Integrated Freeway Incident Management
Using Data Mining and Expert Systems

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ABSTRACT To moderate the delay and minimize the impact area under non-recurring congestion caused by incidents along freeways, one of the viable solutions in incident management is to formulate and implement traffic diversion plans in a timely manner. However, selecting a diversion route requires careful consideration, taking into account the traffic conditions of surface streets. In addition, the traffic diversion plan needs to be updated at regular intervals, as the conditions on surface streets may vary from time to time because of extra traffic brought by diversion. Thus, a real-time determination of incident impact area will be useful in providing decision support for diversion. Therefore, this research builds a prototype of the Expert System for Freeway Incident Management (ESFIM) which adopts data mining techniques. The research tasks of ESFIM focus on applying data mining techniques to incident detection, determination of the incident impact area, the decision on a diversion point, and diversion route generation. The case study indicates that ESFIM enables the user to distinguish the impact area of the incident temporally and spatially. Furthermore, the traffic diversion plan suggested by ESFIM is found effective. The results presented in this research indicate that data mining provides the opportunity to better understand the impacts of an incident, and stands as a convenient tool for developing a traffic diversion plan.
RESEARCH BACKGROUND

Incidents in urban areas are known to contribute between 50 and 60% of total congestion delay (1). When an incident is severe, the traffic management center (TMC) usually adopts a procedure that includes prediction of the incident duration, decision making for traffic diversion, selecting diversion point(s) and alternative routes, and execution of the traffic diversion plan thus derived (2).

Each aforementioned step is usually handled based on previous experience and historical data collected and stored for the purpose. The biggest challenge in deriving a traffic diversion plan lies in the fact that it is highly location dependent. A diversion plan applied to one situation may not always work for another situation even though the intensity of the incident is similar. For instance, threshold values that trigger traffic diversions may vary from one place to another in a network or different networks.

Therefore, the goal of this research is to design a framework of an expert system for freeway incident management which data mining plays a key role (3 and 4) and to develop a traffic diversion plan using data mining in a freeway incident situation. The first and foremost requirement of applying data mining is the data, which is fulfilled by the availability of abundant data from the authority and/or by generating large sets of data from simulation. This research describes how a freeway incident situation can be investigated using data mining and the role data mining plays in “Expert System for Freeway Incident Management (ESFIM)”, thereby demonstrating the opportunities data mining can offer in deriving a suitable and effective traffic diversion plan. The data to be used for analysis are obtained from simulation (5), and a data mining tool (6) is employed to analyze the simulated data.

The research flowchart is shown in FIGURE 1. This research is organized in four sections, including this section. In Methodology Review Section, data mining is introduced and the research tasks of Expert System for Freeway Incident Management (ESFIM) are defined. How the data mining techniques are able to be adopted at developing a traffic diversion plan is demonstrated in Case Study Section. Finally, conclusions derived from the analyses are presented in the last section. Recommendations for future research needs are appended as well.

METHODOLOGY REVIEW

As the name indicates, data mining aims to mine the data for any hidden knowledge, which is not readily feasible through employing other tools. The availability of different methods is important when one is uncertain about which method may lead to the discovery of interesting and useful patterns in the data mined. The competitive advantage of data mining is to discover important trends and patterns in the data. Generally, the data mining techniques commonly used nowadays include decision trees, association, clustering, classification, artificial neural networks, and visualization.

Role of Data Mining in Incident Management

FIGURE 2 depicts how the TMC can adopt the data mining technique at each phase in managing an incident situation. The system shown in FIGURE 2 represents a schema of the proposed Expert
System for Freeway Incident Management (ESFIM), where data mining plays a key role and is programmed as application programming interface (API) for the expert system. There are four steps that the TMC will perform while incidents occur: incident detection, incident verification, deciding whether traffic diversion plans are needed and taking necessary actions. Each phase in ESFIM is referred to the four steps.

