Fleet size estimation for spreading operation considering road geometry, weather and traffic

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Abstract: Extreme weather conditions (i.e. snow storm) in winter time have caused significant travel disruptions and increased delay and traffic accidents. Snow plowing and salt spreading are the most common counter-measures for making our roads safer for motorists. To assist highway maintenance authorities with better planning and allocation of winter maintenance resources, this study introduces an analytical model to estimate the required number of trucks for spreading operation subjective to pre-specified service time constraints considering road geometry, weather and traffic. The complexity of the research problem lies in dealing with heterogeneous road geometry of road sections, truck capacities, spreading patterns, and traffic speeds under different weather conditions and time periods of an event. The proposed model is applied to two maintenance yards with seven road sections in New Jersey (USA), which demonstrates itself fairly practical to be implemented, considering diverse operational conditions.

Key words: fleet size; road geometry; road network; spreading operation; traffic speed; winter road maintenance

1 Introduction

Weather is the second largest cause of non-recurring congestion (Rall 2010), which accounts for 25 percent of all delays. According to a report sponsored by the Federal Highway Administration (FHWA 2009), near 1 billion hours are lost each year due to weather-related delays. Icy and snowy road conditions greatly influence the road safety (Andrey 2010) as well as temporal and spatial variations of traffic volumes (Datla et al. 2008). Spreading of chemicals and abrasives on the road network is a key operation to keep roads for safe passage. During salt spreading a wide array of resources will be utilized to ensure the best possible road condition during/after each snow storm. Early research in this field focused on the guidance on anti-icing practices (FHWA 1995) which

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can be employed under various combinations of conditions in precipitations, pavement temperatures, traffic volumes, and mandated levels of service. A guideline was developed based upon a 4-year anti-icing field test conducted by 15 state highway agencies. Recently, under the mounting pressure of high demand for improving winter road safety and mobility subject to budget constraints, it is imperative for transportation agencies to pursue the most cost-effective usage of their resources. Hence, a sound spreading model is desirable to determine fleet size (i.e. number of spreading trucks) for maintaining designated road sections/network within a given time period considering weather and traffic.

The aim of this research is to develop a model which can be applied in estimating fleet size for salt spreading operation. The proposed model can be practically applied to determine the number of trucks needed for transportation agencies before the start of a snow season, considering the worst case situation including weather and geometry conditions and the corresponding traffic speed. Alternative, the proposed model can be employed to calculate the required number of spreading trucks to call out subject to forecasted weather and expected traffic.

The complexity of the proposed spreading model lies in three aspects:

1. Heterogeneous road geometry and spreading patterns. A transportation agency may be responsible for a large scale network with various types of roadways (i.e. urban vs. rural, freeway vs. arterials); as a result, the pavement width/number of lanes of each road section is a variable.

2. Variable operating speed. A time varying and location dependent speed matrix is required to determine the operating of winter road maintenance operations subject to different weathers and traffics and a cycle time (or called service time) constraint.

3. Mixed types of spreading trucks. Mixed types of spreading trucks with different capacities may be used during the spreading operations.

The proposed model will address all the above issues while estimating truck fleet size for pre-assigned road sections, considering geometric properties of the pavements and ramps (i.e. lane mile, centerline mile, lane number, ramp length and length of acceleration/deceleration lanes), spreading patterns, traffic and weather conditions, and mixed types of truck fleets (i.e. 2.5-Ton, 6-Ton, and 10-Ton trucks).

2 Literature review

Previous studies on salt spreading operation have focused on routing maintenance vehicles for a designated road network, and the objectives are to minimize the total distance traveled and fleet size, subject to operational constraints (Perrier et al. 2007; 2010). The fleet size needed for a large network was determined by road geometric condition, while traffic conditions were not considered. Considering more realistic information (i.e. the joint effect of weather, traffic and geometric conditions), a more complicated model is desirable.

