FHWA-NJ-2014-001

SNOW MODEL ANALYSIS

FINAL REPORT
January 2014

Submitted by

Steven I-Jy Chien, Ph.D.
Department of Civil & Environmental Engineering
New Jersey Institute of Technology
Newark, NJ 07102-1982
Phone: (973) 596-6083
E-mail: Chien@adm.njit.edu

NJDOT Research Project Manager
Paul Thomas

In cooperation with

New Jersey
Department of Transportation
Division of Research and Technology
And
U. S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA-NJ-2014-001	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Snow Model Analysis		**5. Report Date** 1/27/2014 **6. Performing Organization Code**
7. Author(s) Steven Chien, Jay Meegoda, Shengyan Gao		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil and Environmental Engineering New Jersey Institute of Technology University Heights Newark, NJ 07102-1982		**10. Work Unit No.** **11. Contract or Grant No.** NJDOT 2011 – 01
12. Sponsoring Agency Name and Address N.J. Department of Transportation 1035 Parkway Avenue P.O. Box 600 Trenton, NJ 08625-0600	Federal Highway Administration U.S. Department of Transportation Washington, D.C.	**13. Type of Report and Period Covered** Final Report May 2011 – June 2013 **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

This study developed a new snow model and a database which warehouses geometric, weather and traffic data on New Jersey highways. The complexity of the model development lies in considering variable road width, different spreading/plowing patterns for mainlines and ramps, actual (traffic dependent) and recommended plowing/spreading speeds and the use of mixed truck types. On the other hand, the complexity of the developing database lies in extracting geometric details of study road sections, estimating/mapping traffic speed considering the severity of weather (i.e. snow intensity), time of a day (i.e., peak/off-peak period and weekday/weekend), and roadway type (i.e., urban/rural freeways/arterials). The developed model was applied to three maintenance yards in New Jersey which demonstrates its dynamic and flexibility in adapting to various circumstances (i.e., geometry, weather, and traffic) in estimating needed fleet size for salt spreading and snow plowing operations for various scales (i.e., section, crew, yard, region, and statewide). The model outcomes can be used to assist managers to determine the required number of contractor trucks before a winter season and during/after a snow storm based on forecasted weather and traffic condition. The objective of this study is to assist the New Jersey Department of Transportation (NJDOT) in developing a method to estimate quantity of salt and fleet size for winter highway maintenance in the State of New Jersey.

17. Key Words Salt Spreading, Snow Plowing, Fleet Size, Winter Highway Maintenance, Weather and Traffic Condition, GIS	**18. Distribution Statement** No Restrictions.		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No of Pages** 71	**22. Price**

Form DOT F 1700.7 (8-69)

ACKNOWLEDGMENTS

This project was sponsored by the New Jersey Department of Transportation (NJDOT) and the Federal Highway Administration. This project could not have been accomplished without the assistance of numerous individuals. The authors would like to express gratitude to Andrew Tunnard, David Bowlby, Paul Thomas with NJDOT and Dr. Abdel-Malek Layek, Dr. Victor Ososkov, Curley Joshua, Charlie Porter, Bo Du, Hassan Hashmi, Liuhui Zhao and Jason Jawidzik with NJIT.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

1 EXECUTIVE SUMMARY

Salt spreading and snow plowing are the most common countermeasures for snowy and icy pavement surfaces. A snow model is desirable to determine the quantity of salt needed to spread and the fleet size required in cleaning the roads subject to a certain service time constraint for both spreading and plowing operations. This is especially useful in determining the number of contractor trucks needed before the beginning of a winter season. The current snow model used by NJDOT was developed in 1978, which is not accurate due to significant changes in road geometry and lane-mile and traffic conditions in New Jersey over the past 30 years. In this study, a new snow model was developed to estimate quantity of spreading salt/fleet size for spreading and plowing operations considering road geometry, weather and traffic speed, subject to service time limit.

To achieve the objective of this study, a database for road geometry of all snow sections responsible by NJDOT was developed by retrieving data of each snow section from the Straight Line Diagram (SLD, 2009) database. A traffic speed matrix was developed based on roadway type, time period and weather condition. With real-world data, the proposed snow model was applied to three maintenance yards in New Jersey for case study analysis. The results showed that the proposed snow model can adapt to the complexity of varying pavement width/lane number of road sections, different spreading/plowing patterns on mainlines and ramps, weather and time dependent traffic speed, and usage of mixed types of operating trucks/plows.

The estimated results for spreading and plowing operations are presented in deployment worksheets (Appendices A and B). The results indicate that there are no variances of the fleet size under different snow intensity levels during various time periods at lower operation speed. However, at higher operation speed, the impact of reduced traffic speed due to adverse weather on spreading/plowing results become obvious and this is special the case for large capacity trucks. The implementation of the new snow model to all snow sections in New Jersey is expected to assist managers in determining the required number of contractor trucks before the start of a snow season, considering the worst case situation including weather and geometry conditions and the corresponding traffic speed. Additionally, it can be employed to calculate the required number of spreading trucks/plows to call out during/after each winter storm subject to the forecasted weather and expected traffic.

2 INTRODUCTION

2.1 Background

To ensure winter travel as safe as possible, the New Jersey Department of Transportation (NJDOT) utilizes a wide array of resources to improve road conditions during each winter storm. The snow model is a critical tool in NJDOT tool box which can be used to determine the total number of trucks/plows required to spread/clear the roads subject to the service time limit (also called cycle time in this report). Hence, it can be used to determine how many contractor trucks that NJDOT needs to seek in the Snow Contracts and the total amount of salt needs to prepare.

The current snow model was created in 1978 and used formulas applicable to the equitable allocation of trucks spreading anti-icing materials and snow plows by both State and contractual forces. There were two sub models included in the current snow model: spreading and plowing. The formulae that were developed take into account the applicable speed of the vehicle, the number of lanes, and the total lane miles of snow sections. The spreading model assumed an entire cycle to be completed in ninety (90) minutes while that for plowing was two (2) hours. It is found that the model is outdated and makes planning for Winter Season needs very difficult because the NJ highway networks are larger and busier than they were in 1978. In addition, the 1978 model could not consider the impact of traffic speed (i.e. by roadway type, time period, and weather condition) to winter road maintenance operation. Moreover, the geometric data including the lane number, pavement width, shoulder width, and lane miles of ramps have been changed over the past years, which shall be updated to approximate needed number of trucks and amount of salt to ensure safe road condition.

Under the mounting pressure of high demand for improving winter road safety and mobility subject to budget constraints, it is imperative for NJDOT to pursue the most cost-effective usage of their resources. Hence, a robust snow model is desirable to determine the quantity of salt needed to spread and the fleet size required in cleaning the roads subject to a certain service time constraint for both spreading and plowing operations. Also, the road geometry database and traffic speed database of New Jersey Highways need to be updated.

2.2 Objective

The specific objective of this study is to develop a snow model to determine how many trucks and total quantity of salt are needed for salt spreading and snow plowing subject to weather predictions, time of a day, weekday or weekend, and service time constraint.

3 LITERATURE REVIEW

The complexity of the proposed spreading and plowing models lies in three aspects:

1. Heterogeneous road geometry and spreading/plowing patterns. A typical agency may treat a mixed 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. Spreading patterns are based on the number of lanes while the plowing patterns may be varied considering treating the mainline, acceleration/deceleration lanes, shoulder and ramp separately or as a whole.
2. Variable operating speed. A time varying and location dependent traffic speed matrix is required to determine the operating speeds of spreading and plowing trucks subject to different weather and traffic conditions.
3. Mixed types of spreading trucks/plows. Mixed types of spreading trucks/plows with different capacities/plowing widths may be used during the winter maintenance operations.

In this section, previous studies related to the critical concerns listed above are reviewed and discussed below.

3.1 Salt Spreading Operation

Most of 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). However, those studies did not consider detailed road geometry, weather condition, real-time traffic speed and service time constraint in regard the estimation of maintenance fleet size.

Muyldermans et al. (2002) indicated that the number of required vehicles can be estimated as total lane-mile to be serviced divided by vehicle capacity which involved the partitioning of the road network to facilitate the organization of the spreading operations. However, modifications are needed to improve its accuracy. For instance, the spreading pattern shall be determined by the number of lane on a snow section. In addition, the service time constraint is a key parameter affecting the needed trucks for spreading operation.

It was realized that the required number of trucks is also affected by spreading pattern. Spreading pattern is mainly dictated by the number of lanes of a section (or pavement width). On a four-lane undivided roadway (two-lane per direction), the spreading pattern is achieved by spreading simultaneously on two lanes during the singular directional pass of the spreading unit (Cifelli et al. 1979). Hence, for two snow sections with same lane-mile but different lane number to be served (e.g., one is four-lane highway while the other is two-lane highway), the one with large number of lanes (less centerline miles) may be finished earlier than that with small number of lanes (more centerline miles) due to less vehicle miles traveled. However, the spreading pattern for other multilane highways was not clearly defined.

Another issue that should be of concern while estimating fleet size is the traffic speed. During spreading operation, the truck speed is sometimes impeded by traffic due to the adverse weather condition and time of a day. Significant research efforts have been devoted to realizing 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, and it was found that the two types of adverse weather result in reductions of average speed of 7.6 and 18.1 percent respectively comparing with those on sunny days. Daniel and Chien (2009) investigated the impact of adverse weather on traffic speeds on New Jersey roadways by collecting traffic data under a variety of weather and light conditions. It was found that under snow conditions speeds decreased between 5.8 mi/hr (9.3 km/hr or 15%) to 33.8 mi/hr (54 km/hr or 50%).

Agrawal et al. (2005) quantified the impact of different levels of snow intensities and pavement surface conditions on freeway traffic flow for the metro freeway region around the Twin Cities in Iowa State. Four different levels of snowfall intensities are defined in the research: Trace (<0.05 inch/hour), light (0.06-0.1 inch/hour), moderate (0.11-0.5 inch/hour) and heavy (>0.5 inch/hour), and the speed reduction associated with the four-level snow intensities are 3-5%, 7-9%, 8-10% and 11-15%, respectively.

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 is consistent with the findings (Shahdah and Fu, 2010) that clearing bare pavement conditions instead of section width during heavy snowfall could reduce the traffic delay up to 36%, depending on the level of traffic volume.

In addition, during spreading operation trucks with different loading capacities can be employed. Considering the situation with mixed types of trucks, the lane-mile spread per truck was defined as the truck capacity divided by spreading rate (Cifelli et al. 1979). However, the service time constraint for spreading operation that will affect the need number of trucks shall be considered.

3.2 Snow Plowing Operation

Previous studies (Cifelli et al. 1979; Wilson et al. 2003) indicated the number of snow plows is simply determined by the total pavement area divided by plowing area per plow within a given service time period. The total pavement area can be obtained by the lane-mile multiplied by lane width, while the plowing area per plow is the product of plowing width, plowing speed, and service time. Considering the total lane miles is a variable, other parameters including lane width, plowing speed and cycle time are constants. However, this approach ignored the condition on highways with varying pavement width. In addition, the condition of traffic speeds and types of plows with different plow widths were not considered.

Since the pavement width and number of lanes may vary, previous methods were not able to accurately capture complex road geometry, which will lead to underestimating required fleet size. Especially, if the tandem plowing pattern is employed, of which the plowing configuration is always based on the maximum instead of the average section width. In addition, the mainline, shoulder and ramp may be plowed separately depending on the severity of the storm and traffic conditions (NYSDOT, 2006), which was not clearly addressed in previous studies. The proposed plowing model should provide the flexibility to consider these issues.

Plowing speed is sometimes impeded by the congested traffic due to adverse weather. Knowing that the actual plowing speed is a key factor to approximate the fleet size, most of previous studies considered a constant plowing speed. For example Cifelli et al. (1979) suggested a constant plowing speed of 12 mph, and NYSDOT (2006) suggested average plowing speeds of 14.5 mph for expressways and 16.5 mph for other highway classes. Although there are no consensus on relationship between the traffic speed and weather, significant research efforts have been devoted to this area. Based on 15-minute aggregated traffic data in Iowa, Knapp et al. (2000) found that the average plowing speed could be reduced by 16 percent due to severe winter storms. Other relevant studies (Liang et al. 1998; Daniel and Chien, 2009) are mentioned in previous section.

