A GA-based Mesoscopic Simulation Approach for Optimal Freeway Snow Removal Strategy Considering Traffic Congestion

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Abstract: This study proposes a GA-based approach to find the optimal strategy that minimize the overall traffic network costs in case of road closure due to heavy snowfall. A mesoscopic simulation model is adopted to evaluate the system performance in the course of GA implementation. The proposed model is applied to both a simple test network and a real-world freeway network to analyze its performance and practicability. Analysis results suggest that the proposed approach consistently yields near-optimal solutions. They also indicate that the GA-based solution performs much better that the current practice used for determining the snow removal sequence.

Key Words: snow removal, mesoscopic simulation, genetic algorithm

1. INTRODUCTION

Recently abnormal climate change, resulting from environmental pollution, global warming, and El Nino, has brought about unprecedented calamity and therefore we have difficulties to take precautions and recover from damages. Heavy snowfall recorded abnormally high level in the years of 2004 and 2005 in Korea and it has broken the record every year. This makes parts of Korea national freeways as well as municipal roads paralyzed and traffic blocked. In general, calamity due to heavy snow in winter is less frequent than flooding and typhoon in summer. Although the total sum of snow damage is not that big compared to flooding, the average damage due to heavy snowfall is more severe because the snow calamity occurs unexpectedly. Since unexpected and significant calamity causes huge human and material damages, it is very critical to prepare the fundamental solutions to manage and recover from snow calamity.

The emergency management system in Korea was integrated into "Emergency and Safety Management Code" in the year of 2004 when National Emergency Management Agency (NEMa) was established to work as the exclusive organization for emergency management. Until now, however, the recovery operation from heavy snowfall has not been carried out systematically by an effective strategy. Instead, it has been done based on quite simple guidelines in most cases. Korea Expressway Corporation which operates domestic toll expressways provides the guidelines on snow-removing work, highway control and emergency information dissemination. The guidelines indicate that snow-removing work should be done following the order of road traffic volumes on the damaged area (KEC, 2007). National Institute for Disaster Prevention also provides other guidelines on snow-removing management system and deicing chemicals to meet safe and smooth traffic and to cope with the environmental problems in case of heavy snow. They also suggest that snow-removing
work should be done in the order of traffic volume on each road link and give priority to motorway without detailed decision criteria (NIDP, 2003). Other guidelines on snow-removing work provided by The Korea Transport Institute (2008) and Seoul Development Institute are quite similar to those mentioned earlier (2004, 2006).

The Road Weather Management Program operated by the U.S. Federal Highway Administration (FHWA) provides the effective measures to respond to various weather problems such as rain, snow-and-ice, low visibility, hurricanes, and high winds along together with relevant reports, publications, and best practices including advisory, control, treatment, and mitigation strategies through webpage (http://ops.fhwa.dot.gov/Weather/). The webpage also shows the traffic statistics including speed, density, and volume under various weather conditions. With regard to the snow removal strategies, it introduces the examples of applicable models such as micro-simulation and dynamic traffic assignment, but the application cases include only major arterial and expressway. In case of Japan, permanent snow-removing installations have already been deployed in such area where it frequently snows heavily, which helps to carry out snow-removing work as soon as it snows (Kanemura, 1998).

2. METHODOLOGY

2.1 Classification of Accidents and Calamity

To take into account of efficiency and systematic aspect of traffic when recovering from calamity, the types of accident need to be classified by its size and response time from the recovery system operator’s viewpoint (Smith, 2008). Generally, normal accidents which frequently occur on road can be categorized as the short-term incident because they affect a small part of area of interest such as a road link or spot. The calamity that can be classified as mid-term or long-term incidents involves a wider range of affected area and longer time of impact, which requires quite a long time to recover. Road that is swept away (whether a part or all) by flooding can be an example of the long-term incident (Sisiopiku et al., 2007). Table 1 summarizes the classification of calamity on road and its typical characteristics.