Muyldermans et al. (2002) estimated the fleet size based on the total load of a district divided by vehicle capacity in the districting problem, which involves the partitioning of the road network into districts to facilitate the organization of the spreading operations. The total load of a district is the total route length to be treated, and the vehicle capacity is the length that can be serviced by one fully loaded truck. However, factors influencing the fleet size estimation were ignored, including different spreading patterns and the service time constraint.

It was realized that required number of spreading truck is also affected by the spreading patterns. For two road sections with same lane miles, the road section with small centerline mile may take less time than that for the road section with long centerline miles. Spreading pattern is mainly dictated by the type of highway and number of lanes. On a four lane undivided roadway, the passing lane in either direction may be spread simultaneously from the adjacent travel lane (Cifelli et al. 1979). Belt speed, spinner speed
and vehicle position need not be changed since the normal spreading pattern on this type roadway is achieved by spreading simultaneously on two lanes during the singular directional pass of the spreading unit. However, the spreading patterns for other multilane highways were not clearly defined.

Another issue that needs attention is the traffic speed while estimating the fleet size. During the spreading, the spreading truck speed is often impeded by traffic speed due to the adverse weather condition. Significant research efforts have been devoted to understanding the effects of weather conditions on traffic speed. Liang et al. (1998) studied the impact of fog and snow events on a section of a rural interstate freeway in Idaho. They found that the reductions in average speed were 7.6 and 18.13 percent for fog and snow events, respectively, comparing to that on sunny days. Daniel and Chien (2009) investigated the impact of adverse weather on traffic speeds on New Jersey roadways under a variety of weather and light conditions. It was found that under snowy condition the average traffic speed decreased between 9.3 km/h (5.8 m/h or 15%) to 54 km/h (33.8 m/h or 50%). A weather module was also developed as a part of FHWA’s Traffic Analysis Tools (TAT) program to guide traffic engineers and transportation operations managers in analyzing and modeling weather impacts on highway traffic movements (FHWA 2010). Similarly, according to a scanning study of Japan to investigate advanced technologies for winter maintenance operations and implementation (FHWA 2003), expressways in Japan employed variable speed limit signs in response to different road weather conditions, such as wind speed, visibility, air and road surface temperature.

Agrawal et al. (2005) quantified the impact of snow and pavement surface conditions on freeway traffic flow in Twin Cities, Iowa. Four different levels of snowfall intensities are employed in the research: trace (<1.27 mm/h), light (1.52-2.54 mm/h), moderate (2.8-12.7 mm/h) and heavy (>12.7 mm/h). The speed reduction associated with the four-level snow intensities are 3%-5%, 7%-9%, 8%-10% and 11%-15%. Moreover, past studies also suggested that the decrease or increase in speed variation during snow storms is influenced by road and vehicle types (Liang et al. 1998; Hanbali 1994). For instance, Hanbali (1994) found that snowy/icy conditions are associated with an average 18% and 42% speed reduction on two-lane highways and 13% to 22% reduction on freeways (more reduction on lower level of road), respectively. In addition, Chien et al. (2001; 2002) found that the primary causes of speed reduction are excessive roadway congestion, as one would find during peak travel periods, and event-induced impairment to driving conditions due to poor visibility and treacherous roadway surfaces. This finding is consistent with the observation by Shahdah et al. (2010) that winter road maintenance aiming at achieving bare pavement conditions during heavy snowfall could reduce the total highway traffic delay up to 36%, depending on the level of traffic demand. Similarly, FHWA (2006; 2010; 2012) has dedicated many efforts attempting to establish relationship between weather involving rates of precipitation and surface conditions and traffic flow variables. However, limited research was conducted on correlating the weather and traffic speed for specific roadway types during different time periods.

In addition, during spreading operation multiple types of spreading trucks with different capacities can be employed. Considering the operation with multiple truck types, the lane-mile spread per truck by type was defined as the capacity of the truck divided by the spreading rate (Cifelli et al. 1979). Hence, the required number of trucks by type can be calculated based on the total spreading lane miles divided by the lane-mile spread per truck. However, the service time constraint for spreading on the designated road network was not considered.

