Safety Science 87 (2016) 195–201

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

# Identification of freeway secondary accidents with traffic shock wave detected by loop detectors

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ARTICLE INFO

*Article history:*
Received 5 June 2015
Received in revised form 6 April 2016
Accepted 15 April 2016
Available online 22 April 2016

*Keywords:*
Secondary accident
Traffic shock wave
Spatio-temporal gaps
Primary accident

ABSTRACT

Secondary traffic accidents are generally recorded without being specifically noted as such in the accident database, leading to difficulty in the study of such accidents. Previous research generally classified secondary incidents by predefining fixed spatio-temporal boundaries—a method that can be very subjective. Using 10,762 accident records gathered from 2012 upstream loop detector data on a California interstate freeway, this paper proposes a dynamic method for more convincing and accurate classification based on traffic shock waves detected by the loop detectors. This method identifies and associates a secondary accident with its primary accident if it is tested and found to have occurred within the spatio-temporal impact area of the primary accident. Shock waves from each accident are calculated and updated along freeway via multiple detectors, and secondary accidents are identified as those that occur within the spatio-temporal boundaries of a primary accident. Results show that secondary accidents account for 1.08% of California interstate freeway accidents, which is much lower than previous research estimates. Dispersed spatio-temporal gaps between primary and secondary accident pairs were found with an expectation of 71.09 min and 3.88 miles with a standard deviation of 55.36 min and 4.64 miles respectively.



## 1. Introduction

### 1.1. Secondary accident

Freeway accidents not only cause severe travel delays, but can also result in secondary accidents, the risk of which is estimated to be six times greater than that for a primary accident (Tedesco et al., 1994). The high potential for occurrence and the negative consequences of secondary accidents make them an issue of great concern affecting freeway safety. However, secondary accidents and their primary accidents are usually recorded separately as regular accidents in the accident database, and there is no field to specifically identify an accident as secondary. Therefore, it is difficult to distinguish and subsequently study these unique cascading events directly from the information provided in the database. Previous research classified secondary incidents by predefining fixed spatio-temporal boundaries—a method that can be very subjective. This paper proposes a method based on traffic flow shock wave theory to identify secondary accidents using data from upstream loop detectors. The results show that the proportion of secondary accidents that occur on California interstate freeways is smaller than had been estimated in previous studies.

### 1.2. Literature review

Many previous studies were conducted on the characteristics of secondary accidents and proposed numerous identification methods. In much of the earlier research, unified spatio-temporal boundaries were predetermined and any accident that fell within the boundaries of another accident was defined as its secondary accident. Secondary accident identification was addressed early by Raub (1997), who proposed that any crash that occurred within the duration of the primary event plus 15 min and within one mile was assumed to have been related to the primary. The 15-min threshold was based on getaway times provided by Lindley and Tignor (1979) who estimated that this amount of time following an accident can impact traffic. The distance of one mile used to link

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http://dx.doi.org/10.1016/j.ssci.2016.04.015
0925-7535/

the two events spatially was derived from observations of crashes occurring during periods of heaviest traffic flow. For an extended period, studies followed Raub, which proposed a series of different spatial and temporal thresholds. Karlaftis et al. (1999) also applied the predefined identifying parameters of time and distance proposed by Raub. While Hirunyanitiwattana and Mattingly (2006) used sixty minutes and two miles upstream as thresholds, Moore et al. (2004) established thresholds as two hours and two miles on Los Angeles freeways. Zhan et al. (2008, 2009) used incident recovery time of 33.34–52.6 min, incident dissipation time of 0–21.76 min, and maximum queue length of 1.09–1.49 miles as the threshold, calculated based on different lanes blockage assumption according to the Highway Capacity Manual (HCM).

In the aforementioned studies, which applied static methods to classify secondary incidents, there were seldom any uniform thresholds, thus resulting in subjective findings. A comparison of secondary incidents classification results, using different spatial and temporal boundaries, was conducted and showed a high dependence on these boundary numbers (Haghani et al., 2006). The conclusion could be drawn that the predefined criteria cannot meet the variation in the spatio-temporal distribution of secondary incidents because the geometric characteristics, incident type and duration, traffic conditions and other possible contributing factors vary with each primary incident.