During snow plowing, multiple types of plows may be employed for effective operation. For a wide road section, larger plows are preferable, while for narrow ones, small or medium-sized plows would be more efficient. Missouri DOT (Lannert, 2008) embarked on solving the challenges of clearing more lanes and shoulders with fewer trucks and operators by using wider front plows. Similarly, Colorado DOT (FHWA, 2012) used wider front plows to clear a 12-foot lane in one pass and trailer plows to clear widths over 24 feet at high speed to reduce the number of passes (rounds) needed and to save fuel and reduce labor costs. However, there is no systematic research on employing mixed types of plows during plowing operations to enhance the efficiency of winter highway maintenance.

3.3 Summary

In summary, the existing literature related to the aforementioned main complexities of estimating fleet size during winter highway maintenance has not fully addressed those concerns. Tackling these concerns is our intent.

In this project, lane number based spreading patterns should be proposed. Additionally, the plowing patterns considering the mainline and ramp separately and the plowing configuration based on the maximum pavement width should be considered in the proposed model. According to previous studies (Liang et al. 1998; Knapp et al. 2000; Padge et al. 2001; Daniel and Chien, 2009), it can be concluded that traffic speed is affected by the snow fall intensities, roadway types and traffic congestion although there is no consensus on the reduction factors for each variable. Hence, a traffic speed matrix, which is function of highway types, snow intensities, peak hours and weekday & weekend, will be developed in this study.

4 DEVELOPMENT OF THE SNOW MODEL

The aim of this research is to develop a snow model, including 2 sub-models, to estimate the required number of trucks for snow plowing and salt spreading subject to time constrains, geometric properties of the pavements, spreading and plowing patterns, traffic conditions and weather. In this section, the formulations of both the spreading and the plowing models are presented. In addition, the complexities of developing of the two models are discussed and the proposed approaches of dealing with the complexities are also provided.

4.1 Salt Spreading Operation

The spreading model can be used for both contractual and operational purposes. For contractual purpose, it can be used to determine how many contractor trucks needed to seek and total amount of salt to spare before the start of a snow season, which can be determined by considering the worst situation including weather and geometry conditions and the corresponding traffic speed. For operation purpose, it can be employed to calculate the required number of spreading trucks to call out and total quantity of salt to spread subject to forecasted weather and expected traffic condition.

4.1.1 Parameter Definition

Figure 1 shows the geometrical parameters and spreading configuration for a four-lane road section *s*.

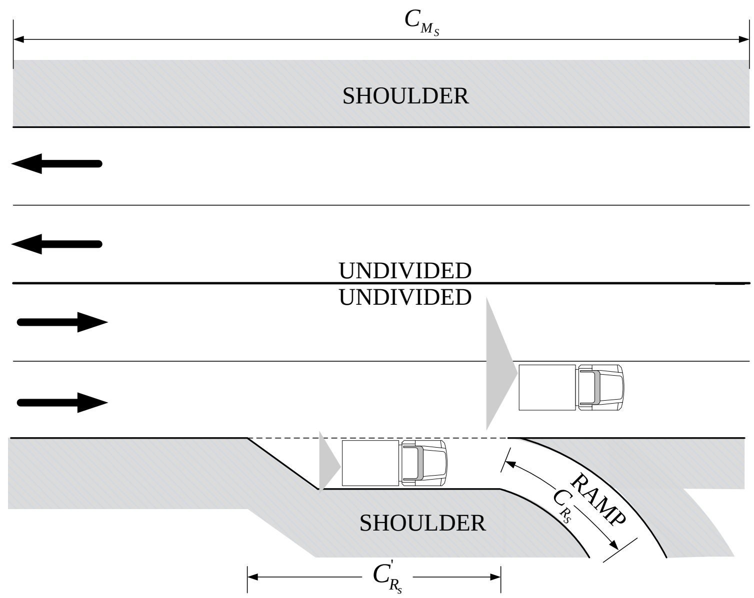

Figure 1. Spreading model parameters with a general road section

In Figure 1, C_{M_S} is the centerline mile of the mainline of the road section s; C'_{R_s} is the centerline mile of the acceleration/deceleration lane. C_{R_s} is the centerline mile of ramp. As shown in Figure 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 Section 4.1.6.

4.1.2 Model Assumptions

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:

- 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 proper amount of salt is being applied with varying spreading truck speeds on the roads.
- 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.
- 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: 0~0.5 in/hr, II: 0.5~1 in/hr, and III: 1~2 in/hr; and time periods of a day can be

classified into: I: AM (6AM-9AM), II: MD (9AM-3PM), III: PM (3PM-6PM), and IV: NT (6PM-6AM).

4.1.3 Spreading Model Formulation

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 of salt carried by the trucks is sufficient to cover the designated total lane-mile for 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_{psitw}, for truck type *p*, section *s*, snow intensity *i*, time period *t*, and weekday or weekend *w*.

I: Formulation of Section Based Fleet Size

$$Y_{psitw} = Max\left(\frac{\lambda_a * (L_s + R_s)}{(\lambda_k * K_p) / q}, \frac{\lambda_a * C_s^{'}}{v_{sitw} * t_s} \right) \quad p \in P, s \in S, i \in I, t \in T, w \in W \qquad (1)$$

Notations:

- Sets
  - *P*: {1, 2, 3}, a set of spreading trucks types; *e.g.*, there are three types of spreading trucks employed by most State DOTs: 2.5-Ton, 6 -Ton, and 10-Ton;
  - *S*: {1, 2, ..., n}, a set of road sections;
  - *I*: {1, 2, 3, 4}, a set of snow intensities; i=1 for 0~0.5 in/hr; i=2 for 0.5-1 in/hr; and i=3 for 1-2 in/hr;
  - *T*: {1, 2, 3, 4}, a set of time periods; t=1 for AM (6AM-9AM), t=2 for mid-day (MD) (9AM-3PM), t=3 for PM (3PM-6PM), t=4 for night time (NT) (6PM-6AM);
  - *W*: {1, 2}, a set of weekday and weekend; w=1 for weekday and w=2 for weekend.

- Parameters

  - Y_{psitw}: number of spreading trucks required for spreading road section *s* (including the mainline and ramps), under snow intensity *i*, during time period *t*, on weekday or weekend (*w*);
  - L_s: total mainline lane miles of road section *s*;
  - R_s: total ramp lane miles of road section *s*;
  - K_p: capacity of the spreading truck type *p*, *e.g.*, 2.5 -Ton truck's capacity is 4.25 tons, and 6 - Ton and 10 -Ton trucks are 7 tons and 12 tons, respectively;
  - q: spreading rate, *e.g.*, usually, the spreading rate is 350 *lb/ln- mi*. This value may vary with the weather condition;
  - $C_s^{'}$: spreading length of road section *s*, which can be determined by the road geometry and spreading pattern and discussed in the Section of Data Processing;

v_{sitw}: spreading truck speed for road section *s*, under snow intensity *i*, during time period *t*, on weekday or weekend (*w*);

t_s: required service time for spreading operation;

λ_a: adjusting factors accounting for the age of fleet. (i.e. $\lambda_a = 1.25$ as suggested by NJDOT (Cifelli et al. 1979));

λ_k: adjusting factors accounting for the capacity of the spreading truck. (i.e., $\lambda_k = 0.9$ as suggested by Cifelli et al. (1979)).

II: Formulation of Crew Based Fleet Size

Then, required number of trucks of type *p* for a maintenance yard which has more than one road section can be expressed as:

$$T_{pitw} = \left(\sum_{s=1}^{n} Y_{psitw} \right)^{*} \qquad p \in P, s \in S, i \in I, t \in T, w \in W \tag{2}$$

In Eq. 2, T_{pitw} is the total number of spreading trucks of type *p* under snow intensity *i* during time period *t* on weekday or weekend *w*, and *n* is the number road sections responsible by a crew. 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 in Section 4.1.5.

4.1.4 Quantity of Salt Estimation

The required quantity of salt to prepare before an approaching of storm is also a major concern to local maintenance yard. As the main factor affecting the quantity of salt is the spreading rate *q* (in unit of *lb/ln-mi*) which depends on the forecasted snow intensity, the estimation of quantity of salt for road section *s* can be expressed as:

$$Q_s = q * (L_s + R_s) \qquad s \in S \tag{3}$$

The definitions of all the parameters in Eq.3 are same as those presented in Eq.1. Here, three spreading rates are proposed (250 *lb/ln-mi*, 350 *lb/ln-mi* and 450 *lb/ln-mi*) depending on different weather conditions and the priority of each road section.

4.1.5 Rounding Criteria

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 Δq_a, the round-down number is accepted, otherwise, round-up number will be used. As for the acceptable service time delay, denoted as Δt_a, 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:

(1) Acceptable Spreading Quantity Adjustment

The difference (denoted as Δq) between the salt carried by the number of trucks and the actually required amount of salt is expressed as

$$\Delta q(x)_{|x=Y^-_{psitw}} = \lambda_a \sum_{s=1}^{n} (L_s + R_s) q - \lambda_k K_p \sum_{s=1}^{n} Y^-_{psitw} \tag{4}$$

where Y^-_{psitw} denotes the round-down number of spreading trucks. If the calculated quantity difference by Eq. 4 is less than the acceptable spreading quantity adjustment, then Y^-_{psitw} will be accepted; otherwise, the round-up ones denoted as Y^+_{psitw} will be used. The total number of spreading trucks (type *p*) may be estimated based on the criterion illustrated in Eq. 5 as:

$$T_{psitw} = \begin{cases} (\sum Y_{psitw})^- & \text{if } \Delta q(x)_{|x=Y^-_{psitw}} \le \Delta q_a \qquad \forall s \in S \\ (\sum Y_{psitw})^+ & \text{otherwise} \end{cases} \tag{5}$$

(2) Acceptable Service Time Delay

The time difference between the estimated spreading time and the service time, (denoted as Δt) is expressed as a function of the round-down number of trucks (denoted as Y^-_{psitw}):

$$\Delta t(x)_{|x=Y^-_{psitw}} = \frac{\lambda_a \sum_{s=1}^{n} C'_s}{\sum_{s=1}^{n} \left(v_{sitw} Y^-_{psitw} \right)} - t_s \tag{6}$$

If Δt is less than the acceptable service time delay denoted as Δt_a, then Y^-_{psitw} will be accepted; otherwise, Y^+_{psitw} will be suggested. The total number of spreading trucks (type *p*) may be estimated based on the criterion illustrated in Eq. 7 as:

$$T_{psitw} = \begin{cases} (\sum Y_{psitw})^- & \text{if } \Delta t(x)_{|x=Y^-_{psitw}} \le \Delta t_a \qquad \forall s \in S \\ (\sum Y_{psitw})^+ & \text{otherwise} \end{cases} \tag{7}$$

Which criterion to be chosen during the fleet size estimation depends on the major estimate in Eq. 1. For instance, if the total required quantity of salt dictates the fleet size, the first criterion (Eq. 4) should be employed; otherwise, the other one (Eq. 6) can be chosen.

4.1.6 Discussions

As mentioned at the beginning of this section that there are three complexities in developing salt spreading model. In this section, the proposed approach of solving each issue is discussed.

(1) Spreading length

In Eq. 1, the parameter of spreading length is introduced. The determination of this parameter depends on the specific spreading pattern of a snow section which is dictated by the number of lanes to spread. In this section, the lane number based spreading patterns are introduced with the corresponding spreading length presented.

- Spreading pattern on two-lane and four-lane highways

  For a two-lane highway with one lane in each direction, the most efficient pattern is to spread chemicals in about the middle third of the pavement. The normal pavement crown will allow salt brine to flow across the remainder of the pavement. As a four lane undivided roadway the passing lane in either direction may be spread simultaneously from the adjacent travel lane. The suggested spreading pattern is presented in Figure 2.

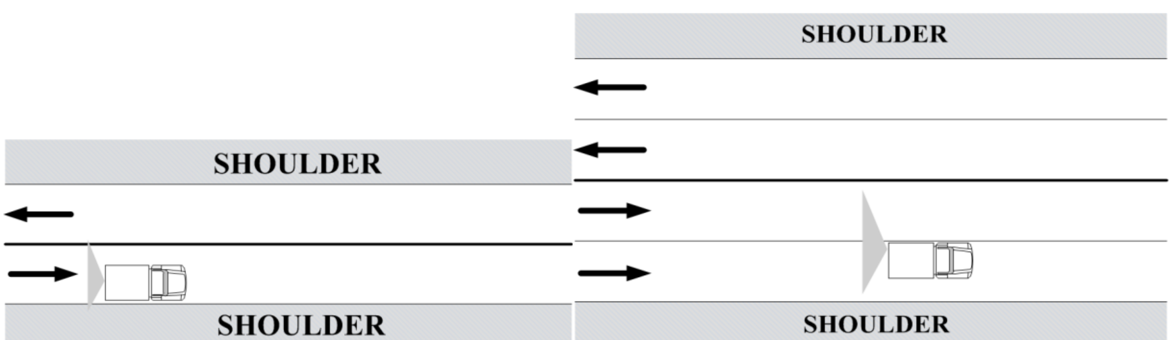

Figure 2. Spreading pattern for two-lane and four-lane highways

The total spreading length for this spreading pattern is equal to twice of the centerline mile, which can be expressed as:

$$C_s^{'} = 2C_{M_s} \quad (8)$$

- Spreading pattern on six-lane and eight-lane highways

For six-lane and eight-lane highways with three and four lanes in each direction, respectively, the full width spreading configuration contains two spreading trucks as shown in Figure 3.