In summary, the proposed model and methods developed in this study can be applied to estimating the fleet size for spreading operation, in which the complexity in dealing with road geome-
try, weather and traffic conditions is discussed. A speed matrix, considering highway types, snow intensities, and time of a day, is developed based on data collected from transportation agencies, Clarus, and INRIX.

3 Model development

Figure 1 illustrates a general spreading configuration and associated geometric parameters for a four-lane road (two lanes per direction).

![Fig. 1 Geometrical parameters and spreading pattern of a road section](image)

In Fig. 1, \( C_{m1} \) is the centerline mile of the mainline of the road section \( s \); \( C_{a1} \) is the centerline mile of the acceleration/deceleration lane. \( C_{r1} \) is the centerline mile of ramp. As shown in Fig. 1, for a four-lane highway with two lanes in each direction, usually one spreading truck is required for spreading the two lanes in one pass. Additional spreading patterns will be suggested in the following part in this section.

To consider the actual road geometry and spreading pattern applied to each road section during spreading operation, the following assumptions are made in formulating the salt spreading problem:

1. Spreading rate (quantity of chemicals spreading per lane mile) for a certain road section is constant, which may vary in different snow events. Spreading systems can be calibrated to ensure that proper amount of materials is being applied with varying spreading truck speeds on the roads.

2. The spreading pattern depends on the number of lanes of a road section. For the two-lane and four-lane highway (one-lane two-way and two-lane two-way, respectively), the road can be treated in one pass; for six-lane or eight-lane highway (three-lane two-way and four-lane two-way, respectively), the road shall be treated in two passes.

3. Roadway types, snowfall intensities and time periods of a day can be classified as needed or approved by responsible agencies (i.e. state DOTs). For example, roadway types may be classified into: I: urban interstate, II: urban arterial, III: rural interstate, and IV: rural arterial; snowfall intensities can be classified into: I: 0-12.7 mm/h, II: 12.7-25.4 mm/h, and III: >25.4 mm/h; and time periods of a day can be classified into: I: AM (6-9 AM), II: MD (9 AM-3 PM), III: PM (3-6 PM), and IV: NT (6 PM-6 AM).

The determination of truck fleet size for spreading operation, considering geometry, weather and traffic conditions, is subjected to two estimates. The first estimate ensures that the total amount materials carried by the trucks is sufficient to cover the designated total lane-mile of spreading, while the second one ensures that the total lane-mile can be treated within the pre-specified service time. As formulated in Eq. (1), the two estimates whichever yielding a greater value is chosen as the determined fleet size, denoted as \( Y_{pitw} \) for truck type \( p \), section \( s \), snow intensity \( i \), time period \( t \), and weekday or weekend \( w \).

\[
Y_{pitw} = \max_{s \in S, i \in I, t \in T, w \in W} \frac{\lambda_a (L_e + R_e)}{(\lambda_a L_k K_p) / q} \lambda_a C_r \quad \lambda_a C_r
\]

Notations:

- Sets
  - \( P \): \{1, 2, 3\}, a set of spreading trucks types; i.e. three types of spreading trucks 2.5-Ton, 6-Ton, and 10-Ton.
  - \( S \): \{1, 2, ..., n\}, a set of road sections.
  - \( I \): \{1, 2, 3\}, a set of snow intensities; i.e. \( i = 1 \) for 0-12.7 mm/h; \( i = 2 \) for 12.7-25.4 mm/h, and \( i = 3 \) for >25.4 mm/h.
In Eq. (2), \( T' \) is the total number of spreading trucks of type \( p \) and \( n \) is the number of responsible road sections. However, as the calculation in the parentheses is not an integer, rounding up or rounding down should be considered and denoted as "*". The rounding criteria are discussed next.

Two criteria are introduced to round the estimated number of spreading trucks by acceptable spreading quantity adjustment and by acceptable service time delay. The purpose to set up acceptable spreading quantity adjustment is to compare the actual quantity of salt carried by the round-down number of spreading trucks against the actual requirement. If the difference is less than the acceptable spreading quantity adjustment, denoted as \( \Delta q_s \), the round-down number is accepted; otherwise, round-up number will be used. As for the acceptable service time delay, denoted as \( \Delta t_s \), it is designed for comparing the estimated operation time with the round-down number of spreading trucks with the service time. If the difference is less than the acceptable service time delay, the round-down number of trucks is accepted; otherwise, round-up one will be employed. Note that the round-up is denoted by "+" and round-down is denoted by "-". The two criteria can be expressed mathematically as follows.