By studying operating traffic data, some study approaches made up for the static method by proposing a range of dynamic definition methods based on concepts such as queuing theory or speed contour analysis. The dynamic methodology described in the study by Sun and Chilukuri (2010) improved upon existing static methodology by marking the end of the varying queue throughout the entire incident using incident progression curves. Incidents were classified as secondary incidents if they fell within the curve. The analysis showed a difference of over 30% compared with the outcomes generated using the static methods. However, this dynamic methodology was based on estimated primary incident progression curves (IPCs) which were regressed with past incident records. The high degree IPC function is not only ideally shaped, but is also accompanied by possible estimation errors.

Except for the method based on the queuing theory, other research proposed speed-based methodology to determine the temporal and spatio extent of the primary incident or to classify secondary incidents. Based on loop data, Chung and Recker (2012) applied binary integer programming (BIP) to an empirical speed matrix under the impact of an accident, to determine actual temporal and spatial extent of delay caused by freeway accidents. This method was also utilized in the research of rubbernecking accident by Chung and Recker (2013). Yang et al. (2013, 2014) used speed data from highway sensors to build a binary speed contour plot to indicate the impact induced by the primary incident, and then classified secondary incidents by judging whether the queue triggered by the primary had reached them. This method was performed on a highway in New Jersey and showed a great reduction in biases caused by subjective fixed spatio-temporal thresholds as a case study. However, for this method a user defined speed percentage reduction factor, which is dependent on users' experience, impacts the identification result.

With the assistance of a speed matrix to describe the impact of the primary incident, Chung (2011, 2013) proposed a method to apply different spatio-temporal boundaries, varying with different types of crashes, to identify the spatio-temporal crash impacted queue region, then locate the secondary incident to determine whether it was associated with the primary incident. Crash shock wave and clearing shock wave generated by the primary accident could also be drawn from the speed matrix. However, it must be noted that speed is only one of a range of traffic parameters to reflect traffic conditions corresponding with a secondary accident. In addition, comparing with speed distribution in crash free time, the congested speed in this study is regard as the indicator of spatio-temporal impact boundary. While a confidence level can be subjectively chosen according to different road section. For example the speed in the upstream loop can reduce from 60 mph to 30 mph due to a primary accident and 30 mph can fall in the 95% confidence level of the crash free speed distribution.

There were also some secondary incident identification methods based on simulation. Chou and Miller-Hooks (2009) developed regression models by simulating representative incidents, which were then assessed using empirical incident data to determine the impact area of the primary incident. Haghani et al. (2006) used data from detectors in simulation software. The study used the boundaries defined by typical shock waves caused by the primary incident to explain dynamic queue formation via a recognition algorithm of the mean occupancy rate patterns, converting the classification process into a feasible geometrical matching operation. These methods based on simulation experiment research are more sound and theoretical.

Shock wave theory can be used to illustrate how the conversion between two different conditions travels along traffic flow. In some studies, this theory has been applied to estimate queue length at a congested signalized intersection, as in the study by Li et al. (2013). Zheng et al. (2015) utilized shockwave theory to consider the impact of queue spillback phenomenon on travel time distributions. In another paper by Li, shock wave theory was used to estimate the real time impact scope of incidents on a city expressway, and the method showed good accuracy and applicability in estimating results. Traffic incidents can change the traffic condition at the incident point, which can result in a transferring shock wave. Shock wave theory shows how this wave is produced and its speed, which can help represent the full-scale impact process of an incident. Based on shock wave theory, one study conducted on accident data attempted to filter secondary accidents. In this study, Moore et al. (2004) applied shock wave filtering using fixed boundaries to identify secondary accidents, which required close manual attention to distinguish shock waves in loop data. However, limited installation of detectors, lack of data, and corrupted records of output data reduced data availability, which resulted in data for only sixteen accidents sufficient to execute this filtering method.

Zheng et al. (2014) proved that the shock wave could be a fair tool to identify the secondary accident. He firstly extracted spatially and temporally nearby crash pairs (up to custom static thresholds) from a large network on the basis of a crash-pairing algorithm. In the second phase, two filters are used to select crash pairs that are more likely to be primary–secondary crash pairs. One of the filters uses shockwave theory to evaluate the dynamic traffic impact of the primary incidents. Then the manual review of identified police reports was carried out to confirm actual secondary crashes. Zheng also extended the shockwave filter to a freeway network scale. However Zheng just considered the release shockwave and queuing shockwave. In an incident when the rescue party or the policeman comes to the crash site to manage the traffic, one more shock wave can be created. Moreover, the shock waves can trace each other, and this situation will be more complicated than Zheng's model. These problems could also exist in free (2011, 2013) and Yang et al.'s (2013, 2014) method.