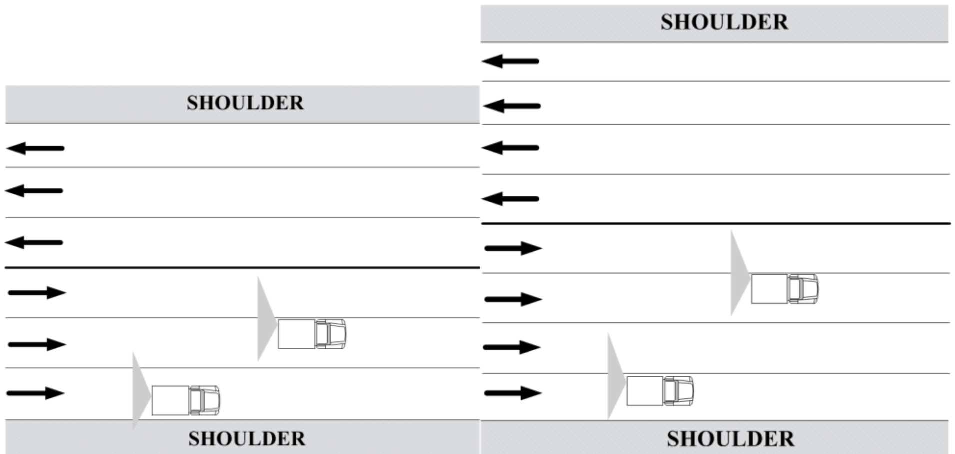

Figure 3. Spreading pattern for six-lane and eight-lane highways

The total spreading length for this spreading pattern is equal to four times of the centerline mile of the pavement, which can be expressed as:

$$C_s^{'} = 4C_{M_s} \quad (9)$$

- Spreading pattern on highways with varying lane numbers

  For most of snow sections, the lane number of each snow section is not always a constant. Changing number of lanes may be due to the acceleration/deceleration lanes as shown in Figure 1. Under these conditions, the spreading length should be calculated by combining the above two situations.

It is noted here that the when considering the spreading length for the ramp, as most of the ramps have lane number of 1~2, its spreading length is equal to the ramp length (centerline mile of ramp). However, while considering the spreading length of the ramp, an adjusting factor (e.g. 2.5) should be applied to the ramp length to take into account the lowered traffic speed of the spreading truck on ramps. This factor can be calibrated according to different traffic and weather conditions. The total spreading length of a snow section is the sum of that of mainline and ramp.

(2) Spreading truck speed

Another important parameter in the spreading model is the truck speed. Usually the maximum operating speed of 20 mph ~ 25 mph is employed. As speed increases, “bounce” and “scatter” of salt become greater and the associated air turbulence might cause problems to retain all the materials discharged over the desired width. In this research, the spreading truck speed of 20 mph is applied. Note that the truck speed is sometimes impeded by traffic congestion, for which a lower speed, between the recommended operating speed and traffic speed, is applied for fleet size estimation. The historic traffic speed is extracted from INRIX and stored in a speed matrix classified by roadway type, snow intensity, time period, and day of a week. The details of processing the speed information from different databases are discussed later in this report.

(3) Mixed types of trucks

The required number spreading trucks for specific types can be calculated using Eqs. 1 and 2. However, sometimes mixed use of spreading trucks is applied. Under this condition for example two truck types are applied, the number of Type-I trucks should be given to determine the resulting spreading length. Subtracting the spreading length traveled and total quantity of salt spread by Type-I trucks from the Eq. 1, the required number of Type-II trucks can be calculated.

4.2 Snow Plowing Operation

In this section, a sound snow plowing model is developed to determine how many trucks are sufficient for transportation agencies before the arrival of a snow season or in a predicted snow storm, considering the weather condition and the corresponding traffic speed as well as the service time constraint.

4.2.1 Parameter Definition

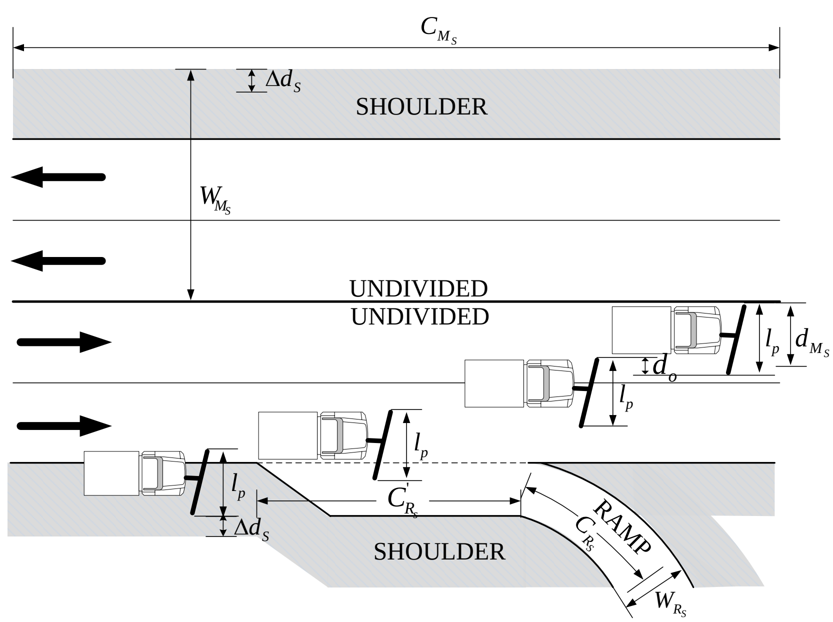

Figure 4. Plowing model parameters with a general road section

As shown in Figure 4, C_{M_S} and W_{M_S} denote the centerline miles and the maximum width of mainline of road section *s*, respectively. Note that the road section width is defined as the sum of the pavement width and shoulder width of the mainline in each direction. Similarly, the maximum ramp width denoted as W_{R_S} is the sum of the pavement width and shoulder width of the ramp. The effective plow width of type *i* plow, denoted as l_i , is affected by the actual plow width and the angle of the plow used. The symbol d_{M_S} denotes the average plowing width on mainline, which is equal to the required plowing width divided by the number of plows, $(W_{M_S} - \Delta d_S)/n$, where Δd_S is the pavement width based to place the plowed snow and *n* is the number of plows (= 4 as shown in Figure 4). The symbol d_o (*i.e.*, 2 feet) is the minimum overlapped plowing width for tandem plowing. Symbols $C_{R_s}^{'}$ and C_{R_s} are the centerline miles of the acceleration/deceleration lane and the ramp, respectively.

4.2.2 Assumptions

To consider the complicate road geometry of each snow section and actual plowing pattern during snow plowing operation, three main assumptions are made for the proposed plowing model:

- Plowing configuration and average plowing width for the mainline and ramps are determined separately based on road geometry and plow sizes.
- Acceleration/deceleration lanes are treated together with the ramp; and the deadheading time (i.e. traveling without service) between two adjacent ramps and reduced speed on ramps can be considered by adding a factor to justify the route length.
- 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: 0~0.5 in/hr, II: 0.5~1 in/hr, and III: 1~2 in/hr; and time periods of a day can be classified into: I: AM (6AM-9AM), II: MD (9AM-3PM), III: PM (3PM-6PM), and IV: NT (6PM-6AM).

4.2.3 Plowing Model Formulation

For a road section *s* under snow intensity *i*, time period *t*, and a day of a week *w* (weekday or weekend), the needed fleet size to clean this section, denoted as P_{sitw} , is defined as the area of road section *s* (i.e. the mainline plus ramps) divided by the product of average plowing width, plowing speed and the operating time. Since plowing the mainline and ramps may employ different types of plows with different operating speeds and average plowing width, the total required fleet size is the sum of two parts needed for the mainline and ramps respectively as expressed in Eq. 10.

$$P_{sitw} = \left(P_{M_{sitw}}^{'}\right)^{*} + \left(P_{R_{sitw}}^{'}\right)^{*} \tag{10}$$

Eq. 11 formulated below calculates the fleet size for plowing mainline, which is equal to the maximum pavement width (excluding acceleration/deceleration lanes) multiplied by the centerline mile of the pavement divided by the committed plowing area per plow which is the product of average plowing width (i.e., d_{M_S} for mainline and d_{R_S} for ramp), plowing speed and the predetermined service time. Similarly, Eq. 12 shown below calculates the fleet size for plowing ramp using the total area of the ramp and acceleration/deceleration lanes divided by the plowing area per truck during the required service time.

$$P'_{M_{sitw}} = \frac{2(W_{M_S} - \Delta d_S)C_{M_S}}{d_{M_S} v_{sitw} t_s} \quad s \in S, i \in I, t \in T, w \in W \tag{11}$$

$$P'_{R_{sitw}} = \frac{(W_{R_S} - \Delta d_S)(\gamma_R C_{R_S} + \gamma'_R C'_{R_S})}{d_{R_S} v_{sitw} t_s} \quad s \in S, i \in I, t \in T, w \in W \tag{12}$$

In Eqs. 11 and 12, the pavement width adjustment, denoted as Δd_s, is introduced to consider the situation if full pavement width plowing is not required, specifically under the condition of very heavy snow intensity. In general cases, Δd_s is given for placing the plowed snow from the mainline. For example, Δd_s can be set equal to the shoulder width, thus the plowing operation only apply to the traffic lanes excluding road shoulders. In addition, Δd_s can also be set as the sum of shoulder width and lane width to consider the potential of just opening only some of the lanes under heavy snow conditions.

Notations:

- Sets
  S: {1, 2, ..., m}, a set of road sections;
  I: {1, 2, 3}, a set of snow intensities;
  T: {1, 2, 3, 4}, a set of time periods;
  W: {1, 2}, a set of days of a week; 1: weekday and 2: weekend.
- Parameters
  $P'_{M_{sitw}}$: fleet size for plowing the mainline of road section *s*, snow intensity *i*, time period *t*, day of a week *w* (weekday or weekend);
  $P'_{R_{sitw}}$: fleet size for plowing ramps of road section *s*, snow intensity *i*, time period *t*, day of a week *w* (weekday or weekend);
  P_{sitw}: fleet size for plowing road section *s* (including mainline and ramps), snow intensity *i*, time period *t*, day of a week *w* (weekday or weekend);
  W_{M_S}: maximum road section width on the mainline, excluding acceleration and deceleration lanes;
  W_{R_S}: area-weighted average width of the ramps of road section *s*;
  d_{M_S}: average plowing width on mainline;
  d_{R_S}: average plowing width on ramps;

v_{sitw}: average plowing speed for road section *s*, snow intensity *i*, time period *t*, day of a week *w* (weekday or weekend);

t_s: pre-determined service time limit for each road section;

γ_R: weight factor for justifying the ramp length due to reduced plowing speed and deadheading time;

$\gamma_R^{'}$: weight factor for justifying the length of acceleration/deceleration lanes due to reduced plowing speed;

Δd_S: pavement width adjustment.

To ensure a sufficient fleet size for snow plowing, the maximum width of a road section is applied. Note that acceleration/deceleration lanes are excluded from the mainline while determining the maximum section width. For ramps, as they are relatively short compared with the mainline, the weighted ramp width is applied to calculate the plowing area on ramps.

By considering the effect of weather and traffic, the plowing speeds employed in Eqs. 11 and 12 are treated as a function of roadway type, weather, time periods, and day of a week.

In Eq. 10, the estimated fleet size in parentheses might be non-integer, therefore, a rounding process denoted as "*" is needed. In the following part of the manuscript round-up is denoted as "+", while round-down is denoted as "-".

4.2.4 Rounding Criteria

Two criteria are introduced to determine the number of plows which can be chosen according the specific demands of each maintenance yard. The first one is based on allowable service time delay, and the other is based on allowable plowing width reduction. With the first criterion, the fleet size is calculated based on fixed plowing width subject to the adjusted service time limit. However in the second criterion, the fleet size is estimated with fixed service time limit subject to adjusted pavement width.