### 3.1 Acceptable spreading quantity adjustment

The quantity difference (denoted as \( \Delta q \)) between the materials carried by the number of trucks and the actually required materials is expressed as

\[
\Delta q(x) = q - \lambda_s \sum_{s=1}^{S} (L_s + R_s) q - \lambda_s K_p \sum_{s=1}^{S} Y_{ps} \tag{3}
\]

where \( Y_{ps} \) denotes the round-down number of spreading trucks. If the calculated quantity difference by Eq. (3) is less than the acceptable spreading quantity adjustment, then \( Y_{ps} \) will be accepted; otherwise, the round-up ones denoted as \( Y_{ps} \) will be used. The total number of spreading trucks (type \( p \)) may be estimated based on the criterion illustrated in Eq. (4) as:

\[
T_p = \begin{cases} 
\left( \sum_{s=1}^{S} Y_{ps} \right) & \text{if } \Delta q(x) = Y_{ps} \leq \Delta q_s, s \in S \\
\left( \sum_{s=1}^{S} Y_{ps} \right) & \text{otherwise}
\end{cases} \tag{4}
\]

### 3.2 Acceptable service time delay

The time difference between the estimated spreading time and the service time, denoted as \( \Delta t \), is expressed as a function of the round-down number of trucks denoted as \( Y_{ps} \). Thus,
If $\Delta t$ is less than the acceptable service time delay denoted as $\Delta t_{a}$, then $Y_{\text{pw}}$ will be accepted; otherwise, $Y_{\text{p}}$ will be suggested. The total number of spreading trucks (type $p$) may be estimated based on the criterion illustrated in Eq. (6) as:

$$T_{p} = \begin{cases} 
\left( \sum_{s} Y_{\text{psw}} \right) -, & \text{if } \Delta t(x)_{s} = Y_{\text{psw}} \leq \Delta t_{a}, s \in S \\
\left( \sum_{s} Y_{\text{psw}} \right) +, & \text{otherwise}
\end{cases}$$

### 4 Data sources and data processing

The data required for the proposed spreading model include geometric, traffic speed and weather data, which can be retrieved from the straight line diagram (SLD), INRIX, and the Clarus, respectively. A brief description of each data source and the method of mapping these data into an applicable format are discussed next.

The SLD is a two-dimensional graphic representation of geometric characteristics of all types of roadways, including the interstate, U.S. and state routes systems used in several state DOTs such as New Jersey, Colorado, Ohio, and North Carolina. All the Interstate and State route information are included in SLD. After mapping each road section to SLD database, the information including lane number, lane mile and centerline mile of the mainline and ramps in each road section can be directly extracted from SLD database. However, as the lane number of a road section may not be constant, there will be more than one number extracted for a given road section and the spreading length of the road section can be calculated for each lane number. The calculation of the spreading length contains two parts; one is for the mainline while the other is for the ramps. For the mainline of two-lane and four-lane highways (with one lane and two lanes per direction, respectively), as the road can be spread in one pass, the total spreading length is equal to twice of the centerline mile of the pavement. For the mainline of six-lane or eight-lane highways (with three lanes and four lanes per direction, respectively), as the road should be spread in two passes, the total spreading length is equal to four times of the centerline mile of the pavement. For the road sections with varying number of lanes instead of constant number of lanes, the spreading length can be calculated by combining the two different situations. For the ramps of a road section, as most ramps have less than two lanes, the spreading operation can be completed in one pass. Hence, the spreading length of ramp is equal to the centerline mile of the ramp. To take into account the reduced traffic speed on ramps, the spreading length of ramp is suggested as multiplying the centerline mile of the ramp by an adjusting factor.