To fill the research gap identified above, the present study establishes the primary accident shock wave impact spatio-temporal scope as the filter for the secondary accident. Upstream loop data records were used to demonstrate the possible shock waves generated by the primary accident. A total of 10,762 accidents that occurred in 2012 on a California interstate freeway with their corresponding upstream loop data were analyzed by the proposed method to demonstrate its reliability and efficiency.

## 2. Methodology

### 2.1. SWBF method

This study proposes a shock wave boundary filtering method (SWBF) for secondary accident classification. Unlike most of the static filtering methods and dynamic methods based on queuing theory, SWBF provides real-time accident impact scope and is equipped with an automatic algorithm to conduct the filtering work circularly. With the help of shock wave traveling speed, the spatio-temporal boundaries of potential primary accidents can be defined, transforming secondary accident filtering into a simple matching exercise. The secondary accident is defined as an accident that occurs in the presence of traffic condition changes within the impact area of a primary accident. In this study, a secondary accident is differentiated from a chain-reaction accident—it was once claimed that accidents that do not lead to a queue cannot trigger a secondary accident (Moore et al., 2004). Chain-reaction accidents occur instantly following another accident and are the result of a direct interruption of the safe traffic environment (e.g., rear-end collision and pileups). Secondary accidents, however, usually result from the flow variation caused by an upstream accident, but are not caused directly by a primary accident—the focus of the present study is on these secondary accidents.

The SWBF method includes three main parts as follows.

(1) *Calculate traveling speed of primary accident impact*

To calculate the impact scope of a primary accident, the process of shock wave generation should be demonstrated first. There are usually three traffic flow condition states following an accident: (1) State 1: the accident occurs and causes a speed-reducing and density-increasing bottleneck until the treatment reaction begins; (2) State 2: after tow trucks or police arrive, the aftermath state commences, causing a further worsening to the flow condition; (3) State 3: after the bottleneck is eliminated, the recovery stage begins. During these three different stages, there are three shock waves are generated, two different upstream forming shock waves and an upstream dispersing shock wave.

According to traffic shock wave theory, the calculation of traffic shock wave speed requires flow and density information for an accident traffic condition. For a traffic condition of flow $q_i$, density $k_i$ and a new condition of flow $q_j$, density $k_j$, its impact traveling speed can be represented by the speed of generated shock wave between them, which can be calculated by the following equation (Eq. (1)),

$$\omega_{ji} = \frac{\Delta q}{\Delta k} = \frac{q_j - q_i}{k_j - k_i} \tag{1}$$

where $\omega_{ji}$ represents accident impact traveling speed, subscripts $j$ and $i$ refer to the two flow conditions between which the shock wave travels.

Using Eq. (1), speed of shock waves mentioned above can be determined with enough flow information (i.e., real time flow and density figures).

(2) *Determine a feasible spatio-temporal district for secondary accident*

Where the shock wave generated by a primary accident reaches is the location of the primary accident impacts. In the SWBF method, determining a feasible spatio-temporal district for secondary accident requires estimating the real time space-time scope of shock waves generated by every potential primary accident. In the first part of SWBF, the speed of the shock wave is attained. In this section, the process for estimating this scope will be proposed.

As mentioned above, an accident is comprised of three states generating three shock waves of different speeds respectively. State 1 spreads toward the upstream, gradually replacing the previous State 0, accompanied by the first upstream forming shock wave named $\omega_{01}$ (which represents its speed; also note that the subscript number of every name represents the two states between which this shock wave is generated). Generally, during the aftermath state, known as State 2, the traffic capacity can worsen with the arrival of emergency vehicles, with additional lanes potentially being affected. This is accompanied by the second upstream forming shock wave named $\omega_{12}$. States 1 and 2 continue to spread upward until dispersal State 3 encompasses the impacted road segment. After the accident bottleneck is relieved, the traffic congestion begins to dissipate, which is defined as State 3 and is accompanied by the upstream dispersing shock wave named $\omega_{23}$. When State 3 replaces States 1 and 2, which means that $\omega_{23}$ catches up with those two forming shock waves, additional time is required for the traffic condition to return to the previous State 0. During this recovery stage, a downstream recovery shock wave $\omega_{03}$ is generated, defining the rear boundary of the impact scope.