In Phase 1, the expert system can detect the incident occurrence and location via data visualization. Once verified, the TMC inputs the data on incident location and incident type into the expert system. Based on the input data, the expert system suggests the incident duration and predicts the resulting incident impact area. Within the information the expert system provides, the TMC can make a decision on whether a traffic diversion plan should be devised. If the traffic diversion plan is triggered, the expert system can develop a traffic diversion plan with essential elements, such as diversion points, diversions percentage, and alternative routes. In the last phase, the TMC should take necessary actions while the traffic diversion plan is being processed.

For revealing the potential of applying data mining to freeway incident management, this research rather focus on employing data mining techniques than building up ESFIM completely. Thereby, TABLE 1 summarizes the four phases of ESFIM and the research tasks.

CASE STUDY
A case study for developing a traffic diversion plan is established in this section. First, a brief description of test network in this research is given then the incident delay is predicted. This is followed by the determination of the incident impact area. Finally, alternative diversion routes are generated at each time interval for the formation of a traffic diversion plan.

Description of the Test Network
In this research, the data for data mining analysis was generated by simulated incidents (5). The test network for case study for this purpose covers approximately 180 sq. km area in Singapore, with AYE (Ayer Raja Expressway) running across the region modeled (see FIGURE 3). In total, there are 21 expressway exits and 23 expressway entries modeled.

AYE has three or four lanes in each direction of traffic, and the number of lanes on arterial streets ranges from one to four. There are 69 signalized intersections, and loop detectors are installed along the expressway at an approximate spacing of 600 meters. The number of simulation runs was 30. The occurrence time of the incident was set to 8:30 am, and the duration of the incident varied from 5 to 30 minutes (7 and 2). The location of the incident was fixed. There was one vehicle breakdown on a four-lane expressway segment, and the middle two lanes were blocked due to the incident. Data generated from the simulation was stored every 60 seconds. The results obtained from simulations are to be analyzed with the employed data mining tools/techniques (6) to light further understandings when and where incidents occur.

Incident Delay Prediction
There are a number of performance measures to be used to evaluate the impact of freeway incidents. Total delay is one of the most common measures. The severity of delay is used to trigger the traffic diversion (2); therefore, the incident delay must be estimated in order to decide
whether the traffic diversion plan will be performed. For freeways, total delay can be calculated by subtracting the free-flow travel time from the total travel time. The decision regarding the initiation of traffic diversion especially depends heavily on the real-time delay estimation. Without knowing the delay that will be caused by an incident, it is impossible to decide whether the diversion is suitable.

Morales (8) proposed a general expression to calculate the total delay due to a freeway incident:

\[
\text{Total Delay} = \frac{\left[ T^1_1(C_1 - C_1)(V_1 - C_1) + T^1_2(C_1 - C_1)(V_1 - C_1) \right] + T^2_2(C_1 - V_1)(V_1 - V_2) + 2T_1T_2(C_1 - C_2)(V_2 - C_2) + 2T_1T_2(C_1 - C_2)(V_2 - C_2) + 2T_2T_1(C_1 - V_1)(V_1 - V_2) + 2T_2T_1(C_1 - C_2)(V_2 - V_1) \right]}{2(C_1 - V_1)} \]  

(1)

where,

\( C_1 \) = Capacity of the freeway (veh/hr)

\( C_1 \) = Reduced capacity due to incident (veh/hr)

\( C_2 \) = Adjusted capacity of the freeway (veh/hr)

\( V_1 \) = Initial demand on the freeway (veh/hr)

\( V_2 \) = Adjusted demand due to diversion (veh/hr)

\( T_1 \) = Incident duration until the complete closure (minute)

\( T_2 \) = Duration of complete closure (minute)

\( T_3 \) = Duration of partial closure (minute)

\( T_4 \) = Time until the first change in demand (minute)

Some researchers have attempted to develop more accurate incident delay prediction models. Al-Deek et al. (9) proposed two separate regression models:

\[
\text{Model } 1: \text{Delay} = -4.26 + 9.71X_1X_2 + 0.5X_2X_3 + 0.003X_3X_4 + 0.0006X_5 
\]  

(2)

\[
\text{Model } 2: \text{Delay} = -0.288 + 3.8X_1X_2 + 0.51X_1X_5 + 0.06X_4 + 0.356X_5^2 
\]  

