I-270 Simulator: An integrated knowledge-base/simulation system for real-time incident management

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ABSTRACT

This paper presents a network simulator for I-270 that integrates the knowledge base with a microscopic traffic simulation model for real-time incident management. The knowledge base is used to keep the operational experience and traffic impact information associated with all recorded previous incidents in the I-270 network. The simulation module, developed with design plans for construction, contains traffic volumes and all detailed geometric features for both mainline segments and interchanges. The proposed system will enable traffic control operators during the incident management period to perform two critical functions: (1) having an immediate estimate of the traffic impacts such as the queue length, average speed due to the detected incident; and (2) performing a subsequent detailed real-time analysis of network traffic conditions under various candidate incident management and/or control strategies with the simulation module. The simulation results also offer the information between departure time and estimated travel time during the period of incident management. To minimize both the learning and executing efforts of our target users, the proposed I-270 simulator offers a GIS-type of map features that allows the operators to perform the input and output tasks through a user-friendly graphical interface.
1. INTRODUCTION

Efficient response to a detected incident so as to minimize the impact of non-recurrent congestion has long been recognized by highway traffic agencies, and a variety of corporative traffic management programs have also been implemented over the past decades (1-5), especially since the emerge of Intelligence Transportation System (ITS). One of the essential aspects which has yet to be better addressed in the incident management is to have a system that can reliably project the incident impacts on the traffic network within a time period sufficiently short for real-time operations, such as display of variable message signs (VMS) at proper locations, implementation of detour plans at critical ramps, and report of traffic conditions through highway advisory radios. With such information, traffic control operators can employ available ATIS or ATMS strategies to prevent the formation of traffic queue or to mitigate the congestion level if traffic shockwaves due to the incident have been propagated.

To provide a reliable estimate of traffic impacts during the period of incident management, however, is a quite challenging task, as the traffic condition (such as queue length, average delay, or speed) over those segments plagued by the incurred incident may vary with a variety of factors which are all time-varying in nature. Examples of such factors include the progress of incident clearance efforts, the speed and volume of the approaching traffic from upstream segments, compliance rate of a detour operation, effectiveness of VMS, and ramp metering control.

In response to this need, transportation professionals over the past several decades have devoted considerable efforts on development of various methods for projection of traffic conditions (6-9). Most of these state-of-the-art studies reported in the literature, either based on statistical methods (7-8), knowledge-base approaches (1-5, 10), or simulation techniques are quite promising in nature, but inadequate for use in real-time incident management where both efficiency and accuracy are essential for every step of its operations. For instance, a short delay (e.g. 10 minutes) in implementing a critical control strategy during incidents could result in a substantially long traffic queue in a high-volume highway network. Hence, from the perspective of traffic control operations, it would be very desirable if there exists an effective system that can provide the following vital functions for incident response and management:

- offering an immediate estimate of network segments that would be impacted by the detected incident over the operational period of the highway emergency response units,
- providing a detailed analysis of the time-varying traffic conditions on those network segments to be plagued by the incident, and
- efficiently assessing the potential effectiveness of various candidate control strategies or congestion-mitigation plans to be implemented during the period of incident clearance.
Currently, a system with all such desirable functions should be sufficient user-friendly to minimize both the learning time and execution efforts of control center operations (11). The knowledge-base/simulation system, named I-270 simulator, to be presented in the ensuing sections is designed with the above functions in mind. Our proposed system features its capability to offer an immediate estimate of traffic conditions based on similar previous incident scenarios stored in the knowledge base. The effectiveness of previous employed congestion management strategies is also available from the knowledge base for incident operations. The preliminary estimated results also allow the microscopic simulation module, embedded in the I-270 simulator, to select the target sub-network and execute its detailed operational analysis under the instruction from the control center operators. To ensure that the potential users under stressed condition (e.g. during incident operations) can execute our proposed system correctly and efficiently, we have employed the GIS type of graphical interface for both the input and output modules.

This paper is organized as follows: the operational structure and key features of the proposed I-270 simulator is presented in the next section. This is followed by an illustrative example of executing the proposed system under an incident scenario in Section 3. Conclusions and further research needs are reported in the last section.

2. OPERATIONAL STRUCTURE OF THE I-270 SIMULATOR

In practice, upon receiving an incident report, the control center operator will immediately dispatch emergency response units (ERU) to the incident site, and then estimate the potential traffic impacts such as the evolution of traffic queues, vehicle delays, and speeds during the incident management period. Such traffic impact information will offer the basis for operators in the control center to determine where and how to inform the approaching motorists, and evaluate the necessity as well as effectiveness of implementing any traffic control strategies. The I-270 simulator reported in this study is designed to assist traffic operators in performing these critical prediction and evaluation tasks in real-time incident management.