To consider the most common situation, the shock wave spreading situation can be simplified into two cases, each equipped with a respective calculating model accordingly.

*Case 1:*

Before being replaced by $\omega_{23}$, $\omega_{01}$ is replaced by $\omega_{12}$ and generates a new backward-collecting shock wave $\omega_{02}$ at time $t_1$. At time $t_2$, $\omega_{02}$ is replaced by $\omega_{23}$ and the impact scope ceases to go further. Fig. 1 illustrates this situation, where $T_1$ is the time for accident response, $T_2$ is time for accident handling, and fold line ABCD shows the impact scope.

In this case, the impact scope can be calculate as this (Eq. (2)),

$$f(t_x) = \begin{cases} \omega_{01} t_x, & \text{if } 0 < t_x \leqslant t_1 \\ \omega_{01} t_1 + \omega_{02}(t_x - t_1), & \text{if } t_1 < t_x \leqslant t_2 \end{cases} \tag{2}$$

*Case 2:*

Before catching up $\omega_{01}$, $\omega_{12}$ is replaced by $\omega_{23}$ and generates a new backward-collecting shock wave $\omega_{13}$ at time $t_1$. At time $t_2$, $\omega_{13}$ catches up $\omega_{01}$ and the impact scope ceases to go further. Fig. 2 illustrates this situation, where $T_1$ = time for accident response,

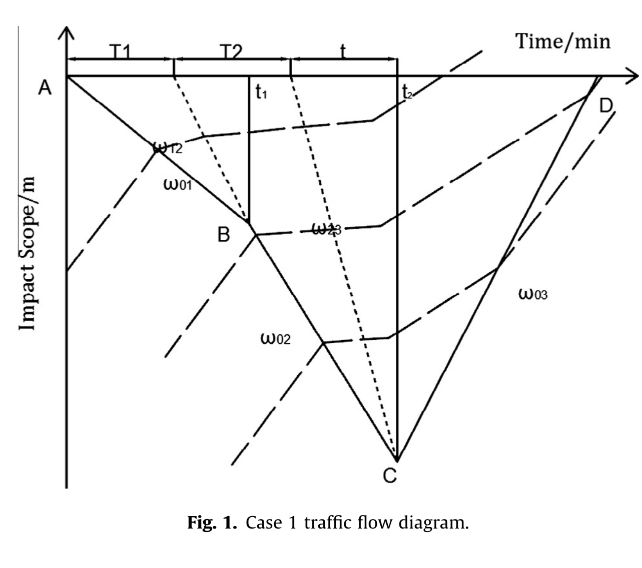


**Fig. 1.** Case 1 traffic flow diagram.

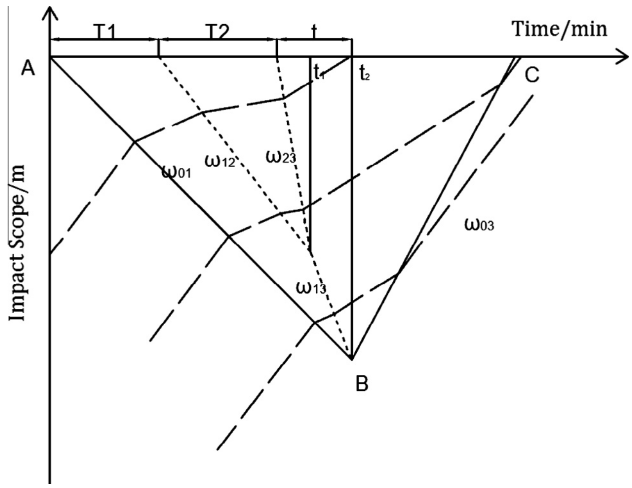


**Fig. 2.** Case 2 traffic flow diagram.

$T_2$ = time for accident handling, fold line ABC shows the impact scope.

In this case, the impact scope can be calculated as (Eq. (3)),

$$f(t_x) = \omega_{01} t_x, \quad \text{if } 0 < t_x \leqslant t_2 \tag{3}$$

(3) *Collaborate the loop data*

Installation of loop detectors, represented by dotted lines, on a typical freeway is shown as Fig. 3.