<table>
<thead>
<tr>
<th>Type</th>
<th>Response Time</th>
<th>Scale of Affected Area</th>
<th>Required Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>Within a day</td>
<td>Link, Spot</td>
<td>Clearance of damaged vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Repair of road surface and/or furniture</td>
</tr>
<tr>
<td>Mid-term</td>
<td>Several months</td>
<td>Corridor</td>
<td>Road restoration and/or construction</td>
</tr>
<tr>
<td>Long-term</td>
<td>More than several months</td>
<td>Area</td>
<td></td>
</tr>
</tbody>
</table>

Transportation analysis models currently used in practice are categorized into two groups: i) operational traffic model and ii) planning model. When immediate evacuation from accident or calamity is needed, traffic operation models are very important because vehicles and pedestrians have to escape from the dangerous areas with high traffic jam in a very short time (Sbayti and Mahmassani, 2006). In recovery situation, however, attention should be focused on recovering normal traffic flow as emergency situation caused by accidents or calamity is already over. In case of mid-term calamity in particular, continuous monitoring and management should be carried out in terms of the total network performance, and therefore
both traffic operation and planning models need to be taken into account according to the scale of accident.

Since the mid-term calamity has wide range of impact and has to take into account of traffic congestion effects, the mesoscopic simulation approach is required to realistically represent the real world situations while overcoming the limitations of macroscopic traffic planning models. The simulation-based dynamic traffic assignment model is used as well to search realistic spatiotemporal traffic routes in the course of network recovery from abrupt breakdown due to calamity (Sisiopiku et al., 2007; Shen et al., 2007). In this study, a GA (Genetic Algorithm) based approach is proposed to efficiently determine the link priorities for heavy snow-removing work among various different strategies for recovery works. GA approach is quite an effective method to search the optimal solution for a NP (Nondeterministic polynomial Time) problem which is the case when the number of recovery road links to be recovered is increased. Cube Avenue 5.0, one of the most commonly used commercial simulators in the world, is adopted to estimate the evolution of traffic network under various road recovery scenarios. Cube Avenue is able to simulate traffic conditions in a realistic manner by reflecting individual vehicle delay and queue. It also can model dynamic road capacity which changes with time and vehicle platoons using packets (Citilabs, 2009).

### Table 2 Analysis and strategy by accident and calamity types

<table>
<thead>
<tr>
<th>Type</th>
<th>Traffic Analysis</th>
<th>Level of Strategy Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>Microscopic</td>
<td>Traffic operation</td>
</tr>
<tr>
<td>Mid-term</td>
<td>Mesoscopic</td>
<td>Traffic operation and network planning</td>
</tr>
<tr>
<td>Long-term</td>
<td>Macroscopic</td>
<td>Traffic network planning</td>
</tr>
</tbody>
</table>

#### 2.2 Recovery Strategies in Case of Heavy Snowfall

Traffic network is always planned and operated from the total network’s viewpoint because even a small single mode traffic network is closely connected with other traffic networks (Sisiopiku et al., 2007). Jenelius et al. (2006) investigate to prioritize the operation and maintenance of road through analyzing its vulnerability which is determined based on the importance and exposure by the type and location of road. The recovery of a damaged road link depends on its various attributes including level of service (travel time, speed), traffic characteristics (traffic volume, heavy vehicle mix), road type, and existence of alternative road, as shown in Table 3. Thus, the development of a road recovery strategy requires a commensurate measure of its performance. Performance measures currently used in common include travel time, network traffic delay, network efficiency, and traffic throughput (Naga and Fan, 2007). In this study, the total network travel time which is the most commonly used measure in evaluating traffic network performance is selected to determine the effectiveness of a road recovery strategy. The current practice in emergency snow removal is generally planned simply by giving priorities to road section with high traffic volumes or road hierarchy. However, this simple strategy cannot guarantee to minimize the total traffic congestion in the course of snow removal.