The weather and traffic speed data are archived based on geocodes of weather stations and TMC locations. The weather data, mainly obtained from the Clarus, which provides an archive weather data collected by road weather information system (RWIS), include pavement temperature and status (i.e. wet, dry, and snow), subsurface pavement temperature, wind speed and direction, precipitation (i.e. amount, occurrence, and type), water level conditions, humidity, and visibility (i.e. snowfall rate) at a 20 minute frequency. The temporal and spatial traffic data in this study are extracted from INRIX of which the data are anonymously collected from GPS-enabled vehicles and mobile devices through traffic message channel (TMC) and compiled into 5-minute-averaged speeds. The time varying weather information of those TMCs nearby the weather stations can be identified via a data mapping process, through which the speed matrix can be developed by correlating the speed data with roadway type, snow intensity, and time periods of a day as shown in Fig. 2. When applying the speed matrix to Eq. (1) in calculating the number of spreading trucks for each road section, there are situations that some road sections may contain more than one roadway types. In such cases, a weighted traffic speed can be calculated and used as the traffic speed for that road section.
5 Case study

In the case study, the above developed spreading model is applied to two highway maintenance yards in New Jersey, one in an urban area (called Yard A with 3 road sections) and the other one in a rural area (called Yard B with four road sections). The road geometry data and traffic data under various weather conditions in different time periods of a day for each section are summarized in Tabs. 1 and 2. The fleet sizes needed for the study yards under different circumstances are then analyzed. Note that Section A-1 in Tab. 1 consists of segments with different road types II (urban arterial), III (rural interstate), and IV (rural arterial), and all sections designated to yard B belong to road type I (urban interstate).

By mapping the road geometry, traffic speed, and weather data, the speed matrix by roadway type, snow intensity, and time period of a day during weekdays are obtained and presented in Tab. 2. Note that the weather data are based on 21 snow days during 2010/2011 snow season in New Jersey and only the data of weekdays are employed in developing the speed matrix which is to be used in the case study. To ensure sufficient fleet size due to traffic congestion in peak time periods, the 5th percentile speed is employed as the reference speed, at which 5% of the traffic is travelling below that speed. If the spreading truck speed is higher than the 5th percentile speed, the operation may be impeded by the traffic, and the reference speed will be used as the spreading truck speed in the proposed model. An example of obtaining 5th percentile speed is illustrated in Fig. 3.

As can be observed in Tab. 2 some speed data marked as "-" are unable to be generated due to insufficient traffic and/or weather data. For those, the spreading truck speed is tentatively assumed not affected by the traffic speed and the recommended operation speed is employed as a

<table>
<thead>
<tr>
<th>Road section</th>
<th>Roadway type</th>
<th>Centerline mile (km)</th>
<th>Lane mile (km)</th>
<th>Number of lanes</th>
<th>Length of acc./dec. lane (km)</th>
<th>Ramp length (km)</th>
<th>Spreading length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>II + III + IV</td>
<td>23.3</td>
<td>70.0</td>
<td>2</td>
<td>5.0</td>
<td>3.7</td>
<td>61.0</td>
</tr>
<tr>
<td>A-2</td>
<td>III</td>
<td>12.7</td>
<td>84.2</td>
<td>3</td>
<td>7.9</td>
<td>1.6</td>
<td>54.7</td>
</tr>
<tr>
<td>A-3</td>
<td>III</td>
<td>16.1</td>
<td>97.4</td>
<td>3</td>
<td>6.0</td>
<td>4.0</td>
<td>74.5</td>
</tr>
<tr>
<td>B-1</td>
<td>I</td>
<td>9.8</td>
<td>41.5</td>
<td>2</td>
<td>2.1</td>
<td>5.5</td>
<td>35.3</td>
</tr>
<tr>
<td>B-2</td>
<td>I</td>
<td>9.3</td>
<td>36.4</td>
<td>2</td>
<td>1.9</td>
<td>4.5</td>
<td>32.0</td>
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<tr>
<td>B-3</td>
<td>I</td>
<td>13.5</td>
<td>75.0</td>
<td>3</td>
<td>0.0</td>
<td>4.8</td>
<td>65.7</td>
</tr>
<tr>
<td>B-4</td>
<td>I</td>
<td>3.4</td>
<td>14.3</td>
<td>2</td>
<td>1.1</td>
<td>11.1</td>
<td>35.4</td>
</tr>
</tbody>
</table>