Prior to the primary accident, traffic flow condition is State 0. Since the primary accident location is not always close to a loop detector, the traffic flow characteristic should be a spatially interpolative value between the outputs of Loop 0 and Loop 1. After the primary incident occurs, Loop 1 is able to detect the flow condition defined as State 1. Then $\omega_{01}$ can be calculated as Eq. (4).

$$\omega_{01} = \frac{d_0 q_{10} + d_1 q_{00} - q_{11}(d_0 + d_1)}{d_0 k_{10} + d_1 k_{00} - k_{11}(d_0 + d_1)} \tag{4}$$

where $q_{00}$ and $k_{00}$ are outputs of Loop 0 before the accident occurs, $q_{10}$, $k_{10}$ and $q_{11}$, $k_{11}$ are outputs of Loop 1 before and after the incident occurs, $d_0$ and $d_1$ fix the distance between Loop 0, Loop 1, and the location of primary accident. As the density $k$ cannot be directly detected by a loop, it can be transformed by the occupancy rate.

$$k = R_{5\min} * \frac{1000}{\text{AVL}} \tag{5}$$

where $R_{5\min}$ is the occupancy in 5 min slice and AVL is the Average Vehicle Length. The unit for $k$ is veh/mile.

Considering that the flow condition is not only determined by the traffic but also by the geometric characteristics of the road, the access situation and other factors, it is innately changing along the freeway. The shock wave generated at the primary accident location continues to change along the traffic stream. The first speed of the forming shock wave $\omega_{01}$, when arriving at Loop 2, will not be well represented by the speed set from Loop 2. To address this issue, data collected by multiple loop detectors along the upstream must be used. As showed in Fig. 4, the speed calculation of shock waves in the SWBF method is continuously amended during its traveling toward the upstream. A new set of characteristic figures containing data from State 0 and State 1 is obtained by each loop detector with the arrival of the forming or dispersing shock waves. This results in an update in shock wave speed, leading to a more accurate estimation and closer representation of the actual situation. When the shock wave calculated from a previous loop arrives at the next loop, the new set of characteristic figures can be found according to the incident time and travel duration of