In this study, a GA-based mesoscopic simulation approach is proposed to find the best snow removal strategy which can minimize the total travel time in the affected area. As seen in Figure 1, the total travel time within the network can be changed substantially from the occurrence of incident to the completion of recovery. Thus, the optimal strategy is to
minimize the integral of the cost function and the optimization problem developed in this study is to minimize the total travel time in the network which is defined by Equation (1).

\[
\text{Total travel time} = \sum_{i=1}^{n} \sum_{j=1}^{m} (T_{ij} \times V_{ij})
\]

where, \( T_{ij} \) = travel time on link \( j \) at time segment \( i \) 
\( V_{ij} \) = traffic volume on link \( j \) at time segment \( i \)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Link Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of service</td>
<td>Travel time, speed</td>
</tr>
<tr>
<td>Traffic</td>
<td>Traffic volume, heavy vehicle mix</td>
</tr>
<tr>
<td>Type</td>
<td>Regular road, bridge, tunnel</td>
</tr>
<tr>
<td>Importance</td>
<td>Existence of alternative routes</td>
</tr>
</tbody>
</table>

Practically the severity of heavy snow can be classified based on amount of snowfall, temperature, surface condition and change in climate (Nixon and Qui, 2005). Maze et al. (2006) also show that traffic speed and road capacity are significantly affected by severe weather. Road conditions are categorized into three types based on the amount of snowfall. Here, the level of "heavy" snow is defined such that both road capacity and travel speed are reduced to be very low but the road is still passable. The level of "severe" snow is the case of "partly shutdown" or "shutdown" due to the high snowfall. Lastly “low" if the snowfall does not influence on the traffic.
Table 4 Road performance by amount of snowfall

<table>
<thead>
<tr>
<th>Level</th>
<th>Road Control</th>
<th>Performance</th>
<th>Capacity</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td>Shutdown</td>
<td>Zero</td>
<td>Zero</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>Operational control</td>
<td>Very low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>No action</td>
<td>Reduced</td>
<td>Decreased</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Application of Genetic Algorithm

The order of link recovery for snow removal can increase infinitely as the size of network increases. In this study, the optimal link recovery order is found by applying Genetic Algorithm to solve this nondeterministic polynomial time problem (Melanie, 1998). Cube Avenue 5.0 Program is used to estimate the total network travel times under all snow-removing strategy evaluated by the Genetic Algorithm as illustrated in Figure 2.

![Figure 2 Application of GA to finding the optimal strategy](image)

3. MODEL APPLICATION

3.1 Test Network

The test network applied in this study consists of 49 links and 34 nodes including 9 traffic zones as depicted in Figure 3. Three road links are assumed to be shut down due to heavy snow. The Origin-Destination (O-D) flow is assumed to be the same volume, 5,460 vehicles per hour, for all O-D pairs.
The simulation experiments are implemented based on the following seven key assumptions:

- All the drivers get the information on road closure resulting from heavy snow
- No additional road closure due to heavy snow occurs after the recovery from heavy snow is complete.
- The methods to use deicing chemicals are not considered.
- Link order based on location of snowplow garage and continuous route are not considered.
- Only two cases are considered for simulation: i) road shutdown ("severe") and ii) degrade of road performance ("heavy").
- Snow removing sequence is decided based on the total travel time only.
- User Equilibrium is the principle for traffic assignment.

Cube Avenue 5.0 enables dynamic assignment in which dynamic O-D flow is applied. The total simulation time includes a warm-up period to establish analysis model as well as the actual time period to analyze. The mesoscopic simulation used in this experiment is differentiated from the microscopic simulation by aggregating several vehicles in a packet instead of dealing with individual vehicle for traffic simulation. Cube Avenue, mesoscopic simulation software applied in this study, needs a set of parameters for simulation run. Key factors in traffic assignment include road capacity, storage, and queue block back time. For any O-D pair, the maximum number of feasible paths should be determined between the origin and destination. It is natural that each simulation run produces different assignment results. Figure 4 illustrates the results of 300 simulation runs for a snow removal strategy. Most of observed values are similar to the mean but in case of congestion, travel time increases geometrically and the distribution has a shape with long right-hand side. Not to reflect these delay values, a median of 10 running times, instead of mean, for each alternative, is applied in this experiment.
A simulation period is set as one hour and one closure link is recovered per one hour. Other critical simulation scenarios are as follows:
Since three links are closed, six different sequences for recovery are possible. The total analysis time consists of 8 time segments, each of which is 60 minutes including the warm-up time and stable network traffic conditions before and after road closure. Simulation results show that Alternative 1 (link sequence 1→2→3) is the best strategy that minimizes the total travel time in the test network. Alternative 6 (link sequence 3→2→1) in which snow-removing work is implemented according to traffic volume is not the optimal solution.