As illustrated in Figure 1, our developed I-270 simulator consists of the following principal modules:

- Interface module for information input and for receiving real-time data;
- Simulation module for real-time analysis and projection of network traffic conditions due to detected incidents;
- Knowledge-base/prediction module for both inventorying previous incident scenarios and performing the preliminary estimate of the traffic impacts due to the detected incident.
- Output module for monitoring and assessing the time-varying traffic conditions on target roadway segments after the onset of an incident.
With the incident related information input by traffic operators from the interface module, the I-270 simulator will automatically perform the following two tasks in parallel:

- Executing the network simulation over the projected incident duration based on the embedded network data and available real-time traffic volumes from detectors.
- Executing the knowledge-base/prediction module to provide an immediate preliminary estimate of the potential traffic impacts due to the detected incident, based on similar type of previous incidents incurred at the same or neighboring freeway segments.

Note that the preliminary estimate of traffic conditions with the knowledge-base/prediction module can be done in less than one minute, but the real-time simulation of the I-270 network will take, for instance, about 5 minutes for the impact period of 50 minutes.

The purpose of executing the knowledge base/prediction function is thus to offer the traffic operator an immediate and best estimate of traffic conditions during the incident period while the simulation module remains interacting with real-time data and executing the microscopic analysis of traffic conditions over the projected incident clearance period.

After completing the initial simulation, the I-270 simulator will automatically replace the traffic conditions estimated from the knowledge-base/prediction module with the simulated results which will then serve as the basis for control center operators to update or revise their incident management plan. Depending on the available on-line detector data, the microscopic traffic simulator can continuously update the projected traffic condition and evaluate the effectiveness of various candidate control strategies to be implemented during the incident management period. The output nodule of the I-270 simulator offers a full flexibility for traffic control operators to monitor the traffic condition of any segment over the selected time horizon under either the current operating plan or various “what-if” scenarios.

A detailed illustration of the above operational procedures and interrelations between all principal modules of the I-270 simulator is presented in Figure 2. The key design features of each principal system module are briefly discussed below:

**Input Interface Module:**

This module employs the GIS design concept that enables the users to first directly identify the approximate location of the target freeway segment from the map (see Figure 3), and then input the related information (if available) through subsequent interactive questions, as the geometry data contained in the I-270 microscopic simulation module are directly imported from the highway design plans which contain more detailed geometric features than those in the GIS. This type of design can circumvent the complex input process required by most commercial simulation programs, and minimize the learning time for target users. In addition, the input module can process both data input by the system operators and real-time traffic information received from traffic sensors.
Knowledge-Base Module:

This module is designed to take advantage of information and operational experience accumulated from previous incident management experiences. For instance, Maryland State Highway Administration (MSHA) has kept a detailed response time, incident duration, lane-blockage conditions, and the approximate traffic impacts on the network for each responded incident. All such incident impact information and management experiences from the year 1997 to 2001 are available for constructing the knowledge base. Such a knowledge base will offer the traffic control operators a reliable reference for estimating the potential impact due to a detected incident (e.g., from previous incidents incurred around the same location and over similar time periods).

Certainly, this type of estimate is preliminary in nature and will be replaced by a more reliable projection from the simulation. However, having such information to immediate assess the incident impact on the traffic network is quite critical in the incident management, as the shockwave generated by an incident will quickly build up the queue if it is not managed in a timely manner.

Prediction Module:

This is a set of statistical models designed to perform a supplemental analysis for the knowledge-based module, as a detected incident may not exist in the current database. Hence, the prediction module will execute its embedded statistical models, based on the candidate set of similar incidents identified by the knowledge base, to provide a quick estimate of the time-varying traffic impacts during the period of incident management. Those statistical models can be presented with the following general expression:

\[ Q^p(i, t) = f(Q(i-1, t), Q(i-2, t), Q(i+1, t), Q(i+2, t), Q(i, t+1), Q(i, t+2), Q(i, t-1), Q(i, t-2)) \]

Where:
- \( Q^p(i, t) \): predicted traffic queue (average speed or delay) in segment i at time t.
- \( Q(k, T) \): traffic queue (average speed or delay) incurred in previous similar incident scenarios on segment k (k=i-1, i-2, i+1, i+2) at time T (T=t-1, t-2, t+1, t+2).