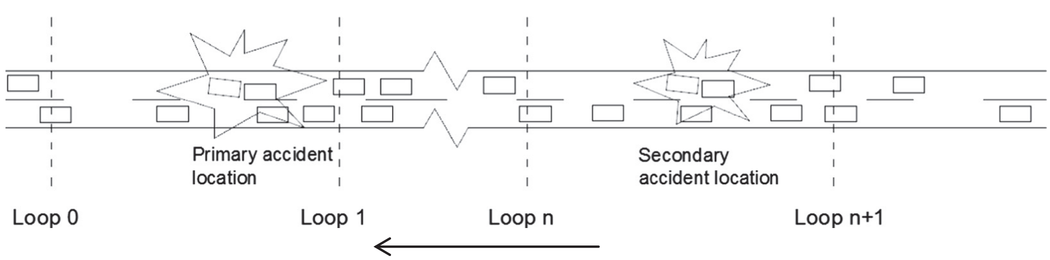


**Fig. 3.** Accident and loop locations.

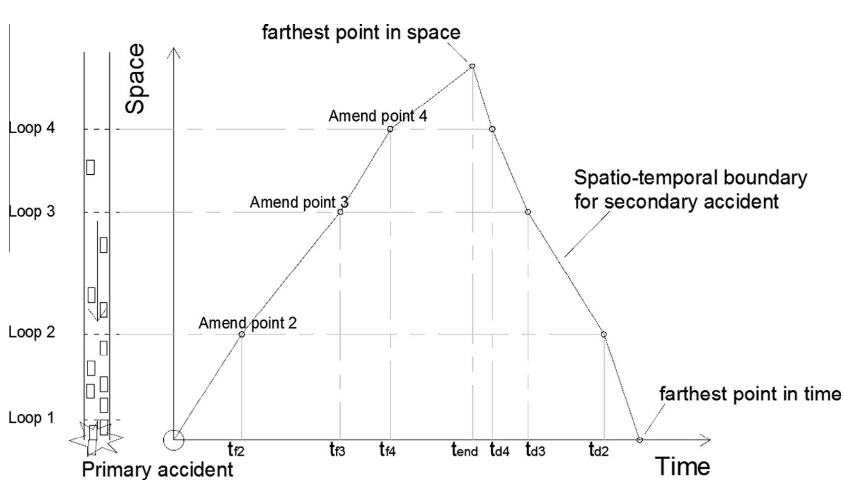


**Fig. 4.** Multiple loop detectors capture the primary accident chock wave.

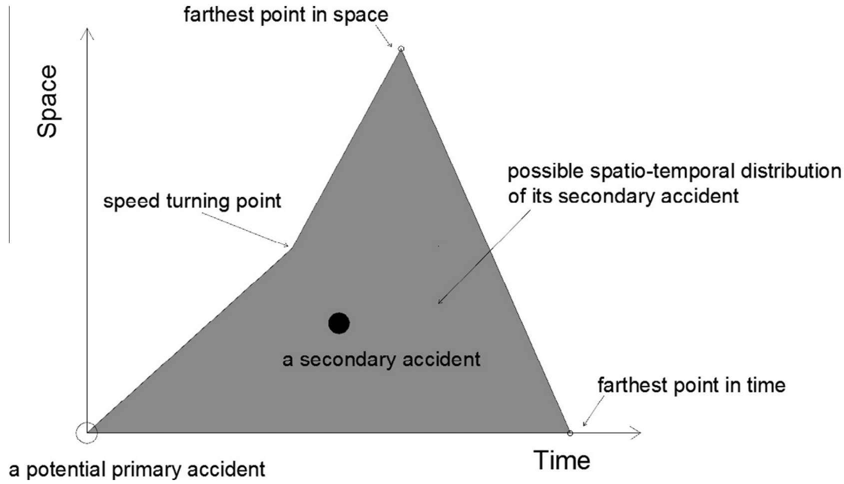


**Fig. 5.** Spatio-temporal secondary accident matching.

previous shock waves. The time points $t_{f1}$, $t_{f2}$, $t_{f3}$, $t_{d1}$, $t_{d2}$, $t_{d3}$ marked on the time axis in Fig. 4 refer to the time when the forming shock waves ($f$) and the recovering shock wave ($d$) arrive at Loop 2, Loop 3 and Loop 4, while $t_{end}$ is the time when the boundary reaches the farthest point in space.

### 2.2. Filter the secondary accidents

After the spatio-temporal district for secondary accident is attained, the filtering process is then transformed into a spatial matching process. As shown in Fig. 5, an accident is defined as a secondary accident if it falls into the primary accident impact range, represented by the gray area in the figure. The speed turning point indicates a changing point of traveling speed within the primary accident impact scope, which is actually a change in the shock wave caused by state converting or flow condition changing.

## 3. Data and transection

### 3.1. Data introduction

Interstate freeway accidents that occurred in California in 2012, collected from California Statewide Integrated Traffic Records System (SWITRS), were used in this study. A total of 10,762 accidents that took place on interstate freeways across eight Caltrans districts were collected, since historical loop data is only available for these eight districts in the Caltrans Performance Measurement System (PeMS). In PeMS, average speed, traffic volume, and average occupancy for every five minutes of all loops located in the upstream of the corresponding accident were collected. Accident data and relevant traffic flow information from the loops were linked according to the time indicator and the location indicator, which is post mile. Additionally SIWTRS and PeMS have different post mile fields that are absolute post mile and California post mile, and California post mile renews by counties. A computer program was composed to match them.

### 3.2. Excluding the invalid loop data

As loop data can be abnormal or missing, a data pre-transaction procedure was carried out. If the traffic flow exceeds 2500 veh/h lane, it was not used to calculate the shock wave. Meanwhile, it happened quite often that the loop data is 0. The next upstream loop data would be used to calculate the shock wave, unless there are more than two adjacent loop data are 0. When these samples were excluded, of the 6675 (62% of 10,762) accidents were left for secondary accident filtering.

### 3.3. Filtering process

A cyclic algorithm was designed to match the loop data with secondary accidents by coding a Matlab program as shown in Fig. 6.

Additionally, accident duration was not recorded in the accident database, however it was necessary to determine the start a dispersal shock wave marked as $T_1 + T_2$ (in Figs. 1 and 2). When an accident occurs, traffic flow at the accident location undergoes an obvious decrease in speed. When this slow down begins to recover, the bottleneck has been released. By identifying the fluctuations in loop data, the duration of accidents can be determined.