**Table 6 Total travel time of test network by recovery strategy**
(Unit: 10^3 minutes·pcu)

<table>
<thead>
<tr>
<th>Link Priority</th>
<th>TS1</th>
<th>TS2</th>
<th>TS3</th>
<th>TS4</th>
<th>TS5</th>
<th>TS6</th>
<th>TS7</th>
<th>TS8</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. 1</td>
<td>1→2→3</td>
<td>26.5</td>
<td>27.8</td>
<td>49.7</td>
<td>53.3</td>
<td>57.4</td>
<td>53.9</td>
<td>28.1</td>
<td>27.7</td>
</tr>
<tr>
<td>Alt. 2</td>
<td>1→3→2</td>
<td>27.3</td>
<td>28.3</td>
<td>53.9</td>
<td>64.3</td>
<td>78.4</td>
<td>73.2</td>
<td>30.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Alt. 3</td>
<td>2→1→3</td>
<td>27.7</td>
<td>29.1</td>
<td>62.7</td>
<td>94.1</td>
<td>101.0</td>
<td>88.3</td>
<td>32.1</td>
<td>28.7</td>
</tr>
<tr>
<td>Alt. 4</td>
<td>2→3→1</td>
<td>27.5</td>
<td>28.5</td>
<td>63.3</td>
<td>90.6</td>
<td>125.7</td>
<td>95.9</td>
<td>32.6</td>
<td>28.7</td>
</tr>
<tr>
<td>Alt. 5</td>
<td>3→1→2</td>
<td>27.2</td>
<td>28.4</td>
<td>53.3</td>
<td>79.5</td>
<td>77.4</td>
<td>75.6</td>
<td>31.7</td>
<td>28.2</td>
</tr>
<tr>
<td>Alt. 6</td>
<td>3→2→1</td>
<td>27.1</td>
<td>28.3</td>
<td>52.8</td>
<td>83.0</td>
<td>75.8</td>
<td>52.1</td>
<td>28.4</td>
<td>28.2</td>
</tr>
</tbody>
</table>

Figure 5 Changes in traffic network conditions

The GA-based approach clearly finds the best solution by enumerating all feasible combinations of link sequence in an efficient manner. The GA is carried out 7 times in total
and the key parameters used are the following:

- Population: 2
- Generation: 2
- Probability of crossover: 50.0%
- Probability of mutation: 3.0%

Table 6 Selection of the optimal strategy for test network by applying GA
(Unit: 10^3 minutes/pcu)

<table>
<thead>
<tr>
<th>Number of GA Runs</th>
<th>Sequence</th>
<th>Total Travel Time</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 → 1 → 2</td>
<td>396.4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3 → 2 → 1</td>
<td>368.5</td>
<td>Based on traffic volume</td>
</tr>
<tr>
<td>3</td>
<td>3 → 1 → 2</td>
<td>394.7</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1 → 2 → 3</td>
<td>337.6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3 → 1 → 2</td>
<td>401.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3 → 1 → 2</td>
<td>389.3</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1 → 2 → 3</td>
<td>342.8</td>
<td>Optimal strategy</td>
</tr>
</tbody>
</table>

3.2 Real-world Freeway Network

The practical applicability of the proposed model is analyzed through a real-world freeway network. As shown in Figures 6 and 7, a sub-area network and its corresponding O-D flows are constructed from Korea National Expressway Database. Sub-area O-D flows are established by the time of day based on the observed daily profile of traffic counts. The total subarea O-D traffic volume during the 13 hour planning horizon is 6,251,019 passenger cars per hour.
In this experiment, the simulation period consists of 13 time segments, since the real-world network is far wider than the test network. With both the warm-up time and stable condition after-recovery being 120 minutes long, respectively, the time duration (time segment) of each stage are defined as follows: i) warm-up: 2, ii) initial stable condition: 1, iii) shutdown: 1, iv) recovery: 6, and v) stable condition after recovery: 2. The following is other critical simulation parameters used in this experiment:

- Analysis time: 60(minutes)×13(Time Segment)
- Shutdown links: 6 links
- Packet size: 50 passenger cars
- Maximum path size: 3
- Number of runs: 10

The GA is carried out 211 times in total and the key parameters used are the following:

- Population: 20
- Generation: 10
- Probability of crossover: 50.0%
- Probability of mutation: 3.0%

After quite a few runs, GA can achieve a converged value of good quality which yields a near-optimal snow removal strategy to minimize the total traffic congestion cost. All simulation results consistently suggest that the GA-based strategy is far better than the current practice of snow removal practice which is based on traffic volume as shown in Table 7.
Table 7 Comparison of the optimal and non-optimal strategies

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Total Travel Time</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>6→5→1→3→4→2</td>
<td>98.95</td>
<td>Optimal strategy</td>
</tr>
<tr>
<td>4→1→3→5→2→6</td>
<td>229.34</td>
<td>Currents strategy based on traffic volume</td>
</tr>
</tbody>
</table>

4. CONCLUSION

In this study, a road recovery strategy is analyzed in case of heavy snowfall which frequently occurs in recent years due to climate change. The current disaster response and management systems consisting of four steps which are prevention, preparation, response, and recovery focuses on prevention and response. However, mid-term incidents such as heavy snowfall generally take far longer time for recovery than short-term incidents. A special attention should be paid to mid-term incidents because they would bring out excessive damages without an effective recovery strategy. In particular, road operators need a systematic and efficient road recovery strategy to minimize the traffic network costs resulting from an occurrence of disaster and incident response actions as well. In general, a main focus is on the traffic accident costs in traffic incident response system. However, heavy snowfall causes not only traffic accidents but also temporary closure or permanent loss of road links, which results in substantial socioeconomic costs.

A toll expressway network is used to test the proposed GA-based approach for finding the optimal snow removal strategy in this study. In case of expressway network, travel time cost is usually more important than traffic accident cost since it is a signal-free road which has
better sight distance and alignment than municipal arterial road. Currently snow-removing work is implemented by giving priorities to road links with high traffic volumes. According to the Korean guidelines for traffic management and response in case of heavy snowfall, traffic volume and road type are the most critical criteria in determining the priority of road recovery. However, traffic patterns are different by route, time, link performance, and, most importantly, spatial structure of traffic network. Traffic volume has a temporal and spatial variation and the importance of a road link is more dependent on network connectivity which affects recovery time and its associated social costs. Therefore, the best strategy to minimize the total travel cost is determined considering both the dynamic nature of traffic network and overall network performance. In this study, the total network travel time is selected as the performance measure to find the optimal road recovering strategy in case of heavy snowfall. The optimal road recovery strategy to find the best sequence of snow removal is determined by minimizing the total network travel time. Both a simple test network and a large-scale real-world network are used to test the proposed approach and the results are compared to the traditional snow removal strategies.

Cube Avenue, a mesoscopic traffic simulator, is adopted to calculate the performance measure through simulation-based dynamic assignment and GA is applied to find the optimal solution for snow removal sequence. The experiment results show that, in case of the test network, a traditional road recovery strategy based on traffic volume costs 368.5 (10^3 minutes\cdot pcu) while the proposed strategy takes 342.8 (10^3 minutes\cdot pcu), which is about 7% reduction in total travel time. In case of the real-work network, the total network travel times for the traditional and proposed strategies are 229.34 (10^6 minutes\cdot pcu) and 98.95 (10^6 minutes\cdot pcu), respectively. The proposed approach yields the solution which saves travel time by 56.9% compared to the existing method, which amounts to 21.7 billion KRW assuming the value of time is 167 KRW/minute.

In this study, the location of snowplow garage and connected routes are not considered, which will be a key addition to the current model in future research. Also, the level of details with regard to calamity and hazard need to be enhanced because snowfall hazard is affected by various factors such as the amount, extent, and duration of snowfall.

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