Representing the allowable service time delay and the allowable plowing width reduction by Δt_a and Δd_a, respectively, the two criteria can be expressed mathematically as follows:

(1) Allowable service time delay

In Eq. 13, $\Delta t(x)$ is equal to the actual plowing time resulting from a round-down number of plows, denoted as P_{sitw}^{-}, minus the service time limit. If $\Delta t(x)$ is less than the allowable service time delay, P^-_{sitw} is applicable. Otherwise, a round-up number must be taken. Thus,

$$\Delta t(x)_{|x=P^-_{sitw}} = \frac{2(W_{M_S} - \Delta d_S)C_{M_S} + (W_{R_S} - \Delta d_S)(\gamma_R C_{Rs} + \gamma^{'}_R C^{'}_{Rs})}{d_e v_{sitw} P^-_{sitw}} - t_s \tag{13}$$

$$P_{sitw} = \begin{cases} P^-_{sitw} & \text{if } \Delta t(x)_{|x=P^-_{sitw}} \le \Delta t_a \\ P^+_{sitw} & \text{otherwise} \end{cases} \tag{14}$$

Note that the actual plowing time is determined by the sum of required plowing area, including the mainline, ramps and acceleration/deceleration lanes, divided by the plowing area of number of plows per unit of time, which is a product of average plowing width, plowing speed and the total number of plows as indicated in Eq. 11. Since the average plowing widths on the mainline and ramps may be different, the one employed in Eq. 13 is an area-weighted average plowing width denoted as d_e formulated in Eq. 15:

$$d_e = \frac{A_M d_{M_s} + A_R d_{R_s}}{A_M + A_R} \tag{15}$$

where A_M and A_R are the areas of the mainline and ramp as discussed while formulating Eqs. 11 and 12, respectively. d_{M_s} and d_{R_s} are the corresponding average plowing width.

(2) Allowable plowing width reduction

In Eq. 16, $\Delta d(x)$ is equal to the actual pavement width adjustment using the round-down number of plows, denoted as P^-_{sitw} minus predetermined pavement width adjustment, which is also the difference between the actual and the required plowing width. If $\Delta d(x)$ is less than the allowable plowing width reduction, P^-_{sitw} is accepted. Otherwise, a round-up number is required. Thus,

$$\Delta d(x)_{|x=P^-_{sitw}} = \frac{2W_{Ms}C_{Ms} + W_{Rs}(\gamma_R C_{Rs} + \gamma^{'}_R C^{'}_{Rs}) - d_e v_{sitw} t_s P^-_{sitw}}{2C_{Ms} + (\gamma_R C_{Rs} + \gamma^{'}_R C^{'}_{Rs})} - \Delta d_s \tag{16}$$

$$P_{sitw} = \begin{cases} P^-_{sitw} & \text{if } \Delta d(x)_{|x=P^-_{sitw}} \le \Delta d_a \\ P^+_{sitw} & \text{otherwise} \end{cases} \tag{17}$$

The actual road pavement width adjustment in Eq.16 is calculated by using the maximum pavement width (excluding the acceleration/deceleration lanes) to subtract the actual plowing width, which is equivalent to the total road section area subtracting the actual plowing area during the service time limit divided by the total centerline mile of mainline and ramps.

4.2.5 Discussions

In this section, the main parameters of the plowing model (Eqs. 11 and 12) including the maximum snow section width, weighted ramp width, plowing speed and the practical issues with plowing operation including the overlapped snow sections, mixed types of plows, lane number based plowing configurations and the situation of considering the mainline and ramp separately are discussed.

(1) Maximum snow section width

It is known that for most of snow sections, the pavement width/number of lanes of each snow section is not always a constant. For instance, as to the snow sections of Columbia Yard with the following assignments:

- Snow section 5216261: Rt.80 MP: 0.5-5 & Rt. 46 MP: 0-10
- Snow section 5216262: Rt.80 MP: 12-19
- Snow section 5216263: Rt.80 MP: 2-12

The lane number of the three snow sections ranges from 2 to 4 according to SLD 2009,. The percentages of lane number of the last two sections (5216262 and 5216263) are summarized in Table 1.

Table 1 – Number of lanes of the snow sections with the Columbia Yard

Snow Sections in Columbia Yard	Number of Lanes	Primary Direction		Secondary Direction	
		Mileage	Percentage	Mileage	Percentage
5216262 MP: 12-19.9	3	3.57	45.2%	7.29	92.3%
	4	4.33	54.8%	0.61	7.7%
	Total	**7.9**	**100%**	**7.9**	**100%**
5216263 MP: 2-12	2	1.59	15.9%	1.59	15.9%
	3	4.73	47.3%	8.41	84.1%
	4	3.68	36.8%	0	0
	Total	**10**	**100%**	**10**	**100%**

As indicated in Table 1, the lane number varies within a snow section. Traditional methods dealing with varying snow section width were using the product of lane-mile and average lane-width instead of pavement width (Wilson et al. 2003); however, the impact of varying section width cannot be considered. In Eqs. 11 and 12, the maximum snow section width and centerline mile are introduced. Hence, it can be used to determine the plowing pattern accurately. The tandem plowing pattern and configuration are usually determined based on the maximum snow section width (Figure 5) during the winter highway maintenance.

Figure 5. Tandem plowing pattern[1]

It is worth noting that the maximum snow section width in Eqs. 11 and 12 does not include the width of acceleration/deceleration lanes which will be taken care by the tricks clearing the rams.

(2) Weighted ramp width

Similar to the snow section width, the ramp width for a snow section is not a constant either. As the ramps have lower priority than that of mainline of a snow section (Caltrans, 2009), it is not necessary to use the maximum ramp width in the calculation. In addition, there are some situations that the length of wide ramps is much short than that of narrow ramps. For example, for the snow section 5314260 with Trenton Yard, the total ramp length is 5.9 miles while the ramp width above 40ft is only 0.9 mile. Under this

[1] Photo is obtained from http://www.wintermaintenance.com/2006/09/.

condition, using the maximum ramp width will lead to overestimate of number of required plowing trucks. To this end, the weighted ramp width is used in Eq. 12.

(3) Overlapped snow sections and ramps

A certain highway segment or ramps may be shared by two neighboring snow sections for turning around or other purposes. For dealing with the overlapping mainlines and ramps, the following approach is employed and discussed below:

- Overlapping mainline: as the overlapping is not long, it is considered by both the two adjacent snow sections without causing much over estimation. Otherwise, the reassignment of snow sections is suggested.
- Overlapping ramps: the whole length of overlapped ramps are divided into two halves and assigned to each of the two adjacent snow sections.

(4) Plowing speed

In Eqs. 11 and 12, the plowing speed is considered as a function of roadway type, weather condition, time periods, and the day of a week. This can be developed by correlating the traffic data, road geometry data and weather data during each time period of different databases. The details of processing the speed information from different databases will be provided in the data processing part of this research.

(5) Mixed types of plows

During the snow plowing operation, multiple plow sizes may be employed for one road section. The appropriate combination of different sizes of plows can be recommended based on the total overlapped plow width of each combination subject to a plowing width constraint.

Regarding the plowing width constraint, the total plowing width of a combination of different sizes of plows must be greater than the required pavement width to be treated. Assume there are types of plows in a combination; this constraint can be expressed as,

$$\sum_{p=1}^{m} l_p n_p - W_{M_S} - (\sum_{p=1}^{m} n_p - 1) d_o + \Delta d_S \geq 0 \qquad (18)$$

In Eq.18, l_p is the effective plow width of type *p* plows (as described in Figure 4) while n_p denotes the total number of type *p* plows in the combination. W_{M_S}, d_0 and Δd_S are defined in the general plowing configuration shown in Figure 4.

Total overlapped plow width for the combination can be estimated by subtracting the total required plowing width from the sum of the effective plow width of all the plows in the combination. Assume that there are a total of y plow combinations satisfying the required plow width described in Eq. 19. For plow combination *j*, the total effective plow width can be expressed as $\sum_{p=1}^{m} l_p n_{jp}$, where n_{jp} denotes the number of type *p* plows. The required plowing width is determined by the maximum road section width less the pavement width adjustment, which is $(W_{M_S} - \Delta d_S)$. The total overlapped width of plow combination *j*, denoted as O_j, is determined by the total effective plow width less the required plowing width. Thus,

$$O_j = \sum_{p=1}^{m} l_p n_{jp} - (W_{M_S} - \Delta d_S) \quad \forall j \in \{1, ..., y\} \tag{19}$$

where *y* represents the number of plow combinations.

After obtaining the total overlapped plow width calculated by Eq. 19 for all combinations satisfying the plowing width constraints, the combination with the minimum overlapped plow width can be recommended as the best combination, as it ensures effective resource utilization. However, it should be noted here that as some winter maintenance agencies may have different concerns regarding the selection of the best combination. For instance, in the cases of limited number of a certain type of available plows, the criterion of selecting the best according to the smallest overlapped plow width may not be applicable. However, it is worth mentioning that although different selecting criteria may be employed, the total overlapped width can still be considered as an important parameter.

(6) Lane number based plowing configurations

In Eq. 11, the full width plowing configuration and the average plowing width are determined by the maximum snow section width. However, it is also suggested the lane number based plowing configuration:

- 4-lane divided highway with shoulders – 4 plows are required
- 6-lane divided highway with shoulders – 6 plows are required
- 2-lane undivided highway with shoulders – 3 plows are required

Comparing the lane number based plowing configuration with the snow section width based plowing configuration, it can be found that they are consistent with each other for 2-lane highway (1 lane per direction) and 6-lane highway (3 lanes per direction). For the 4-lane highway (2 lanes per direction), 5 plows are required for full width plowing according to section width based configuration, while 4 plows are suggested according to lane number based configuration. However, the lane number based configuration cannot take into account the effect of the plow width/plow type. It is noted here that all the results presented in this reported are according to the snow section width based configuration.

(7) Plowing the Mainline and Ramp Separately

In order to consider the practical plowing pattern, it is assumed that the mainline and ramp are plowing separately with the fleet size for each of them reported as shown in Eq. 10. The main difference between considering plowing the mainline and ramp together or separately lies in rounding the fleet sizes. While considering them separately, the estimated truck fleet size for each of them should be rounded to integers before adding them up.

5 DATA COLLECTION AND ANALYSIS

Both snow plowing and salt spreading models require significant amount of data. These data can be classified into three main classes: snow section data, traffic data and weather data. Snow section data includes roadway functional type, depot location, centerline mile or lane-mile of the section, number of lanes, pavement width, shoulder width and ramp width, location of intersections for turnaround and *etc*. Traffic speed data and weather data include traffic speeds and snow intensity on snow days for each road segment during different time periods, respectively. Finally, by correlating the three databases the traffic speed matrix can be developed for each roadway type at different time periods under various weather conditions.

In this section, the data sources of each type of data are identified and briefly described. The main procedures for processing the required geometric information, speed information and weather information are summarized. In addition, the development of traffic speed matrix is also performed.

5.1 Snow Section Data

The original snow section data provided by NJDOT at the beginning of the project is a list of snow section with starting and ending mileposts and also the location of each maintenance yard as shown in Figure 6.

	A	B	C	D	E
1	**SNOW_SECTION**	**SRI**	**MPFROM**	**MPTO**	**FACILITY**
2	5210261	00000208	4.4	10.7	Paterson
3	5210262	00000208	0	4.4	Paterson
4	5210263	00000020	0	4	Paterson
5	5211261	00000017	12.3	20.7	Ramsey
6	5211262	00000017	19	27.2	Ramsey
7	5211263	00000287	58.2	67.6	Ramsey
8	5212261	00000009W	0	11.2	Fort Lee
9	5212262	00000001	62.7	64.9	Fort Lee
10	5212262	00000046	70	71.8	Fort Lee
11	5212263	00000063	0	3.1	Fort Lee
12	5212263	00000093	0	3.5	Fort Lee
13	5212264	00000067	0	1.9	Fort Lee
14	5212264	00000005	0	3.4	Fort Lee
15	5213261	00000080	60.5	68.7	Lodi
16	5213262	00000080	60.5	68	Lodi
17	5213263	00000080	55.1	63.8	Lodi
18	5213264	00000017	3	12.3	Lodi

(a) Snow section assignment

X	Y	SUB_REGION	YARD
-74.140458	40.934268	N3	210 PATERSON
-74.123771	41.066758	N3	211 RAMSEY
-73.972869	40.85983	N4	212 FORT LEE
-74.06834	40.886233	N4	213 LODI
-74.230774	40.899377	N3	214 TOTOWA
-74.275012	40.784322	N3	215 WEST ORANGE
-75.092676	40.926208	N1	216 COLUMBIA
-74.3025	40.986761	N2	217 RIVERDALE
-74.70223	40.89765	N2	218 NETCONG
-74.067784	40.795935	N4	219 SECAUCUS
-74.43199	40.820162	N3	220 EAST HANOVER
-74.33224	40.718013	N3	221 SUMMIT
-74.064766	40.739864	N4	222 JERSEY CITY
-74.195254	40.676614	N4	223 ELIZABETH

(b) Maintenance yard location

Figure 6. Original snow section data provided by NJDOT (2011)

To obtain the detailed geometric data of each road section, the Straight Line Diagram (SLD) database is applied. SLD is a two-dimensional graphic representation of physical roadway characteristics of highways, including the Interstate freeways, the US highways and State Routes. After mapping each road section to the SLD database, the pavement width, shoulder width, ramp width, centerline mile of mainline and ramps, *etc.* can be obtained.