For a single primary accident, there may be more than one secondary accident. Furthermore, a secondary accident may be a primary accident for another secondary accident. Such situations were also taken into consideration during the program coding.

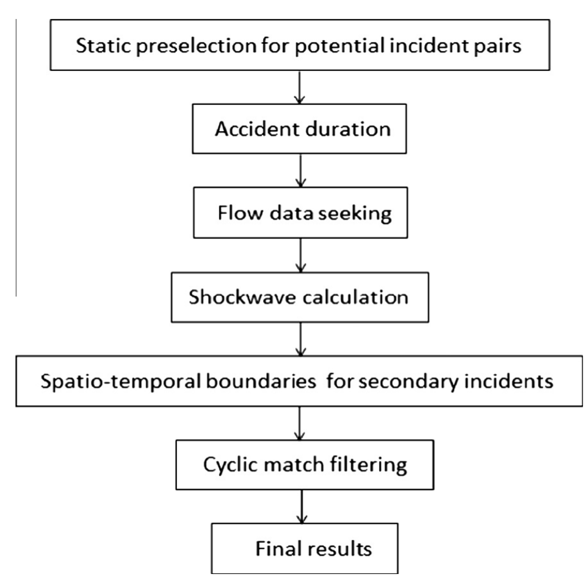


**Fig. 6.** Steps in the shock wave boundary filtering (SWBF) method.

**Table 1**
Identification of secondary accident results in previous research.

| Author | Spatial boundaries | Temporal boundaries | Results | Data |
|---|---|---|---|---|
| Raub (1997) | 1 mile | 15 min | More than 15% of the crashes may be secondary | Northern Chicago, metropolitan region (sample size 1796 crashes) |
| Karlaftis et al. (1999) | 1 mile | 15 min | 34.7% of the crashes may be secondary | Borman Expressway (741 crashes) |
| Hirunyanitiwattana and Mattingly (2006) | 2 miles | 60 min | 4.35%, more secondary accidents in rural districts | California highway system (sample size: more than 350,000 incidents) |
| Moore et al. (2004) | 2 miles | 2 h | 1.5–3%, lower frequency of secondary accidents | Los Angeles Freeway (sample size 84,684 crashes) |
| Zhan et al. (2009) | Max queue length 1.09–1.49 miles | Incident recovery time: 33.34–52.6 min, incident dissipation time: 0–21.76 min | 3.23% | Florida District 4 I-595 and I-75 (sample size 7895 crashes) |
| Sun and Chilukuri (2010) | Incident progression curve based | | 7.14% | I-70 and I-270 in Missouri (sample size 5514 crashes) |
| Chung (2013) | Speed matrix based | | 7.5% and 3.8% in 2 directions respectively | Freeways in Orange County, CA (sample size 6200 crashes) |
| Yang et al. (2013) | Binary speed contour plot based | | 8.4% are secondary (user's defined speed reduction factor 0.7) | A 27-mile segment of a major highway in New Jersey (case study sample size 1188 crashes) |

**Table 2**
Applying the fixed boundary method to the study data.

| Author | Spatial boundaries (miles) | Temporal boundaries (min) | Result pairs | Coincident pairs |
|---|---|---|---|---|
| Raub (1997) | 1 | 15 | 47 | 21 |
| Hirunyanitiwattana and Mattingly (2006) | 2 | 60 | 71 | 32 |
| Moore et al. (2004) | 2 | 120 | 112 | 51 |

## 4. Results

After the process of SWBF filtering, 114 of the original 10,762 California freeway accidents were confirmed as primary accidents, while 116 were confirmed as secondary accidents, including 2 tertiary accidents. The rate of primary and secondary accidents for the tested accident dataset is estimated to be 1.06% and 1.08%. These represent relatively lower percentages than did the previous research as shown in Table 1, and even lower than Moore's findings of 1.5–3%.

According to the results, the insufficiency of the fixed boundaries used in previous studies is obvious. Relying on fixed boundaries to define secondary accidents omits some accident pairs with extraordinary time or space intervals, while it includes others which conform to the boundaries despite these having no actual causal relationship. To verify this, a series of fixed boundaries used by Raub, Hirunyanitiwattana, and Moore was tested on the accident dataset used in this study. Results are shown in Table 2.