(3)

where,

\( X_1 \) = number of lanes affected
$X_2$ = number of vehicles involved in the incident

$X_3$ = incident duration, in minutes (difference between time of incident detection and time of incident clearance)

$X_4$ = traffic demand upstream of incident 15 minutes before occurrence of incident

The model Morales proposed was based on a deterministic queueing diagram. This method makes a few assumptions, such as that the demand and capacity are constant. The first model Al-Deek et al. proposed is similar to the deterministic queueing method. This model is a practical way of estimating delays caused by an incident, particularly for online applications (2). The second model Al-Deek et al. proposed assumes the effect of the incident duration with respect to incident delay to be linear. This is an unrealistic assumption due to incident duration not being linearly correlated with incident delay (2). Therefore, the first model Al-Deek et al. proposed was chosen for incident delay prediction in this research. Moreover, the incident severity index for determining whether there is a need for traffic diversion is summarized in TABLE 2 according to the method proposed by Kachroo et al. (2).

In the case study, there was a vehicle breakdown on a four-lane expressway segment and the number of lanes affected was two. The incident detection time was assumed to be three minutes (2), and the traffic flow upstream of the incident was collected from the loop detectors in the test network. The results of the incident delay prediction calculated by Equation (2) and the decision regarding whether traffic diversion should be performed are tabulated in TABLE 3.

As shown in TABLE 3, the values of the incident severity index range from 2 to 4, which indicate that all the scenarios have the need to trigger traffic diversions. Although the incident duration of some cases is lower than 15 minutes (e.g., Cases 6, 10, 12, 17, 27 and 28), all of the average incident delays are greater than 24 minutes. This may be because two lanes were affected by the incident even though there was only one vehicle involved in the incident. For the current analysis, the results from Case 8, the worst situation of all cases, were used in the data mining to investigate the incident and its resulting impact for developing the traffic diversion plan in this research.

Determine the Incident Impact Area

Data mining techniques suggested by Lee et al. (3 and 4) are chosen for the representations of the incident impact area. The results of representing the incident impact area along AYE and in its vicinity in the case study are described as follows.

AYE Incident Impact Area

The incident impact area of AYE was illustrated using three stacked bar charts with multi-dimensions (see FIGURE 4 to Figure 6). As shown in FIGURE 4, the width of each stack of detectors which represents the system performance measured in terms of delay during that interval (3), shows an increase at time T1 and regains the original width at time T2. The duration measured between T1 and T2 stands for the time when the overall system performance was affected by the incident. Note that the speed on detector DET 1047 decreases abruptly at time T1. This is the location (the region between detectors DET 1047 and DET 1049) where the incident occurred.
Another observation is on the headway (height of rectangles). Note that at time T1, for detectors above detector DET 1047, there is a sharp increase in headway. These detectors were located downstream of the incident, and hence where there was a sudden flow reduction caused by the incident. Furthermore, for the same detector, the headway exhibits a sharp reduction, notably at time T3. This was the instant when the incident was cleared.

It can be found from FIGURE 4 that it took about 84 minutes (T2 – T1) to return to normal traffic conditions when there was no action taken for traffic diversion. In addition, the area around detector DET 1023 was shown as a bottleneck after the incident was cleared since the speed of detector DET 1023 remained low until the overall system was back to normal conditions. Therefore, the TMC should prevent diverting traffic at the exits located in the region of detector DET 1023.

In FIGURE 5, five kinds of shock waves can be observed (3):

- Frontal stationary shock wave: $\alpha AB$, $\alpha CD$, $\alpha DE$ and $\alpha U$
- Backward forming shock wave: $\alpha AE$, $\alpha HK$ and $\alpha DG$
- Forward recovery shock wave: $\alpha JK$
- Backward recovery shock wave: $\alpha RK$ and $\alpha EG$
- Rear stationary shock wave: $\alpha FG$

Before the incident occurred (time T1), the area around detector DET 1023 had become a bottleneck. Congestion occurred between detectors DET 1015 and DET 1023, causing a frontal stationary shock wave ($\alpha CD$) and a rear stationary shock wave ($\alpha FG$). This may be due to recurrent situations where the normal demand exceeds normal capacity during the peak period.