For processing the geometric information of snow sections, a three-step procedure is performed and discussed below:

Step 1

Map all the snow sections onto the SLD database according to their mileposts. NJDOT has 75 maintenance yards covering 278 snow sections statewide. There are 27 yards in North region, 30 yards in Central region and 18 yards in South region. Each yard is responsible for 3-4 snow sections with the centerline mile around 9 miles. Figure 7 presents the spatial distributions of the maintenance yards and snow sections via GIS (Geographic Information System).

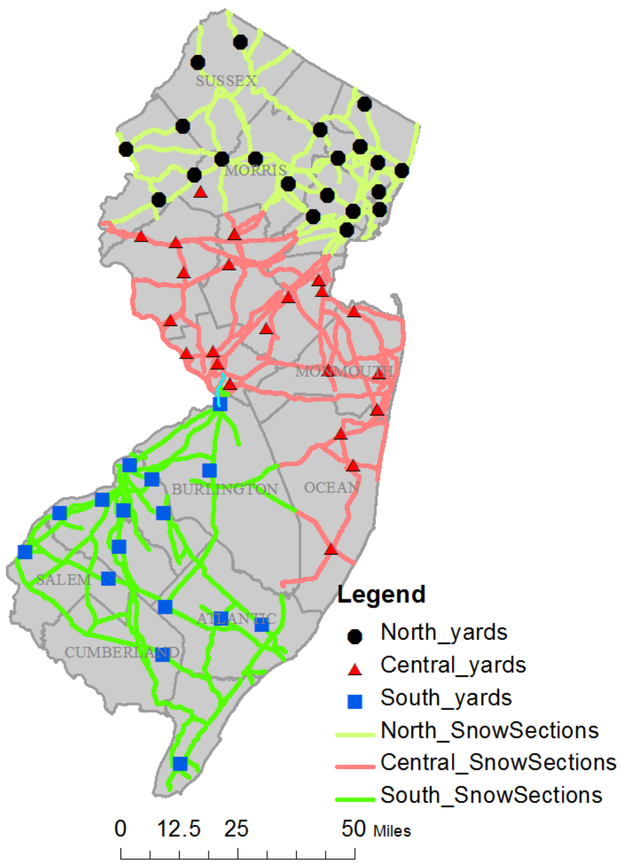

Figure 7. Spatial distribution of maintenance yards and snow sections

Step 2

Considering varying pavement width, the existing snow sections need to be broken down into smaller segments which have single values of variables such as pavement width, shoulder width, ramp length, ramp width and *etc*. The subdivision process is shown in Figure 8.

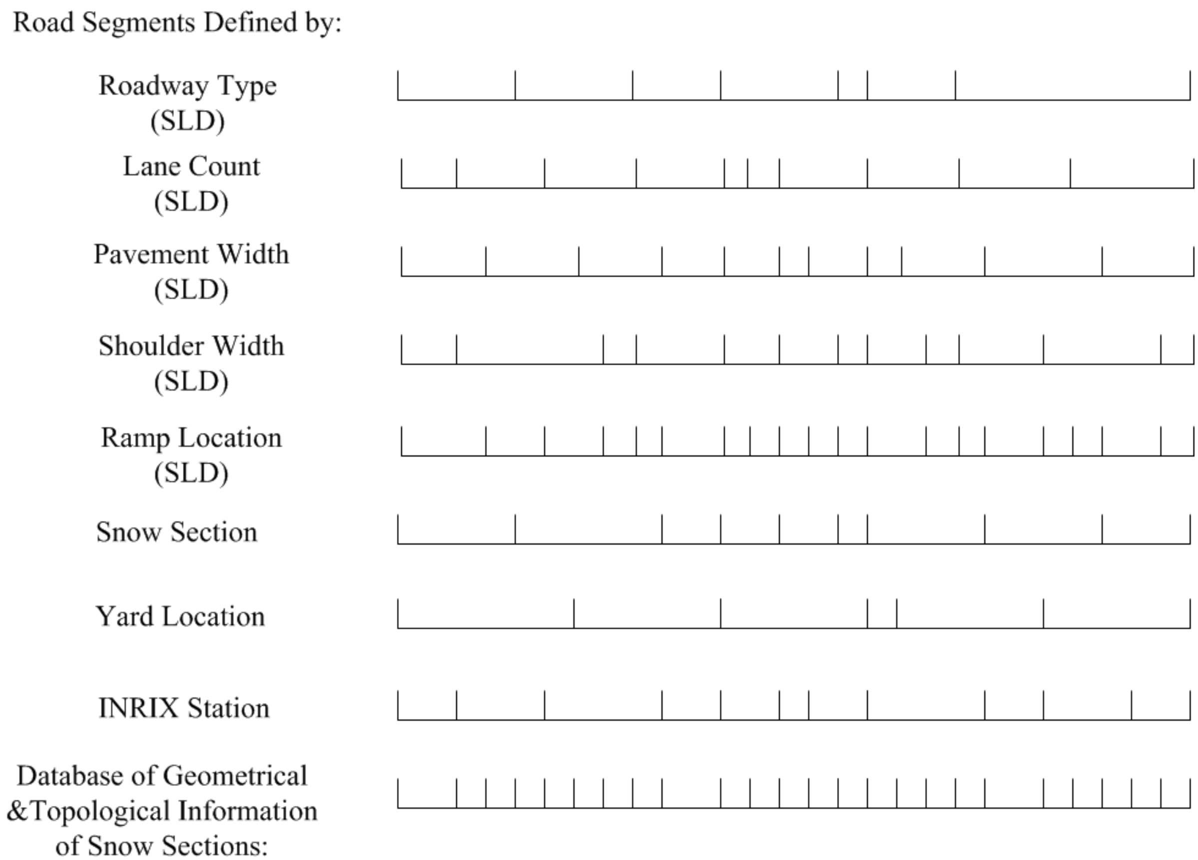

Figure 8. Subdivision process of the snow sections

Step 3

In the third step, the extracted geometric data can be further processed to generate the required data for the model inputs.

Salt Spreading Operation:

The main input for the spreading model is the spreading length, and the calculation of which contains two parts: mainline and ramps. For the mainline of two-lane and four-lane highways (with one-lane and two-lane per direction, respectively), the section can be spread in one pass per direction. Thus, the total spreading length is equal to the centerline mile of the pavement multiplied by two. For the mainline with three lanes and four lanes per direction, the section per direction should be treated in two passes, and the total spreading length is the centerline mile multiplied by four. For the road sections with varying pavement width, the spreading lane-mile can be estimated considering two different situations. For ramps, as most ramps have less than or equal to two lanes, the spreading operation can be completed in one pass. Hence, the spreading lane-mile is the centerline mile of the ramp. Considering reduced speed on ramps, the spreading lane-mile is weighted by multiplying an adjusting factor (Cifelli et al. 1979). While calculating the required quantity of salt, the actual lane-mile of the section is employed.

Snow Plowing Operation:

The maximum road section width is the major input affecting the required fleet size. However, it is costly to be determined by the widest pavement width. Thus, the widths of acceleration/deceleration lanes, considered as part of the ramp service area, are excluded. For ramps, as they are relatively short compared with the mainline, the weighted ramp width is applied to calculate the plowing are on ramps.

5.2 Traffic Speed Data

Three main traffic data sources are identified for extracting the traffic speed data for each roadway type: weight in motion station data (WIM), Congestion Management System (CMS) and INRIX data.

WIM stations are defined by the America Society of Testing and Materials (ASTM) as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle". In addition to weight information, WIM sites also collect traffic volume, speed, directional distribution, lane distribution, date and time of passage, axle spacing, and vehicle classification. Travel speeds are measured continuously at various points along New Jersey highways at WIM sites. There are total 82 permanent WIM sites throughout the state of New Jersey with the distribution of WIM stations are shown in Figure 9. Since the number of sites is limited, the speed data was not used in this study.

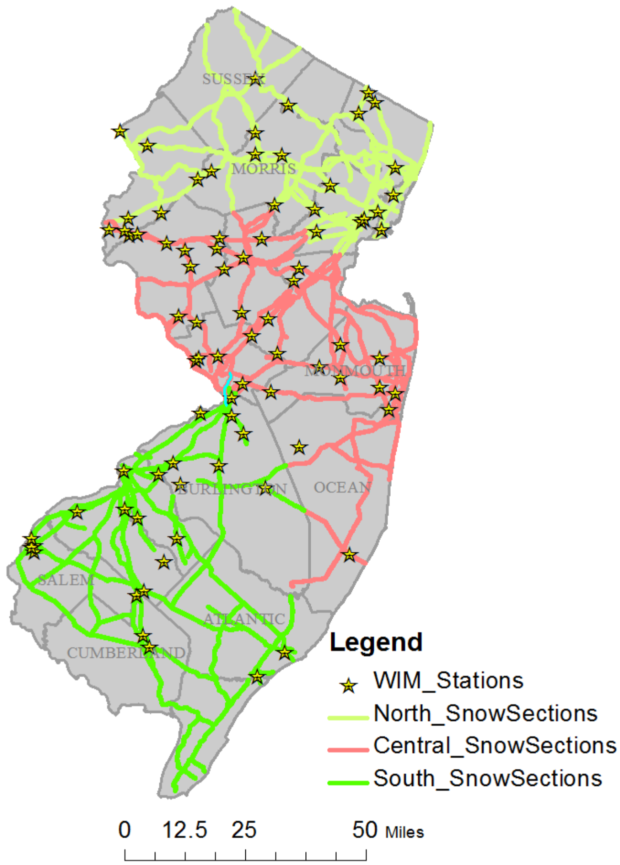

Figure 9. Spatial distribution of WIM stations in New Jersey[2]

The traffic data in different time periods can be extracted from NJCMS, which include traffic volumes, roadway geometry, and roadway operational information for approximately 5,250 roadway segments in all 21 New Jersey counties.

The speed data can be retrieved from the INRIX database. INRIX reports the temporal and spatial traffic data. The stored traffic data in this database are anonymously collected from GPS-enabled vehicles and mobile devices through Traffic Message Channel (TMC) and compiled into 5-minute-averaged speeds.

INRIX reports 5-minute-averaged traffic speeds on freeways, highways, and secondary roadways including arterials and side streets based on real-time and historical information on freeways, highways, arterials and side streets. In this study, the historic INRIX information is applied for approximating traffic speed under different weather and traffic conditions on New Jersey highways. The distribution of TMC locations are shown in Figure 10.

---

[2]Information obtained from http://www.state.nj.us/transportation/refdata/roadway/tmssites.shtm.