Compared with the results from previous filtering processes, the SWBF method excluded some ambiguous accidents pairs, which may meet the fixed static boundaries but have no cause and effect relationship. Shown in Fig. 7, the selected accident pairs, according to the fixed boundaries adopted by authors as shown in Table 2, can only account for a portion of the pairs filtered by SWBF. The open red diamonds represent 65 accidents pairs which were omitted by the fixed filtering standards, making up 56.03% of the total of 116. Cross marks shown in blue[1], gray, and black represent accident pairs that were mistakenly included by the fixed filtering standards. Therefore, in this case, the SWBF method helped to exclude 52.68%, 54.17%, and 55.32% of the accident pairs with vague spatio-temporal relationships. The solid red diamonds represent the overlap between secondary accidents identified by both the SWBF filtering method and the fixed boundaries method.

Additionally it can be seen in Fig. 7 that the distribution of secondary accident time and space is dispersed. The mathematical expectations of the spatio-temporal spaces are 71.09 min and 3.88 miles with the standard deviation of 55.36 min and 4.64 miles respectively.

## 5. Discussion

The proposed method defined the secondary accident as an accident that occurs in the presence of traffic condition changes within the impact area of a primary accident. However the real secondary accident frequency in California freeways could be more due to the following facts.

(1) If an accident occurs under congested condition, the shock wave would be very little or neglectable. In such conditions, the secondary accident can still occur. This could be the limits for loop data based method to identify the secondary accident.
(2) The inducing factor to the secondary accident in this paper is the primary accident instead of the incident. While other incidents which are not included in the SWITRS such as a single vehicle breaking down can also cause secondary accident. But the proposed method can be still applied in the incident record data.
(3) Only 62% of the loop data in the upstream of the 10,762 accidents are valid. Quality of loop data plays an important role in the proposed method.

## 6. Conclusion

This paper described a new method for secondary accident identification based on shock waves detected by freeway loop detectors, instead of filtering the secondary accidents based on human experience determination of time and space boundaries. A total of 10,762 accidents that took place on California interstate freeways in 2012 were collected together with the historical loop data. With the help of shock wave traveling speed, the spatio-temporal boundaries of potential primary accidents can be defined, transforming secondary accident filtering into a simple matching

[1] For interpretation of color in Fig. 7, the reader is referred to the web version of this article.

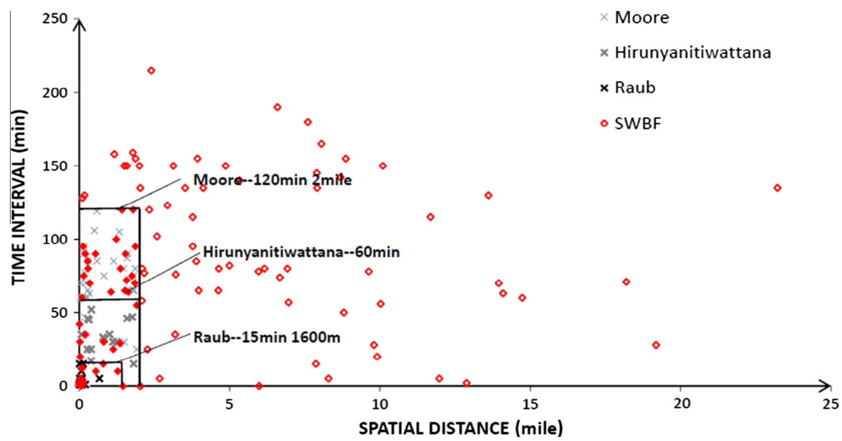


**Fig. 7.** Filtering results of different methods.

exercise. The secondary accident is defined as an accident that occurs in the presence of traffic condition changes within the impact area of a primary accident. Results from the shock wave boundary filtering (SWBF) method show a comparatively lower rate (1.08%) of freeway secondary accidents in California than were identified using previous methods. The spatio-temporal gap between the primary and secondary accidents is largely dispersed. Compared with the previous study of static filtering methods, SWBF can eliminate more than 50% of accident pairs with vague spatio-temporal relationships.

## Acknowledgments

This research is supported by the National "Twelfth Five-Year" Plan for Science & Technology Support Project in China (2014BAG01B04), the National Natural Science Foundation (71301119) and the Shanghai Natural Science Foundation China (12ZR1434100).

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