Note: II (37%); III (21%); IV (42%).
Table 2 Traffic speed matrix (weekdays)

<table>
<thead>
<tr>
<th>HC</th>
<th>Snow intensity</th>
<th>AM</th>
<th>MD</th>
<th>PM</th>
<th>NT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (km/h)</td>
<td>Mean (km/h)</td>
<td>Mean (km/h)</td>
<td>Mean (km/h)</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>87</td>
<td>45</td>
<td>93</td>
<td>71</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td>82</td>
<td>39</td>
<td>84</td>
<td>32</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td>87</td>
<td>27</td>
<td>95</td>
<td>40</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>76</td>
<td>42</td>
<td>76</td>
<td>40</td>
</tr>
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<td>II</td>
<td></td>
<td>72</td>
<td>40</td>
<td>82</td>
<td>61</td>
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<td>III</td>
<td></td>
<td>74</td>
<td>35</td>
<td>68</td>
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<tr>
<td>I</td>
<td></td>
<td>97</td>
<td>69</td>
<td>101</td>
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<tr>
<td>II</td>
<td></td>
<td>92</td>
<td>71</td>
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<tr>
<td>III</td>
<td></td>
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<td>37</td>
<td>95</td>
<td>71</td>
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<td></td>
<td>90</td>
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<tr>
<td>II</td>
<td></td>
<td>87</td>
<td>69</td>
<td>89</td>
<td>76</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td>-</td>
<td>-</td>
<td>92</td>
<td>82</td>
</tr>
</tbody>
</table>

Note: 1 km/h = 0.62 mph; HC-highway classification; "-"-not available.

substitute. The required fleet sizes under different circumstances for both yards are estimated. The calculation details for Yard A under snow intensity III during the AM peak (6-9 AM) is illustrated and discussed next.

The spreading truck speed for each road section can be determined by comparing the recommended spreading truck speed (i.e. 48.3 km/h (30 mph)) with the reference speed. For both Sections A-2 and A-3 of Yard A, the reference speed of 37 km/h (23 mph) is used as the spreading truck speed, because it is less than the 48.3 km/h (30 mph). Similarly, for Section A-1 (containing three types of roadways) the spreading truck speed is 41.1 km/h (25.6 mph) which is calculated based on the weighted average (35 x 37% + 37 x 21% + 48.3 x 42% = 41.1 km/h).

The developed model is applied to the seven road sections of two yards with a predetermined service time limit of 1.5 h considering (1) single type of spreading trucks and (2) multiple types of spreading trucks. Constant spreading rate of 99 kg/km is assumed, and the acceptable spreading quantity adjustment and acceptable service time delay are set as 45 kg and 15 min, respectively.

5.1 Operation with single type of spreading trucks

In this case, single 6-Ton spreading trucks are used for the spreading operation which can carry 7 t of material. As each road section may have different spreading patterns due to varied road geometry and roadway types, the required number of trucks for each road section is calculated separately. The result for the yard based fleet size can be obtained by summing up the results for each road section according to Eq. (2). In order to calculate the required number of spreading trucks for each road section, Eq. (1) can be applied. It is found that 1.59, 1.85 and 2.19 of 6-Ton trucks are required for each of the three sections of Yard A. Hence, the total required fleet size for spreading is 5.63.

In the calculation of the required number of spreading trucks, it is observed that the estimate of the total salt quantities in Eq. (1) is much stricter than that of the service time. As a result, when rounding the fleet size to an integer, the criteria by acceptable spreading quantity adjustment shall be applied. According to Eq. (3), it can be obtained that by using the round-down number of trucks (5 trucks) it introduces the
quantity difference of round 3629 kg between the total quantity of salt carried by the round-down number of spreading trucks and the actually required quantity of salt. This is far beyond the acceptable the spreading quantity adjustment of 45 kg; as a result, the rounding up result is employed, and six 6-Ton spreading trucks are suggested for the Yard A.