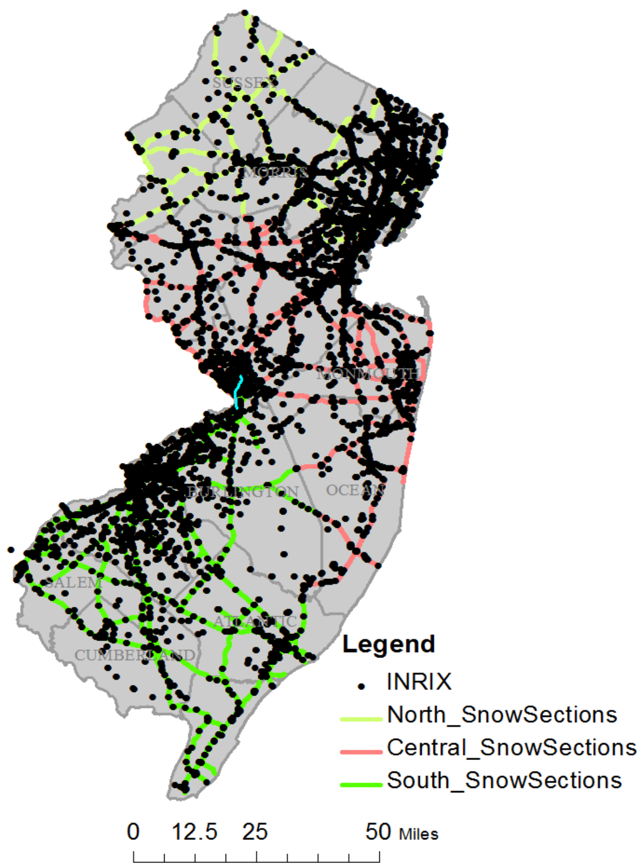

Figure 10. Spatial distribution of INRIX station in New Jersey

For each TMC the geocode of the start and the end point are known, which are applied for mapping them over the snow sections.

Since extracting INRIX information is to referring the speed data subject to different weather and traffic information, a 10-mile radius area was created for each RWIS (Road Weather Information System) station and TMC lying completely within that radius were applied to develop a speed matrix (see Figure 11). Finally, the selected TMC locations are plotted with weather stations and snow sections shown in Figure 12.

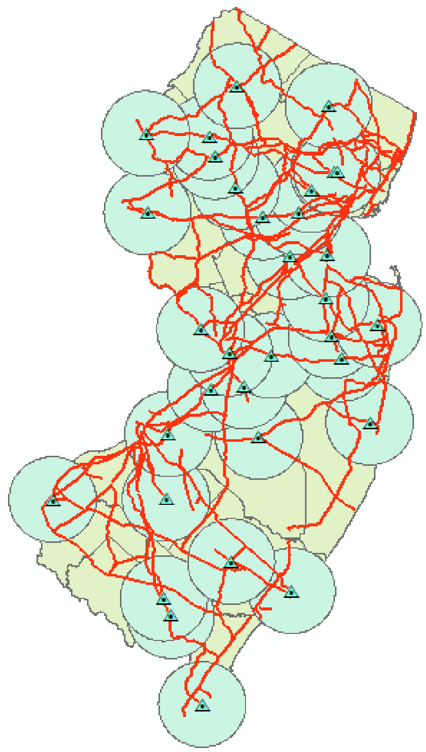

Figure 11. Spatial distribution of RWIS stations with 10-mile radius area

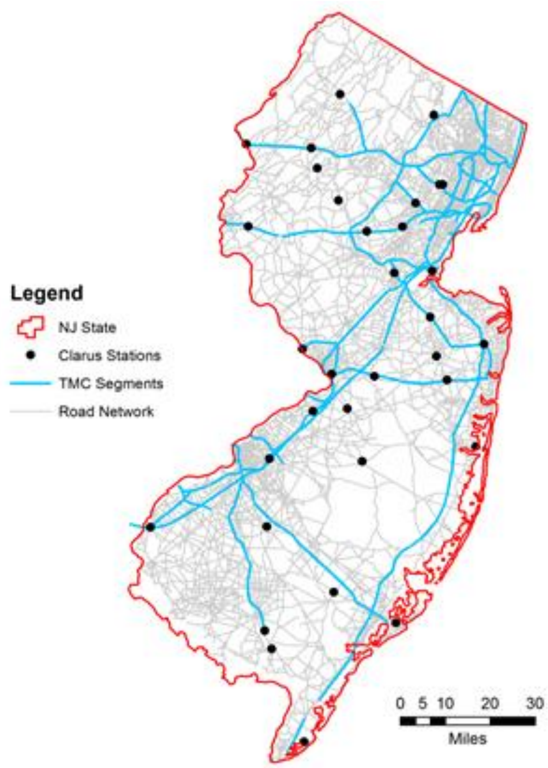

Figure12. Selected TMC segments, RWIS stations and snow sections

5.3 Weather Data

As mentioned in the introduction, the traffic speed is affected by weather conditions, such as snowfall rate, wind speed, moisture content, road temperature, *etc*. In order to study the effect of snowfall on traffic speed, historic snowfall rate information should be extracted.

The STWRC (surface transportation weather research center) provides an active archive of the Environmental Sensor Station (ESS) data which is stored in Clarus system. The Clarus Initiative (Clarus is Latin for "clear") is a Federal Highway Administration (FHWA) initiative to develop and demonstrate an integrated surface transportation weather observing, forecasting and data management system, and to establish a partnership to create a Nationwide Surface Transportation Weather Observing and Forecasting System. Observation types for New Jersey from *Clarus* included:

- Rate of rainfall or water equivalent of snow
- Relative humidity
- Pavement surface status
  (Dry, trace moisture, wet, chemical wet, icewarning, icewatch, snowwarning, snow watch, absorption, dew, frost, absorption at dew point.)
- Surface visibility
- Description of precipitation intensity
  (no precipitation, snow light, snow moderate, snow heavy, rain light, rain moderate, rain heavy, frozen light, frozen moderate, frozen heavy.)
- Description of precipitation type
- Two-minute average of the wind speed

The data for the above observation types are recorded every 20 minutes (Coordinated Universal Time, UTC is used in the *Clarus* system). The storm data from the Clarus data website can be extracted and converted into excel files. To efficiently analyze the data, a macro was created in Excel that converts the large amounts of weather data to a more compact form containing only the desired key storm parameters. Similar to the traffic speed data, the highway segments or the snow sections lying within a 10-mile radius circle share the weather data from the same RWIS station. The distribution of weather stations used for collecting the weather data are shown in Figure 13.

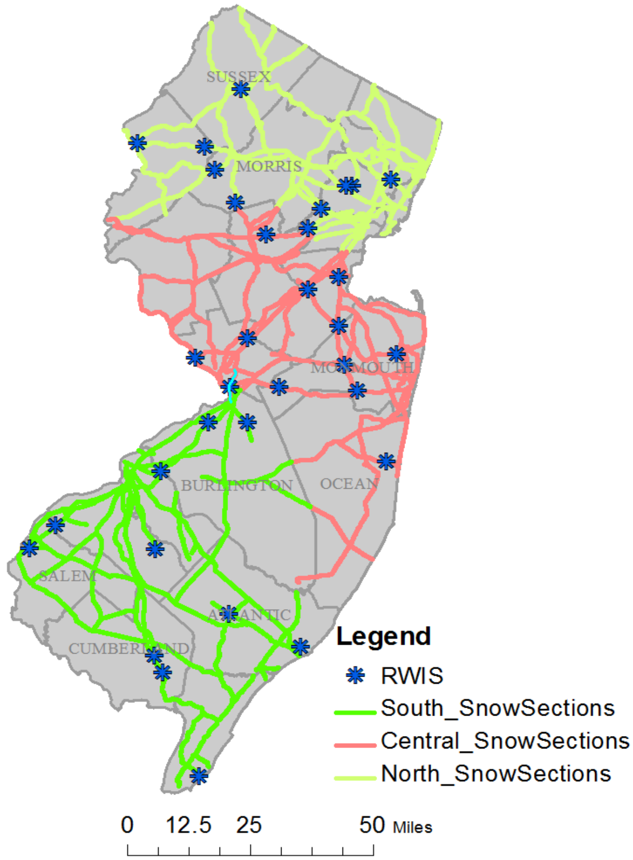

Figure 13. Spatial distribution of weather stations and snow sections in New Jersey

During weather data processing, it was observed that the *Clarus* data continuity and availability for all times are not guaranteed since it is an experimental system. These improperly data are replaced with the averaged observation data in the time period adjacent to it. It was also found that two RWIS stations did not report any data throughout the winter season. After examining all the data, these stations were not considered in the analysis and resulting in a total of 33 stations. The extracted data for Jan 27, 2011 for the first 3 hours is summarized in Table 2.

Table 2 – Sample data extracted from *Clarus*

Station/ Time	00:00 UTC			01:00 UTC			02:00 UTC		
	0	**20**	**40**	**0**	**20**	**40**	**0**	**20**	**40**
31-0	N/A	0.322	N/A	4.282	1.728	N/A	N/A	N/A	N/A
31-1	N/A	0.862	0.143	0.07	0.25	0.322	0.503	0.862	0.468
31-10	4.822	0.648	1.115	0.54	2.088	N/A	2.52	1.582	1.728
31-11	0.108	0	1.368	0	0.108	0.108	0	0.395	1.33
31-2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31-3	1.62	1.042	0.72	0.503	0.54	0.035	0.143	1.402	N/A
31-4	N/A	0.215	0	N/A	0.18	0.035	0.035	0.108	0.468
31-5	N/A	0	0.035	N/A	0	0.468	0.035	0	0.143
31-6	1.008	4.282	0.215	0.322	0.468	N/A	0.36	0.43	0.395
31-7	0	0	0.108	N/A	0.143	0.503	N/A	0.215	0.288
31-8	0	0.07	0.828	0.503	1.115	0.07	0.108	0.07	0.108
31-9	0.035	0.143	0.322	0.322	N/A	0.07	0.07	0.143	0.288
607-0	0.035	0.035	0.035	0.07	0	0.07	0.25	0.035	0.468
607-10	0	0.035	0	0.035	0.035	0.215	0.215	1.51	0.43
607-11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-14	N/A	0.36	0.18	N/A	1.762	0.468	N/A	0.503	0.288
607-16	0.07	0.97	3.6	2.34	2.05	7.38	5.29	9.648	9.61
607-2	0	0.035	0	0.395	0.18	0.143	0.395	1.475	0
607-4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
607-8	0	0	0	0.215	0.07	0.07	N/A	0.07	0.25
607-9	2.41	0.54	0.25	0.25	0.215	0.143	0.143	0.288	0.468
609-0	0	0	0.108	0.108	0.468	0.18	0.862	0.648	1.222
609-1	0	0.035	0.035	0.035	0.18	0.36	0.648	2.555	1.655
609-10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
609-2	0.108	0.18	1.115	N/A	2.628	4.102	4.75	6.083	3.708
609-3	0.035	0.035	0	0.035	0.035	0.07	0.035	0.36	1.26
609-4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
609-5	0	0.215	0.035	0.035	0.07	0.143	0.143	0.215	0.108
609-6	0	0	0.035	0.25	0.07	0.108	0.108	0.682	1.008
609-7	0.322	0.322	0.25	0.322	0.682	0.143	0.25	0.648	0.43
609-8	0.25	0.322	0.54	0.54	1.908	1.87	3.562	2.195	3.383
609-9	0.035	0.108	0.18	0.108	0.755	0.72	2.808	7.99	2.41

The data of similar pattern was extracted for the other snow days for all the 24 hours of the day. The data with the N/A means that no value was reported by that station on that particular day and during the interval of the hour.

5.4 Traffic Speed Matrix

After the data sources were identified, the weather stations in Clarus and TMC Locations in INRIX could be applied to analyze the impact of weather to traffic speed for each snow section via a data mapping process. Then, the speed data could be classified by roadway type, snow intensity, time of a day, day of a week (weekday/weekend), based on which the proposed speed matrix can be developed.

According to the real traffic condition under different weather conditions and time periods, snow intensities are defined as three levels (See Table 3). Level 1 indicates the snow fall rate ranges within 0-0.5 *inch/hour*; Level 2 ranges within 0.5-1.0 *inch/hour*; and Level 3 ranges within 1.0-2.0 *inch/hour*.

Table 3 - Snow Intensity Classification

Snow Intensity Level	**Snow Fall Rate (*inch/hour*)**	**Description**
1	0-0.5	Light
2	0.5-1.0	Medium
3	1.0-2.0	Heavy

According to NJCMS, roadways are classified into four types which are Urban Interstate, Urban Arterial, Rural Interstate and Rural Arterial (see Table 4).

Table 4 - Highway classification for the snow model in New Jersey

Proposed Highway Types	Functional Classes of Highways in New Jersey
Urban Interstate (I)	Urban interstate
	Urban freeway-expressway
	Urban collector
Urban Arterial (II)	Urban principal arterial
	Urban minor arterial
	Urban local
Rural Interstate (III)	Rural interstate
	Rural major collector
	Rural minor collector
Rural Arterial (IV)	Rural principal arterial
	Rural minor arterial

According to NJCMS, the time of a day can be divided into four periods as defined in Table 5.