Simulation Module:

It is the core of the I-270 traffic simulator, featuring its ability to simulate the actual traffic condition over the period of incident operations, or to assess the effectiveness of various candidate incident management strategies. Since the entire simulation needs to be executed at a sufficiently fast speed for real-time operations (e.g. 5 minutes for 1 hour simulation), the simulation module is capable of simulating only the sub-network that is likely to be impacted by the detected incident, rather than the entire I-270.

Note that as the simulation output is for use in the operational analysis (such as incident response and detour management), this simulation module has modeled the entire I-
270 network with its highway design plans, and included all its key geometric features such as vertical and horizontal alignments, the length of deceleration and acceleration lanes, radius of on- and off- ramps. Both mainline and ramp traffic volumes over peak and off-peak periods are also calibrated and embedded in the simulator. In addition, the simulator is capable of automatically updating its traffic volume with available on-line detector data.

The current simulator is build with CORSIM – the corridor simulation program by FHWA. Its data set, however, is sufficiently detail and comprehensive for use in most existing corridor simulation programs.

Output Module:

While executing the I-270 simulator, this module will first yield the projected traffic conditions from the knowledge-base/prediction module in response to the urgent need of the traffic operators. All such results will then be automatically replaced with those from real-time simulation and updated continuously as more real-time data become available. With this proposed module, the system operators can choose either to view the animation result from simulation or from pre-format statistical comparisons of traffic conditions on selected segment over the time window of concern. Examples of such output options are shown in Figure 4. Traffic operators can also use the output module to display the estimated travel time of different departure times for commuters from different origins, based on the real-time simulation results.

Overall, the proposed I-270 simulator has taken advantage of strengths from simulation, knowledge base, and GIS, and integrated all information such as roadway geometry, volume and control strategies as an effective system for incident management. Traffic operators with such a system can first reference previous incident scenarios to provide immediate incident impact assessment, and then evaluate various operational plans with a real-time simulation analysis. They can also continuously monitor traffic conditions in either the entire network or on target segments with the proposed output module, and take necessary actions in advance to minimize the formation of congestion.

3. AN EXAMPLE OPERATION OF THE I-270 SIMULATOR:

To facilitate the illustration, we will use the following incident scenario to present the operating process of the developed I-270 simulator.

Incident Scenario:

At 8:20AM, one incident occurred on the south bound of I-270 between exit 5 and exit 6. The second right lane has been blocked. The location of the incident is about 1500 feet from exit 6. The estimated time for recovering the traffic is about 40 minutes.
Operations with the I-270 Simulator:

Upon receiving the incident report, the operator in the control center shall take the following actions:

- Dispatching emergency response units to manage the incident, and
- Using the simulator interface to input the detailed incident related information, including:

  1. Zoom in the interface map to the segment of I-270 between exit 6 and exit 5, and click on the map to identify the incident area (see Figure 3).
  2. Input information related to the detected incident by answering the following four questions:
     a. direction of the blocked lanes (see Figure 5),
     b. approximate distance from the incident location to the nearest upstream or downstream interchange,
     c. distribution of blocked lanes due to the incident (see Figure 6),
     d. incident onset time and the estimated duration.

Prediction of traffic impacts

With the above information input by the operator, the I-270 simulator will automatically provide the estimated time-varying impacts of the detected incident on the I-270 with its knowledge-base/prediction module, while executing its simulation module. The actions to be taken by the knowledge-base module includes:

1) Searching previous incidents occurred on the same traffic bound within the same freeway segment; and then
2) Identifying those having the same number of lanes blocked as the detected one; and then
3) Narrowing down the candidate set to those having their starting time within the range of 30 minutes earlier or later than the detected incident; and finally
4) Sending all documented impacts and operations related information of the candidate set of incidents to the prediction module.

In this assumed incident scenario, the knowledge-base module has yielded 4 similar previous incidents for further execution of the prediction task (see Table 1).

From these previous incidents, the prediction module, which contains statistical models, will first identify the sub-network of I-270 which would be impacted by the detected incident (see Table 2), and then perform the preliminary estimation of its traffic conditions based on procedures shown in Figure 7.
Execution of the simulation

While the I-270 simulator is generating the preliminary incident impact information with its knowledge base and prediction modules, its simulator module will be simulating the network traffic conditions with real-time information. The geometry features of the I-270 network embedded in the simulation are as detailed and accurate as those available from highway design plans, which include:

- Freeway segments (both horizontal and vertical alignments)
- Local roads
- Ramps
- HOV lanes
- Signal controls at ramps and surface streets
- Traffic signs

The simulation module covers the entire I-270 and part of the I-495 network. An example interchange and sub-network included in the simulator are shown in Figure 8 and Figure 9.