At time T1, an incident occurred at a location near detector DET 1047 that caused a front stationary shock wave ($\alpha AB$) and a backward forming shock wave ($\alpha AE$). At detector DET 1023, a new frontal stationary shock wave ($\alpha DE$) and a backward forming shock wave ($\alpha DG$) were formed at time T4. At time T3, the incident was removed and a backward recovery shock wave ($\alpha RK$) was created. At time T5, another backward recovery shock wave ($\alpha EG$) was caused and a new backward forming shock wave ($\alpha HK$) was formed in the region from detector DET 1023 to detector DET 1007.

At time T6, a bottleneck in the region of detector DET 1023 was reestablished and a frontal stationary shock wave ($\alpha U$) resulted. Further reduction in input demand caused a forward recovery shock wave ($\alpha IK$) at time T7. The overall system returned to normal traffic conditions at time T2.

In this case, a frontal stationary shock wave occurred at detector DET 1023 after the incident was cleared; therefore, the area around detector DET 1023 was a bottleneck after the clearance of the incident. The point of intersection of the frontal stationary shock wave and the forward recovery shock wave indicates the termination of congestion; hence, the whole system returned to normal conditions after time T2. Furthermore, the speed of the area around detector
DET 1023 was low during the morning peak hours, which indicated that the traffic in this region might be heavy.

Another observation is on the backward forming shock waves. A backward forming shock wave indicates the congestion is gradually extending to sections farther upstream and to the area in the time-space domain where excess demand is being stored. In this case, the backward forming shock waves included $\omega AE$ and $\omega HK$ due to the incident. Therefore, the incident impact area on AYE was the area between detectors DET 1047 and DET 1007.

Incident Impact Area on Surface Streets

The results of the incident impact area on surface streets (4) are shown in FIGURE 6. FIGURE 6 illustrates the incident impact area based on the link speed of every sector at every time interval. The X-division denotes the time interval, while the Y-division denotes the distance of the sector away from the incident location. The value of the link speed is represented by drawings of various colors drawings.

The major incident impact area can be clearly observed by continuous white sectors that are circled in red, and the distance from the incident location extends to about 3 km. Apart from the major incident impact area, the darker blue sectors that stretch across horizontally are arterial streets with heavy traffic or intersection delays.

Traffic Diversion and Control

In this research, the alternative diversion routes were evaluated firstly at the time the incident is detected, and then the alternative diversion routes were reevaluated at the end of each time interval. Therefore, the alternative diversion route for the current time interval may not be available for the next time interval. In other words, the traffic diversion plan could be formed by more than one alternative route.

Related assumptions are given due to the focus of this research is on exploring the potential of employing data mining in freeway incident management. The assumptions that define the scope of generating alternative diversion routes are as follows:

- Time to start the diversion: five minutes after incident occurrence
- Time to terminate the diversion: once incident is removed
- Interval for reevaluating diversion route: five minutes
- Destinations of vehicles that are affected by the incident: Zone 26, Zone 27, Zone 31 and Zone 32 (see FIGURE 7)
- Diversion rate: 100 percent

The aforementioned assumptions are made for reducing the complexities while the route generation procedure was adopted. The incident location, affected destination zones, possible diversion exits and possible return entries are illustrated in FIGURE 7.

As the results show in TABLE 3, a corridor/freeway traffic diversion plan is suggested for Case 8. However, since only one expressway is included in the case study, corridor traffic diversion is chosen. As the results of incident impact area indicate that the region around detector
DET 1023 (located between Exit 1 and Exit 2) is a heavy traffic area during the morning peak hours and is a bottleneck after the clearance of the incident. Moreover, the major incident impact area is 5 km from the incident location (the region around Exit 4), and Exit 4 is the exit immediately preceding the incident location. Therefore, Exit 3 is chosen as the diversion point.

For the return point, Entry 1 is the nearest entry downstream of the incident location. However, this point is adjacent to the incident location and is not available for corridor diversion. To avoid the incident clearance activities being affected by the diverted traffic and to alleviate the impact on the surface streets due to the diverted traffic, Entry 2 is chosen as the diverted traffic return point. Therefore, the links between Exit 3 and Entry 2 are selected to form the alternative diversion routes. Four alternative diversion routes, G1, G2, G3 and G4, are generated for Case 8, as shown in FIGURE 8.