Table 5 - Definitions of time periods

Proposed Time Periods	Time Period	Description
TP-1	6:00 AM – 9:00 AM	AM Peak
TP-2	9:00 AM – 3:00 PM	Mid-day
TP-3	3:00 PM – 6:00 PM	PM Peak
TP-4	6:00 PM – 6:00 AM	Night Time

After mapping the different databases, the speed matrix can be developed by correlating the speed data with snow intensity, roadway type, time periods and day of a week as shown in Figure 14.

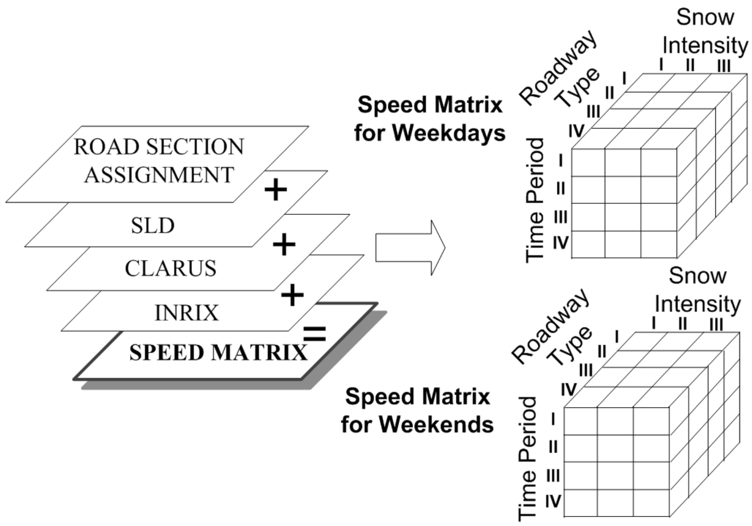

Figure 14. Development of Traffic Speed Matrix

To develop such a speed matrix, weather and traffic data during the winter season of 2010-2011 were used for the data processing. There were a total of 21 snow days during that winter season with different snow fall intensities. A list of the days and maximum snow accumulation in New Jersey reported by CoCoRaHS (Community Collaborative Rain, Hail & Snow Network) is shown in Table 6.

Table 6 – A list of snowfall events (December 2010 ~ April 2011)

Snow Days	Max. Accumulation (inches)
12/26/10 ~ 12/27/10	32
1/0711	6
1/08/11	8
1/11/11 ~ 1/12/11	9.8
1/17/11 ~ 1/18/11	2.6
1/20/11 ~ 1/21/11	5.5
1/26/11 ~ 1/27/11	19.5
2/01/11 ~ 2/03/11	4.5
2/20/11 ~ 2/21/11	8
2/21/11 ~ 2/22/11	6
3/21/11	4.2
3/23/11 ~ 3/24/11	11
4/1/11	4.2

Through data mapping, each TMC segment with its closest weather station was identified. Then, extracting the 20-minute interval snowfall intensity and the 5-minute traffic speed for each TMC segment, and combining the data belonging to same roadway type, snow intensity, and time period. Then the collected data was further divided into two categories: weekday and weekend.

The analysis was performed to determine the mean speed, standard deviation and 5th percentile speeds for each Highway class type in four time periods under different snow intensities. The developed speed matrix for both weekday and weekend are presented in Table 7. Note that the weather and traffic data are based on 21 snow days during 2010/2011 in New Jersey. 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 truck speed is higher than the 5th percentile speed, the operation will be impeded by the traffic, and the reference speed will be used as the truck speed in the proposed model.

Table 7 - Traffic speed matrix (weekday/weekend)

	Snow Intensity	**6 AM - 9 AM**		**9 AM - 3 PM**		**3 PM - 6 PM**		**6 PM - 6 AM**	
		Mean (mph)	5th % (mph)	Mean (mph)	5th % (mph)	Mean (mph)	5th % (mph)	Mean (mph)	5th % (mph)
HC-1	1	54/60	28/49	58/58	44/44	58/58	40/37	58/59	46/49
	2	51/NA	24/NA	52/49	20/29	NA/45	NA/21	55/53	32/22
	3	54/NA	17/NA	59/52	25/18	NA45	NA/21	56/48	33/20
HC-2	1	47/51	26/29	47/49	25/24	47/48	22/22	49/51	31/33
	2	45/NA	25/NA	51/42	38/28	NA/43	NA/20	47/43	30/22
	3	46/NA	22/NA	42/NA	17/NA	NA/43	NA/29	46/47	30/32
HC-3	1	60/62	43/54	63/62	52/52	63/60	53/47	62/62	52/53
	2	57/NA	44/NA	60/56	47/44	NA/55	NA/36	55/55	34/33
	3	51/NA	23/NA	59/56	44/48	NA/52	NA/36	55/52	36/31
HC-4	1	56/56	42/45	56/55	43/43	56/55	43/43	57/56	44/44
	2	54/61	43/51	55/58	47/34	NA/52	NA/36	56/56	44/44
	3	NA/NA	NA/NA	57/53	51/31	NA/59	NA/51	56/58	42/51

Note: HC: highway classification
NA: unavailable data; suggest to use the recommended operating speed as a replacement

6 CASE STUDY AND RESULT ANALYSIS

To demonstrate the applicability of the proposed snow model, case studies were performed on three maintenance crews selected by NJDOT. The required geometric data of the snow sections assigned to the three crews and speed data for each of them under different weather conditions during different time periods were extracted from the developed geometric database and speed matrix, respectively. Total required quantities of spreading salt for each crew and required fleet size of plows for each snow section were estimated and discussed in this chapter.

6.1 Site Identification

The three maintenance crews are: The Newark Yard - Crew 226, The Sand Hill Yard - Crew 310 and The Middle Twp. Yard - Crew 428. The spatial distribution of snow sections of the three crews is presented in Figure 17.

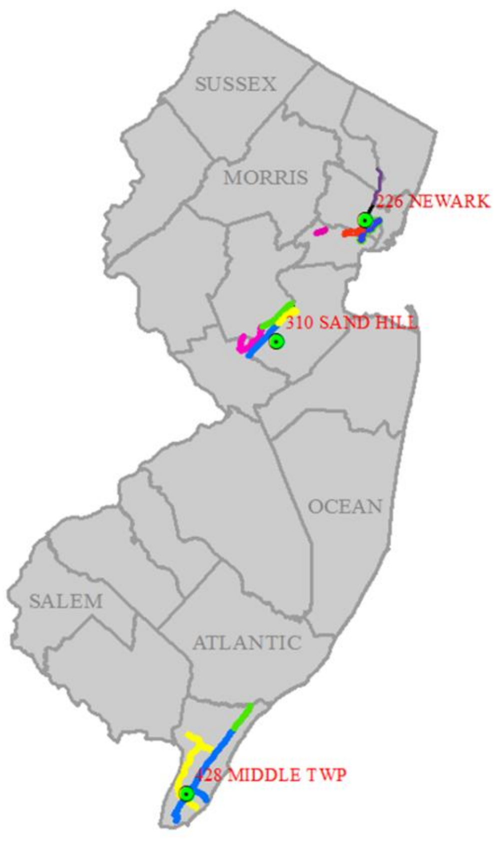

Figure 17. The locations of Crews of 226, 310 and 428

6.2 Data Collection

The database for salt spreading is crew based, while for plowing is snow section based.

Figures 15-17 present the detailed geometric information and the New Jersey Winter 2012-2013 deployment of spreading trucks of the three crews, while the Table 8 describes the assignments of snow sections for plowing operations.

Strategic Deployment Plan
Winter 2012-2013
Region North

Area Super 25: Richard Christensen
Crew Super: Bruce White
Assist Crew Super: Melvin Hunter

Crew: 226 - Newark

Beat	Route	Section Limits	Deployment	Truck Size	Actual Section Limits	# of Lane Miles Spread	Salt Tons Needed
1 & 2	Local 1 & 9	45.4 to 51.5 Ramps & Service Rd.	Yard	2 1/2 Ton 7 Ton	45.4 to 51.5 Ramps & Service Rd.	11.4	2.0
3	Express 1 & 9	45.5 to 51.5	45.5	**Contractor**	45.14 to 51.3	41.3	7.2
4 & 5	Local 1&9	45.5 to 51.5	Yard	**Contractor** 7 Ton	45.14 to 51.3	41.3	7.2
6 & 7	22	Ramps 60.0 to 55.5	Yard	2 1/2 Ton **Contractor**	Ramps 54.0 to 60.5	25.6	4.5
8 & 9	Local 78	49.28 to 58.4 58.4 to 49.28	58 Yard	**Contractor** **Contractor**	49.29 to 58.4	56	9.8
10	78	78 & 1&9 Ramp Complex	Yard	Tandem	54.5 to 58.4	34	6.0
11 & 12	78	Ramps 55 to 49.28	45.5 55	7 Ton 7 Ton	Ramps 55 to 49.28	18	3.2
13 & 14	81 & 78 Connector	0.5 to 1.2 2 mile Connector Road	0.5	**Contractor** 7 Ton	0.5 to 1.2 46.5 to 48.5 (rt 1&9)	33	5.8
					TOTAL	**227.6**	**45.6**

TRUCKS PER CREW		
TD	**Size**	**Salt Tons**
5025	6	7
5810	6	7
5977	6	7
11805	6	7
11915	6	7
5254	2 1/2	5
10873	2 1/2	5
4206	Tandem	10
8 trucks	**Contractor**	**160**
	Total Tons	**215**

Figure 15. Salt spreading plan for Crew 226 of the Newark Yard[3]

[3] Information obtained from NJDOT Spreading Deployment Plan (2012).

Area Supervisor		**33**	**Glenn Holzlohner**					
Crew Supervisor		**310**	**John Mateyka**					

6 Truck Plan

Beat #	Truck	Route	Contractor or DOT	Description	Section Limits	Lane Miles	Salt Tons Needed	Deployment Location
1	8 Ton	27	DOT	From Georgetown-Franklin Road, South Brunswick to Route 206, Princeton Boro	0 - 6.9	14.23	2.5	206 MP 57.3
		206	DOT	From Route 27, Princeton Boro to Cherry Valley Road, Princeton Twp	53.9 - 57.3	7.29	1.3	
2	8 Ton	27	DOT	From Georgetown-Franklin Road, South Brunswick to Sandford Street, New Brunswick	6.9 - 15.4	23.54	4.1	27 MP 6.9
3	8 Ton	1	DOT	From Route 130, North Brunswick to Aaron Road, North Brunswick	21.38 - 24.6	9.96	1.7	1 MP 24.6
4	2 1/2 Ton	1	DOT	From Aaron Road, North Brunswick to Raymond Road, South Brunswick	15.85 - 21.38	12.04	2.1	1 MP 21.38
5	8 Ton	1	DOT	From Raymond Road, South Brunswick to Fischer Place, West Windsor	11.38 - 15.85	12.96	2.3	1 MP 15.85
6	2 1/2 Ton	91	DOT	From Van Dyke Road, New Brunswick to Route 1, North Brunswick	0 - 2.3	4.6	0.8	91 MP 2.3
		26	DOT	From Route 1, North Brunswick to Naussau Street, North Brunswick	0 - 2.1	4.88	0.9	
					Total	**89.5**	**15.7**	

TRUCKS PER CREW		
TD	**Truck**	**Salt Tons**
10538	2 1/2 Ton	5
10900	2 1/2 Ton	5
5546	8 Ton	7
5659	8 Ton	7
5479	8 Ton	7
5982	8 Ton	7
Total		**38**

Figure 16. Salt spreading plan for Crew 310 of the Sand Hill Yard[4]

[4] Information obtained from NJDOT Spreading Deployment Plan (2012).

