A	Mon	3/24/2003	17:47:00	17:54:00	5.4	Disabled Vehicle	0	12
K45	SH	Tue	3/25/2003	9:08:00	9:16:00	15.0	Non-Injury Collision	0	734
K46	SH	Tue	3/25/2003	11:35:00	11:48:00	15.3	Disabled Vehicle	0	89
K47	SH	Tue	3/25/2003	16:19:00	16:23:00	14.9	Abandoned Vehicle	0	0
K48	BK	Tue	3/25/2003	16:45:00	17:10:00	5.0	Non-Injury Collision	0	2,047
K49	BK	Tue	3/25/2003	16:48:00	17:19:00	6.9	Injury Collision	0	2,401
K50	BK	Tue	3/25/2003	17:10:00	17:30:00	5.0	Injury Collision	45	3,302
K51	SH	Tue	3/25/2003	17:30:00	17:40:00	3.0	Disabled Vehicle	271	2,802
K52	SH	Tue	3/25/2003	18:15:00	18:30:00	14.9	Disabled Vehicle	0	1,079
K53	SH	Thu	3/27/2003	11:04:00	11:08:00	13.0	Disabled Vehicle	0	0
K54	SH	Sun	3/30/2003	14:00:00	14:04:00	14.8	Disabled Vehicle	0	0
K55	SH	Mon	3/31/2003	10:07:00	10:20:00	13.0	Non-Injury Collision	0	908

Statistics of IID by incident categories are summarized in Table 7-9. With the absence of fatal accidents over the three months study period, the calculated statistics show that injury collision is the incident category with the highest impacts on freeway traffic flow. The median value of IID introduced by an injury collision is 2,852 vehicle-hours, more than 274% of that caused by a non-injury collision, and 19 times longer than that resulted from a blocking disabled vehicle incident.

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

Description	Median	SD	Max
Abandoned Vehicle	14	101	280
Blocking Disabled	148	244	762
Debris Blocking Traffic	45	48	131
Disabled Vehicle	37	1,243	6,176
Injury Collision	2,852	947	3,546
Non-Injury Collision	1,038	3,817	13,228

Based on the four year incident data, about 1,500 injury collisions occur each year on Washington State highways. Delays caused by these incidents are tremendous. Therefore, WSDOT may want to develop a specific strategy to deal with injury collisions. One point worth mentioning is that the AC time (i.e., the time from Arrival to Clearance) of injury collisions includes not only the time spent for clearing blocking vehicles but also the time needed by police officers and paramedic units to observe the incident site, do cardiopulmonary resuscitation (CPR), and safely transport the injured driver or passenger to hospital.

Although there was no fatality collision observed within the analysis time period on the studied corridor, the delay caused by a fatality collision is expected to be much higher than that induced by an injury collision because the average AC interval of a fatality collision is longer than three hours (Incident Response Quarterly Update, 2006).

The incident category with the second longest median delay is non-injury collision. The median incident delay for a non-injury collision is 1,038 vehicle-hours.

The number of non-injury collisions increased remarkably every year and in 2005 the occurrence frequency became over 5,500 incidents per year. The variation of incident delay in this category is the highest which may correspond to different numbers of involved vehicles, collision severity, and axle numbers of damaged vehicles.

For the rest of incident categories, as expected, the blocking disabled vehicle incident is the one with the highest impact on traffic flow. 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 associate 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 delay, its occurrence frequency is very high (about 50% of all incidents). Based on the calculated results, all other incident categories seemed to induce only short delays and their impacts on freeway operations are limited.