Note that to minimize the execution time the simulator, based on the preliminary estimate from the knowledge-base module, will simulate only the sub-network to be impacted by the incident, rather than the entire network.

System output

As soon as executing the I-270 simulator, the operators can choose to directly view the animation of the entire system during the incident operations, or to review traffic conditions with the preset output formats. For instance, the operator may monitor the traffic impacts due to the incident by first selecting the display of delay charts and average speed distributions, and then targeting the roadway segment between exit 9 and exit 5, from 8:30 to 9:50 (see Figure 10).

Note the output module of the I-270 simulator offers the following functions:

- 6 different formats in line or bar charts for selected output displays (see Figure 4);
- Up to 2 charts could be selected to display concurrently;
- Customized the information displayed in charts (see Figure 11) and the animated map (see Figure 12), based on the roadway segment and time period selected by the operator;
- Always display the selected segment with its traffic conditions in a map view (see Figures 11 and 12) to ensure the consistency and accuracy;
- Offer the estimated travel time vs. each departure time for drivers from different origins (see Fig. 13).
As soon as the simulator completes its first run of simulation, the output module will replace the preliminary estimated results with those from the real-time simulation. The interrelation between the preliminarily estimated results and those from the simulation module for this example incident scenario is shown in Figure 14. Since the simulation result offers the evolution of traffic queues over time from the incident site, control center operators can thus assess where and how to display VMS messages, and implement pre-designed detour plans before the formation of traffic queues. Since the simulation time is much shorter than the actual time duration, traffic control center can also employ the simulator to evaluate the effectiveness of various candidate traffic management strategies.

4. CONCLUSIONS

The study has presented a knowledge-base/simulation system to assist traffic operations in real-time incident management. Our proposed system has taken advantage of strengths from microscopic simulation, knowledge base, and GIS, offering the flexibility for control center operations to perform the immediate preliminary estimate of incident impacts and subsequent detailed real-time operational analysis. With the proposed system, traffic control center can learn from previous incident management experience, and also use state-of-the-art simulation for efficient real-time analysis. Since the simulation module, based on the preliminary estimated results, can automatically decompose the network and simulate only the sub-network to be impacted by the incident, its computational speed is far faster than real-time. This distinguished feature allows traffic control center to effectively evaluate all candidate incident response plans and management strategies prior to their implementation.

Our on-going research is to integrate the proposed system with an optimization module that can assist traffic control operators in selecting the most effective plans such as ramp metering, integrated freeway/surface street control, in contending with non-recurrent congestion.
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Table 1. 4 similar incident cases that are generated from the knowledge base and are used for preliminary prediction of traffic conditions due to the detected incident

<table>
<thead>
<tr>
<th>Current Incident</th>
<th>Time</th>
<th>Duration</th>
<th>Lane Blockage</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar Case 1</td>
<td>8:00AM</td>
<td>60 min</td>
<td>Most Right Lane</td>
<td>800 ft from upstream Ex 6</td>
</tr>
<tr>
<td>Similar Case 2</td>
<td>8:00AM</td>
<td>60 min</td>
<td>Most Right Lane</td>
<td>2876 ft from upstream Ex 6</td>
</tr>
<tr>
<td>Similar Case 3</td>
<td>8:30AM</td>
<td>60 min</td>
<td>Most Right Lane</td>
<td>800 ft from upstream Ex 6</td>
</tr>
<tr>
<td>Similar Case 4</td>
<td>8:30AM</td>
<td>60 min</td>
<td>Most Right Lane</td>
<td>2876 ft from upstream Ex 6</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Similar Case 1</th>
<th>Impact Segment</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar Case 2</td>
<td>From Exit 9 to Exit 5</td>
<td>8:00-8:40</td>
</tr>
<tr>
<td>Similar Case 3</td>
<td>From Exit 9 to Exit 5</td>
<td>8:30-9:10</td>
</tr>
<tr>
<td>Similar Case 4</td>
<td>From Exit 9 to Exit 5</td>
<td>8:00-9:10</td>
</tr>
<tr>
<td><strong>Estimated Impact Segment</strong></td>
<td>From Exit 9 to Exit 5</td>
<td>8:00-9:10</td>
</tr>
<tr>
<td><strong>Current Incident</strong></td>
<td>From Exit 9 to Exit 5</td>
<td>8:20-9:00</td>
</tr>
</tbody>
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1. **Prediction Module**
   - **Time intervals without incident impact**
     - Identical to base case
   - **Time intervals impacted by incident**
     - Data in case 1: 8:00 to 8:40
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