Each alternative route was evaluated regularly using the decision support function (4 and 6). The aggregated preference score for a link was calculated based on the assigned range and the weight. Moreover, the performances for each alternative diversion route measured at 5-minute intervals (see TABLE 4) in order to perform the real-time route generation procedure. The last route generation process for Case 8 was executed at 8:55 am because the incident was removed at 8:57 am.

As shown in TABLE 4, the traffic diversion plan for Case 8 included alternative diversion routes G1 and G3. The sequence of alternative diversion routes performed was G3, G3, G1, G3 and G3 from 8:35 am to 8:55 am. The alternative route was changed every five minutes till the incident was removed.

The evaluation of the traffic diversion plan is tabulated in TABLE 5. Note that the travel time and delay are system-wide. It is found that performing the traffic diversion plan can cut the total delay by 70.873 minutes in this case study. As seen in TABLE 5, the travel time increased 3.42% while the delay decreased 7.18% if the traffic diversion plan was executed. Since the total delay was reduced by performing the traffic diversion plan, the increase in travel time may imply that the detoured vehicles no longer traveled on shortest paths.

Another observation is on total delay (see FIGURE 9 and FIGURE 10). As shown in Figure 9, the total delay for diversion is higher from 9:15 am to 9:25 am. It might be caused by the flow of diverted traffic being too large to be digested by the surface streets, or by intersection delay resulting from the diverted traffic. Moreover, the total delay for diversion is lower than the situation without diversion from 9:25 am to 9:45 am, which means that the backward recovery shock wave (aBH), the frontal stationary shock wave (aHf) and the forward recovery shock wave (aHf) in FIGURE 5 were alleviated due to performing the traffic diversion plan.

In FIGURE 10, the cumulative total delay for diversion and the case without diversion are similar from 8:35 am to 8:45 am. However, the overall performance is better if the traffic diversion is performed because the cumulative total delay for diversion is lower than the situation without diversion after 8:45 am.
CONCLUSIONS AND NEEDS FOR FUTURE RESEARCH

A prototype of the Expert System for Freeway Incident Management (ESFIM), which adopting data mining techniques, was built in this research. The results of case study indicated that ESFIM enabled the user to distinguish the impact area of the incident temporally and spatially. Moreover, the traffic diversion plan was formed by a dynamic route generation procedure in ESFIM and was concluded to be effective.

For future research, applying data mining to develop ESFIM comprehensively so as to enable better and swifter incident management as well as optimum traffic diversion measures should be studied further. Once the ESFIM is developed completely, it should be linked with a database which can provide real-time data collected from detector stations. For case study, variation of incident location and of diversion point(s) should be taken into account; the adoptability of ESFIM can thereby be tested. The duration of enforcing the diversion plan should consider the trade-offs between the level of service on both freeway sections and surface streets in the vicinity. Moreover, the traffic diversion plan developed by this research chose surface streets as the alternative routes; therefore, further study can derive traffic diversion plans using ESFIM for a network that includes parallel freeways.

For the route generation process, the determination of hierarchy and the weights assigned to groups and criteria are arbitrary; thus, further research is needed in order to determine the influence of individual criterion. Furthermore, the rules for the route generation procedure, such as the time to start and terminate the diversion, the interval for reevaluating the diversion route, the trip destinations that may be affected by the incident and the diversion rate, were assumed in this research. Variations of the aforementioned factors should be deliberated.
REFERENCES

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TABLE 1 Four Phases of ESFIM and Research Tasks