Finally, we want to mention that the proposed algorithm has its limitations. It is based on the deterministic queuing diagram which assumes both vehicle arrival and departure follow the uniform distribution and vehicles' physical lengths are negligible. However, the freeway traffic arrival process may vary over time and with vehicle composition, highway geometry, and volume. 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. However, as mentioned in Chapter 2, researchers disagree on whether the deterministic queuing diagram will underestimate delay. Additionally, one background traffic profile serves for a range of traffic flow. This may also generate calculation errors. All these issues deserve further research efforts to improve the accuracy of IID calculation.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

In this study, a new algorithm was developed for quantifying IID on freeways based on a modified deterministic queuing theory. IID refers to the difference between the total delay and the recurring travel delay at the time and location associated with the impact of an incident. The innovative aspect of the delay calculation in this study is that a dynamic traffic-volume-based background profile, which is considered a more accurate representative of prevailing traffic conditions, is applied. Based on the concept of LOS, three levels of background profiles were generated. Each profile level corresponds to different levels of traffic flow: high, medium, and low. In other words, the background profile is selected based on the actual level of traffic flow and is specific to the traffic condition associated with each incident. Moreover, to reflect different traffic patterns on weekdays and weekends, two sets of traffic-volume-based background profiles were generated and used for IID calculation. By using the traffic-volume-based background profile, the calculated delays should be a lot 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 Bridge on SR 520 was developed using the VISSIM traffic simulation tool. The simulation model was calibrated 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 the estimation accuracy. Results from the validity tests demonstrated that the proposed algorithm can provide reasonable estimates of IID and capture the evolution of traffic flow during incident duration.

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 18 incidents that occurred in January 2003 on the eastbound SR 520 Evergreen Point Bridge and all of the 147 incidents that occurred from January through March 2003 between MP 1.68-15.75 of the I-405 corridor. The IID estimates are valuable for us to understand the cost 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.

Principal findings of this research are as follows:

1) An injury collision typically results in a very long delay on freeways. Its delay could be longer than 274% of the delay caused by a non-injury collision and longer than 19 times the delay from a blocking disabled vehicle incident.
2) The frequency of non-injury collisions increased significantly over the years. In 2005, there were over 5,500 non-injury collisions that occurred on the freeways. Considering 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.
3) 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 confirmed the appropriateness of using a deterministic queuing diagram for delay calculation, several previous studies 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 considering shock wave movements in traffic flow, need to be investigated in future research.

Additionally, temporal transferability of the generated background traffic profiles should be examined. The concept of traffic-volume-based background profiles should be tested using data from other freeway corridors. Also, a thorough estimation of deterministic queue diagram accuracy is desired.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support to this project from Transportation Northwest (USDOT University Transportation Center, Federal Region 10) and the Washington State Department of Transportation. The authors also wish to express sincere appreciation to the WSDOT's Incident Management personnel, specifically, Mr. Bill Legg and Ms. Diane McGuerty for their valuable suggestions and help with the incident data collection.

GLOSSARY OF ACRONYMS

ARIA	Advanced Roadway Incident Analyzer System
CAD	Computer Aided Dispatch
FHWA	Federal Highway Administration
LOS	Level of Service
PSRC	Puget Sound Regional Council
TDAD	Traffic Data Acquisition and Distribution
TSMC	Traffic System 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

BIBLIOGRAPHY

1. 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.

2. Al-Ghamdi, A. S. (2001). Analysis of Time Headways on Urban Roads: Case Study from Riyadh. *Journal of Transportation Engineering*, ASCE, Vol.127, No. 4, pp. 289-294.

3. Cheevarunothai, P., Y. Wang, and N. L. Nihan. (2007). Using Dual-Loop Event Data to Enhance Truck Data Accuracy. Transportation Research Record. In Press. Transportation Research Board, Washington, D.C.

4. 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.

5. 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.

6. Coifman, B., (1997). Time Space Diagrams for Thirteen Shock Waves. California PATH Working Paper #UCB-ITS-PWP-97-1. Accessed online at http://www.ceegs.ohio-state.edu/~coifman/documents/TSW.pdf on May 8, 2007.

7. Coifman, B. (2002). Estimating Travel Times and Vehicle Trajectories on Freeways Using Dual Loop Detectors. *Transportation Research Part A* (36), pp. 351-364.