The number of spreading trucks required for both yards under all different circumstances are obtained similarly and presented in Tab. 3.

<table>
<thead>
<tr>
<th>Tab. 3 Estimated fleet sizes with 6-Ton trucks</th>
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<tbody>
<tr>
<td>Yard</td>
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<tr>
<td>------</td>
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<tr>
<td>A</td>
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<td></td>
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<td>B</td>
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</tbody>
</table>

It can be observed that the fleet size for both Yards A and B do not vary for all snow intensities during different time periods, which denotes the required quantity of 6-Ton spreading trucks is not dictated by the traffic condition and service time limit, but determined by the constrain of total required materials. It is expected that this situation will be different for high capacity trucks. To confirm this, the simulation with 10-Ton trucks is conducted with results presented in Tab. 4.

<table>
<thead>
<tr>
<th>Tab. 4 Estimated fleet sizes with 10-Ton trucks</th>
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<tbody>
<tr>
<td>Yard</td>
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<td>------</td>
</tr>
<tr>
<td>A</td>
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<td></td>
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<td></td>
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<tr>
<td>B</td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

As can be observed from Tab. 4, the results vary greatly during the time periods of AM peak and MD period mainly due to the low traffic speed (see Tab. 2). By comparing Tables 3 and 4, it can be concluded that for low capacity trucks, the required number of spreading trucks is mainly determined by the total required quantity of the spreading materials for the yard, while for the high capacity trucks, it is mainly controlled by the traffic condition and service time limit. As a result, to make high efficient use of the winter maintenance resources, it is preliminarily recommended that for the road sections with low traffic speed, the low capacity trucks are preferred, while for the road sections with high traffic speed the large capacity trucks are recommended.

5.2 Operating with multiple types of spreading trucks

In case two types of trucks are employed for spreading operations: 6-Ton trucks with carrying capacity of 7 t and 10-Ton trucks with capacity of 12 t. The model developed in this study can also apply to estimate additional trucks by type considering the quantities of existing truck types already in place. For example, assuming that only two 6-Ton trucks are in place for a designated network, the needed number of 10-Ton trucks can be determined by Eqs. (1) and (2).

First, the total quantities of salt carried by the two 6-Ton trucks and the spreading length can be calculated. Considering the capacity adjusting factor of 0.9 and spreading rate of 99 kg/km, total quantities of salt carried by the two 6-Ton trucks is 11430 kg, which is equivalent to 72 lane-mile spread. If the spreading trucks speed is 48.3 km/h, the total spreading length of the two trucks during the service time of 90 min is 145 km.

To estimate the required quantity of trucks for Yard B under snow intensity III during the AM peak (6-9 AM), subtracting the lane mile to spread and the spreading length by the two 6-Ton trucks from Eq. (1), there is a need for additional 3.05 trucks (10-Ton) to complete the work. According to rounding criteria presented Eq. (6), the number of 10-Ton trucks is rounded to 3. Sim-
Similarly, the results for all other circumstances are presented in Tab. 5.

<table>
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<th>Yard</th>
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<th>AM</th>
<th>MD</th>
<th>PM</th>
<th>NT</th>
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<tr>
<td></td>
<td>III</td>
<td>2</td>
<td>3</td>
<td>2</td>
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</tbody>
</table>

Note: **" - type I truck (6-Ton); **" - type II truck (10-Ton).

By comparing the results of the case with single type of 10-Ton spreading trucks (Tab. 4) with that of the case with both types of trucks, it can be found that using mixed type of spreading trucks leads to a decrease of the fleet size, which can be considered to optimize the utilization of winter maintenance resources during spreading operation.