<table>
<thead>
<tr>
<th>Phase</th>
<th>Components</th>
<th>Research Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Occurrence time</td>
<td>Incident detection (occurrence time and location)</td>
</tr>
<tr>
<td></td>
<td>Incident location</td>
<td></td>
</tr>
<tr>
<td>Phase 2</td>
<td>Incident duration</td>
<td>Incident, impact area determination</td>
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<td></td>
<td>Incident impact area</td>
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<tr>
<td>Phase 3</td>
<td>Where to divert</td>
<td>Diversion point</td>
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<tr>
<td></td>
<td>When to divert</td>
<td></td>
</tr>
<tr>
<td></td>
<td>How to divert</td>
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</tr>
<tr>
<td></td>
<td>How long to divert</td>
<td></td>
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<tr>
<td>Phase 4</td>
<td>Response agencies</td>
<td>Diversion routes</td>
</tr>
<tr>
<td></td>
<td>Route guide plan</td>
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<tr>
<td>Incident Severity Index</td>
<td>Rules</td>
<td>Diversion Strategy</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------</td>
<td>--------------------</td>
</tr>
<tr>
<td>1</td>
<td>If incident duration time ≤ 30 mins and average incident delay ≤ 15 min/veh</td>
<td>No diversion</td>
</tr>
<tr>
<td>2</td>
<td>If incident duration time ≤ 60 mins and average incident delay &lt; 30 min/veh</td>
<td>Point diversion* / Corridor diversion*</td>
</tr>
<tr>
<td>3</td>
<td>If incident duration time ≤ 120 mins and average incident delay &lt; 45 min/veh</td>
<td>Point diversion / Corridor diversion</td>
</tr>
<tr>
<td>4</td>
<td>If incident duration time ≥ 120 mins and average incident delay &gt; 45 min/veh</td>
<td>Corridor diversion / Freeway diversion*</td>
</tr>
</tbody>
</table>

*Point diversion: divert traffic from the exit ramp immediately preceding the incident link to the entry ramp immediately following the incident link.

*Corridor diversion: divert traffic at least two exits upstream of the incident to a few entries downstream of the incident.

* Freeway diversion: divert traffic from one freeway to another.
### TABLE 3 Predictions of Incident Delay and the Decision on Traffic Diversion

<table>
<thead>
<tr>
<th>Case</th>
<th>Incident Duration (min)</th>
<th>Average Incident Delay (min/veh)</th>
<th>Severity Index</th>
<th>Diversion Strategy</th>
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<tr>
<td>1</td>
<td>17.38</td>
<td>35.37</td>
<td>3</td>
<td>Point / Corridor</td>
</tr>
<tr>
<td>2</td>
<td>19.32</td>
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<td>13.68</td>
<td>31.67</td>
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</tr>
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<td>Point / Corridor</td>
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<td>11.18</td>
<td>28.78</td>
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</table>
### TABLE 4 Performance Score of Alternative Diversion Routes for Each Interval

<table>
<thead>
<tr>
<th>Time</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>Diversion Route</th>
</tr>
</thead>
<tbody>
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<td>08:35</td>
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<td>58.52</td>
<td>59.96</td>
<td>55.86</td>
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<td>50.04</td>
<td>50.63</td>
<td>44.93</td>
<td>G3</td>
</tr>
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<td>49.92</td>
<td>47.88</td>
<td>49.26</td>
<td>46.64</td>
<td>G1</td>
</tr>
<tr>
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<td>48.04</td>
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<td>43.36</td>
<td>G3</td>
</tr>
<tr>
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<td>50.31</td>
<td>49.12</td>
<td>50.37</td>
<td>46.00</td>
<td>G3</td>
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</table>
### TABLE 5 Evaluation of Traffic Diversion Plan

<table>
<thead>
<tr>
<th>Action</th>
<th>Total Travel Time (min)</th>
<th>Total Delay (min)</th>
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</thead>
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<tr>
<td>No diversion</td>
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<td>967765</td>
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<tr>
<td>Diversion</td>
<td>34905528</td>
<td>916892</td>
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</table>
FIGURE 1 Research flowchart.
FIGURE 2 Applying data mining to incident management.
FIGURE 3 Test network for case study.
FIGURE 4 Analysis of incident impact area on AYE.
FIGURE 6 Analysis of incident impact area on surface streets.
FIGURE 7 Affected destination zones, possible diversion exits and return entries.
FIGURE 8 Four alternative diversion routes: G1, G2, G3 and G4.
FIGURE 9 Total delays for case study.
FIGURE 10 Cumulative delays for case study.