8. Daganzo, C. F., (1995). Requiem for Second-Order Fluid Approximations of Traffic Flow. *Transportation Research: Part B.* Vol. 29B, No. 4, pp. 277-286.
9. Dutzik, T., and R. Pregulman, (2003). "More Roads, More Traffic: Why Highway Constructions Won't Solve Traffic Congestion in Washington." WashPIRG Foundation.
10. 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.
11. 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.
12. Garcia-Molina, H., J.D. Ullman, and J. Widom. 2002. *Database Systems: The Complete Book*. Prentice-Hall, Inc. Upper Saddle River, New Jersey.
13. Gomes, G., A. May, and R. Horowitz (2004). Congested Freeway Microsimulation Model Using VISSIM. *Transportation Research Record 1876*. 71-81. Washington D.C.
14. 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.
15. 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.

16. 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.

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

18. 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.

19. 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.

20. 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.

21. 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.

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

23. Magnuson Partnership for International Trade and Transportation (2007). *Mic Dinsmore: The FAST Corridor*. Accessed online at http://www.google.com/search?hl=en&rlz=1T4GGLJ_enUS223US223&q=port+of+seattle+lose+traffic on June 22, 2007.

24. Matthias, H., and S. K. Boris, (1998). Local Cluster Effect I Different Traffic Flow Models. Physica A, Vol. 255, pp. 163-188.

25. 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.

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

27. 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.

28. Newell, G. F., (1993). A Simplified Theory of Kinematic Waves in Highway Traffic, Part II: Queueing at Freeway Bottlenecks. *Transportation Research: Part B*. Vol. 27B, pp. 289-303.

29. 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 for Washington State Transportation Center (TRAC) and Washington State Department of Transportation (WSDOT), Agreement T2695, Task 57.

30. 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.

31. Payne, H. J., (1971). Models of Freeway Traffic and Control. In: Mathematical Models of Public Systems. In: Bekey, G.A. (Ed.),. Simulation Councils Proc. Ser., Vol. 1, pp. 51-60.

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

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

34. 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.

35. 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.

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

37. 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.

38. Road Information Program. (2004). The Cost of Traffic Congestion in the Puget Sound Region: the Region's 20 Worst Traffic Jams and the Steps Needed to Relieve Traffic Congestion. Accessed online at http://www.tripnet.org/PugetSoundCongestionStudyOct2002.pdf on Mar. 5, 2004.

39. Shrunk, D. and T. Lomax. The 2005 Urban Mobility Report. Texas Transportation Institute. The Texas A&M University System (http://mobility.tamu.edu/) Accessed on July 4, 2005.

40. 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.

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

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

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

44. WSDOT Incident Tracking System. (2003), Definitions and Instructions WSDOT Incident Tracking System, not available online, April 15.

45. Whitham, G. B., (1974). Linear and Nonlinear Waves. Wiley, New York.

46. Windover, J. R., and M. J. Cassidy, (2001). Some Observed Details of Freeway Traffic Evolution. *Transportation Research: Part A*, Vol. 35, pp. 881-894.

47. Zhang, H. M., (1998). A Theory of Nonequilibrium Traffic Flow. *Transportation Research: Part B*. Vol. 32, No. 7, pp. 485-498.

48. Zhang, H. M., (2000). Structural Properties of Soluations Arising from a Nonequilibrium Traffic Flow Theory. *Transportation Research: Part B*. Vol. 34, pp. 583-603.

49. Zhang, H. M., (2002). A Non-Equilibrium Traffic Model Devoid of Gas-Like Behavior. *Transportation Research: Part B*. Vol. 36, pp. 275-290.

50. Zhang, H. M., (2003). Driver Memory, Traffic Viscosity and a Viscous Vehicular Traffic Flow Model. *Transportation Research: Part B*. Vol. 37, pp. 27-41.

51. Zhong, H. O., (2005). Equilibrium Functions of Traffic Flow. Physica A, Vol. 351, pp. 620-636.