5.3 Sensitivity analysis

According to analysis results presented in Tabs. 3 and 4, the variation of fleet size mainly occurs during AM and MD time periods. It is noted here that as the speed data are not complete for the PM peak, hence, the variation of fleet size during PM peak is not representative. To investigate the effect of snow intensity on fleet size, a sensitivity analysis is performed for both yards during the AM and MD time periods considering by employing single type of spreading trucks 6-Ton and 10-Ton, respectively. The results are presented in Figs. 4 and 5, respectively.

As indicated in Figs. 4 and 5, the fleet size with large trucks (i.e., 10-Ton) increases as the snow intensity increases in the AM peak and MD period. As the service time constraint is the primary factor affecting the required fleet size under this situation, it is sensitive to the weather conditions (i.e. snow intensity). However, for small trucks (i.e., 6-Ton), the fleet size seems not affected by the snow intensity and time of a day for the study yards, which is mainly dictated by the total amount of spreading materials. Thus, the impact of reduced traffic speed due to adverse weather seems insignificant. In addition, as expected, the sensitivity of the fleet size to the weather condition is higher in urban area than that in rural area mainly due to the lower traffic speed in urban area (see Tab. 2).

Spreading rate is also a critical factor to determine needed fleet size for spreading operation, which is defined as the amount of materials to spread per lane mile. It may vary depending on geometry and weather conditions. To investigate its effect, the required fleet size under three different spreading rates (i.e., 71, 99, 127 kg/km) during the AM peak are analyzed. The results are presented in Fig. 6.

As indicated in Fig. 6, the fleet size, in general, increases as the spreading rate increases for both types of trucks and this trend is more obvious for the yard in rural area than that in the urban area.
area. The main factor contributing to this regional effect is the low traffic speed in urban area which reduces the effect of spreading rate on fleet size. Moreover, the spreading rate has more significant influence on the small capacity trucks than that on the large capacity ones due to limited truck capacity.

6 Conclusions

In this study, a model is developed to estimate fleet size for spreading operation considering road geometry, weather and traffic, which is capable of capturing the heterogeneity of service lane-mile, spreading rates and patterns, traffic speeds and truck types while estimating fleet size. A methodological approach of processing and mapping geometry, weather, and traffic data for generating the speed matrix is discussed. In case study, the proposed model is applied to estimate fleet size for two maintenance yards in New Jersey, one in a rural area and the other in an urban area. With the collected weather, geometry and traffic data, a speed matrix subject to various dimensions (i.e. roadway type, snow intensity, and time of a day) is developed. It is found that the model is fairly practical and effective to estimate fleet size, especially in capturing the diversity of operational conditions.

A sensitivity analysis is conducted to explore the relationship between model parameters and fleet size. As indicated in Figs. 3 and 4 the fleet size with large trucks (i.e. 10-Ton) increases as the snow intensity increases in the AM peak and MD period, because the service time constraint is the primary factor affecting the required fleet size; thus, it is sensitive to the weather conditions (i.e. snow intensity). However, for small trucks (i.e. 6-Ton), the fleet size seems not affected by the snow intensity and time of a day for the study yards, which is mainly dictated by the total

Fig. 5 Fleet size vs. snow intensity (MD period)

Fig. 6 Fleet size vs. spreading rate
amount of spreading materials. Thus, the impact of reduced traffic speed due to adverse weather seems insignificant. In addition, the fleet size increases along with the increase of spreading rate and the influence is more significant on the small capacity trucks than that on the large capacity ones. The results also show the regional effect of traffic speed on spreading operation that the impact of snow intensity, traffic speed and spreading rate on fleet size could be greater for the yard in an urban area than that in a rural area.

This research lays the basis for the application to deploy resources during winter highway maintenance, such as assisting transportation agencies to allocate numbers of trucks over different yards. The developed model can also be applied to evaluate operational performance under various scenarios, such as partitioning a regional network into small sectors subjected to workload and contiguity constraints as discussed in a study conducted by Perrier et al. (2006; 2010) and winter highway maintenance resource optimization.

Acknowledgments

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References


Massachusetts Highway Department, 2006. Snow & ice control generic environmental impact report. 2006-4-19-06.


New Hampshire Department of Transportation. Winter maintenance snow removal and ice control policy.