Area Supervisor 47	Dave Pusey							
Crew Supervisor 428	Jim Iapalucci							

7 Truck Plan

Beat #	Truck	Route	Contractor or DOT	Description	Section Limits	Lane Miles	Salt Tons Needed	Deployment Location
1	2 1/2 Ton	9	DOT	Sea Isle Blvd. (Oceanview) to Beesley Point bridge (Upper Twp.)	21 - 31.4	10.4	1.8	9 MP 31.4
2	2 1/2 Ton	9	DOT	Indian Trail (Burleigh) to Sea Isle Blvd.(Oceanview)	9.6 - 21	11.4	2.0	9 MP 9.6
3	2 1/2 Ton	9 & 109	DOT	Sandman Blvd.(Erma) to Texas ave. (Cape May) Also Sandman Blvd. to Indian Trail Rd.(Burleigh)	1.23-3.06 & 3-9.6	9.68	1.7	RT-109 MP-1.9
4	8 Ton	47	DOT	West Rio Grande Ave. (Wildwood) to Indian Trail Rd.9(Burleigh)	0.7- 8.82	11.46	2.0	47 MP 3.7
5	2 1/2 Ton	47	DOT	Indian Trail (Burleigh) to RT-83 (Dennisville)	8.82-17.54	8.87	1.6	47 MP 8.82
6	8 Ton	47	DOT	RT-83 (Dennisville) to West Creek (Dennis twp.) Also RT-83	17.54-24.51 &0-3.81	11.38	2.0	47 MP 24.51
7	2 1/2 Ton	147	DOT	RT-9 to (Burleigh) to Walnut Ave.	0 - 4.20	8.4	1.5	147 MP 4.20
					TOTAL:	**71.59**	**12.5**	

Contractor: 0 Trucks

TRUCKS PER CREW		
TD #	**Truck Size**	**Salt Tons**
5350	8 Ton	8
5463	2 1/2 Ton	5
5459	2 1/2 Ton	5
10564	2 1/2 Ton	5
11776	2 1/2 Ton	5
5606	2 1/2 Ton	5
5497	8 Ton	8
	Total Tons:	**41.0**

Figure 17. Salt spreading plan for Crew 428 of the Middle Twp. Yard[5]

[5] Information obtained from NJDOT Spreading Deployment Plan (2012).

Table 8 - Geometric data of the three crews for plowing operation

SNOW_SECTION	SRI	MPFROM	MPTO	Center line mile	FACILITY
5428261	00000109	1.5	3.06	1.56	Middle Twp.
5428262	00000083	0	3.8	3.8	Middle Twp.
5428261	00000147	0	4.2	4.2	Middle Twp.
5428263	00000009	25	31	6	Middle Twp.
5428262	00000047	0.7	20.9	20.2	Middle Twp.
5428261	00000009	3	25	22	Middle Twp.
5226265	00000081	0.5	1.2	0.7	Newark
5226265	00000078	46.5	48.5	2	Newark
5226264	00000078	56.4	58.5	2.1	Newark
5226261	00000022	55.2	60.3	5.1	Newark
5226263	00000001	45.4	51.2	5.8	Newark
5226262	00000001	45.4	51.5	6.1	Newark
5245262	00000021	0	8.1	8.1	Newark
5245261	00000021	6	14.35	8.35	Newark
5310262	00000026	0	2.1	2.1	Sand Hill
5310265	00000091	0	2.3	2.3	Sand Hill
5310263	00000206	53.9	57.2	3.3	Sand Hill
5310262	00000001	20.4	25.1	4.7	Sand Hill
5310263	00000027	0	7	7	Sand Hill
5310264	00000027	7	15	8	Sand Hill
5310261	00000001	11.4	20.7	9.3	Sand Hill

By comparing the road section assignments for both spreading and plowing operations, it can be observed that both databases contain the mileposts of the responsible road sections. However, the road sections are not clearly defined for the spreading operation shown in Figures 15-17 as that for plowing operation shown in Table 8. To prepare the geometric data for model implementation, the detailed geometric information of each road section was extracted from the developed geometric database for this project based on the provided mileposts. Tables 9 and 10 present the processed geometric data of the three crews for spreading and plowing, respectively.

Table 9 - Geometric data of the three crews for Spreading Model

Facility	Crew ID	Roadway Type	Geometric Information				
			Mainline		Ramp		Total Spreading Length (mile)
			Centerline Mile (*mile*)	Lane Mile (*mile*)	Centerline Mile (*mile*)	Lane Mile (*mile*)	
Newark	**226**	I (77%) II (23%)	28.3	118.0	28.0	40.0	161.6
Sand Hill	**310**	II (100%)	36.3	123.0	6.7	7.6	88.8
Middle Twp.	**428**	II (67%) IV (33%)	62.1	142.1	1.0	1.1	76.1

Note: 1 *mile* = 1.6 *km*; 1 *ft* = 0.3048 *m*

Table 10 - Geometric data of the three crews for Plowing Model

Facility	Section ID	Roadway Type	Geometric Information						
			Mainline					Ramp	
			Centerline Mile (*mile*)	Lane Mile (*mile*)	No. of Lanes	Max Section Width (*ft*)	Length of Acc/Dec Lanes	Ramp Length (*mile*)	Weighted Ramp Width (*ft*)
Newark	5226261	II (100%)	5.1	21.2	2	34	0.8	2.0	17.3
	5226262	I (100%)	6.1	25.7	2	34	1.3	3.4	23.8
	5226263	I (100%)	5.8	22.6	2	34	1.2	2.8	23.9
	5226264	I (100%)	2.1	8.9	2	34	0.7	6.9	26.2
	5226265	I (100%)	2.7	14.6	3	46	0.0	0.5	22.1
Sand Hill	5310261	II (100%)	9.3	45.2	3	46	0.7	4.2	22.2
	5310262	II (100%)	6.8	32.3	3	46	0.5	2.4	21.8
	5310263	II (100%)	10.3	22.0	1	22	1.1	0.1	21.2
	5310264	II (100%)	8.0	21.6	1	22	5.4	0.0	14.0
	5310265	II (100%)	2.3	4.5	1	22	0.0	0.0	20.0
Middle Twp.	5428261	II (84%) IV (16%)	27.8	66.7	1	22	10.2	0.8	22.8
	5428262	II (100%)	24.0	54.7	1	22	6.4	0.2	17.0
	5428263	II (49%) IV (51%)	6.0	12.0	1	22	0.0	0.0	16.8

To simulate different scenarios for both plowing and spreading operations, the corresponding traffic speed can be extracted from Table 7. It can be observed that in Table 7 there are some speed data marked as "NA" representing the unavailable data which are unable to be generated due to insufficient traffic and/or weather data.

The operating speed can be determined by comparing the recommended plowing/spreading speed with the traffic speed presented in Table 7. If the recommended operating speed is lower than the traffic speed, the recommended speed will be employed as the operating speed in both models. Otherwise, the traffic speed will be employed. In this way, it can ensured that the both the winter maintenance operations are not interfered by the traffic flow. For instance, consider the spreading operation under snow intensity III during the AM peak on weekdays with recommended spreading speed of 25 mph: For crew 310, the traffic speed of 22 mph is used as the operating speed, because it is less than the 25 mph. For the crew 226, as it includes two roadway types; hence, the weighted traffic speed can be estimated as 18.2 mph (17*77%+22*23%=18.2 mph). As it is less than the recommended spreading speed of 25 mph, it is employed as the operating speed for Crew 226. Similarly, for crew 428, the operating speed can be obtained as 23.0 mph (22*67%+25*33%=23.0 mph). It is noted here that as the traffic speed for highway type IV during AM peak under the snow intensity of III is not available, the recommend spreading speed of 25 mph is used as the finalized operating speed during the model implementation.

6.3 Case Study Analysis

Both the developed spreading and plowing models were applied to the three crews with a predetermined service time limit of two hours for plowing and one and half hours for spreading. The required truck fleet sizes for both spreading and plowing under different combination of weather and traffic conditions were estimated.

During spreading operation, three types of spreading trucks were employed: 2.5-Ton, 6-Ton and 10-Ton with three spreading rates 250 *lb/ln-mi*, 350 *lb/ln-mi* and 450 *lb/ln-mi*, respectively. During plowing operation, the employed plows were uniform in size with the plow width of 11 *ft* (the effective plow width is 9 *ft* with 35 degree angle) with overlapped plowing width of 2 *ft*. The allowable plowing width reduction is set as 2 *ft*. In addition, the weight factors for justifying the centerline mile accounting for the reduced speeds or deadheading time for plowing the ramp was set as $\gamma_R = 2.5$. The results for both spreading and plowing operations are presented in the flowing tables. Tables 11-13 summarize the plowing results for each section of the three crews while Tables 14-16 summarize the spreading results of the three crews (spreading rate at 250 *lb/ln-mi*).

Table 11 - Plowing results for Crew 226 with the Newark Yard

Area Super 25: Richard Christensen Crew Super: Bruce White Assist Crew Super: Melvin Hunter		Crew: 226 - Newark							
Recommended Plowing Speed of		15 mph (Lower Bound)				20 mph (Upper Bound)			
Snow Sections	TP* / SI*	AM	MD	PM	NT	AM	MD	PM	NT
5226261	1	3	3	3	3	3	3	3	3
	2	3	3	3	3	3	3	3	3
	3	3	3	3	3	3	3	3	3
5226262	1	4	4	4	4	3	3	3	3
	2	4	4	4	4	3	3	3	3
	3	4	4	4	4	3	3	3	3
5226263	1	3	3	3	3	3	3	3	3
	2	3	3	3	3	3	3	3	3
	3	3	3	3	3	3	3	3	3
5226264	1	9	9	9	9	8	8	8	8
	2	9	9	9	9	8	8	8	8
	3	9	9	9	9	8	8	8	8
5226265	1	2	2	2	2	1	1	1	1
	2	2	2	2	2	1	1	1	1
	3	2	2	2	2	2†	1	1	1

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

†: The result in red color denotes the fleet size at weekdays and weekends are different and the fleet size at weekend is one less than that on weekdays.

Table 12 - Plowing results for Crew 310 with the Sand Hill Yard

Area Super 33: Glenn Holzlohner Crew Super: John Mateyka		**Crew: 310 - Sand Hill**							
Recommended Plowing Speed of		**15 mph (Lower Bound)**				**20 mph (Upper Bound)**			
Snow Sections	TP* / SI*	AM	MD	PM	NT	AM	MD	PM	NT
5310261	1	5	5	5	5	4	4	4	4
	2	5	5	5	5	4	4	4	4
	3	5	5	5	5	4	4	4	4
5310262	1	4	4	4	4	3	3	3	3
	2	4	4	4	4	3	3	3	3
	3	4	4	4	4	3	4†	3	3
5310263	1	3	3	3	3	3	3	3	3
	2	3	3	3	3	3	3	3	3
	3	3	3	3	3	3	3	3	3
5310264	1	3	3	3	3	3	3	3	3
	2	3	3	3	3	3	3	3	3
	3	3	3	3	3	3	3	3	3
5310265	1	2	2	2	2	2	2	2	2
	2	2	2	2	2	2	2	2	2
	3	2	2	2	2	2	2	2	2

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

†: The result in red color denotes the fleet size at weekdays and weekends are different and the fleet size at weekend is one less than that on weekdays.

Table 13 - Plowing results for Crew 428 with the Middle Twp. Yard

Area Super 47: Dave Pusey **Crew Super: Jim Iapalucci**		**Crew: 428 - Middle Twp.**							
Recommended Plowing Speed of		**15 mph (Lower Bound)**				**20 mph (Upper Bound)**			
Snow Sections	TP* / SI*	AM	MD	PM	NT	AM	MD	PM	NT
5428261	1	8	8	8	8	5	5	5	5
	2	8	8	8	8	5	5	5	5
	3	8	8	8	8	5	5	5	5
5428262	1	6	6	6	6	5	5	5	5
	2	6	6	6	6	5	5	5	5
	3	6	6	6	6	5	5	5	5
5428263	1	2	2	2	2	1	1	1	1
	2	2	2	2	2	1	1	1	1
	3	2	2	2	2	1	1	1	1

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

Table 14 - Spreading results for Crew 226 with the Newark Yard

Area Super 25: Richard Christensen Crew Super: Bruce White Assist Crew Super: Melvin Hunter												
Crew: 226 - Newark												
Recommended Spreading Speed: 20 mph (Lower Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 19.7 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	7	0	0	7	0	0	7	0	0	7	0	0
	0	7	0	0	7	0	0	7	0	0	7	0
	0	0	7	0	0	7	0	0	7	0	0	7
2	7	0	0	7	0	0	7	0	0	7	0	0
	0	7	0	0	7	0	0	7	0	0	7	0
	0	0	7	0	0	7	0	0	7	0	0	7
3	7	0	0	7	0	0	7	0	0	7	0	0
	0	7	0	0	7	0	0	7	0	0	7	0
	0	0	7	0	0	7	0	0	7	0	0	7
Recommended Spreading Speed: 25 mph (Upper Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 19.7 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	7	0	0	7	0	0	7	0	0	7	0	0
	0	5	0	0	5	0	0	5	0	0	5	0
	0	0	5	0	0	5	0	0	5	0	0	5
2	7	0	0	7	0	0	7	0	0	7	0	0
	0	6	0	0	6	0	0	5	0	0	5	0
	0	0	6	0	0	6	0	0	5	0	0	5
3	7	0	0	7	0	0	7	0	0	7	0	0
	0	7	0	0	6	0	0	5	0	0	5	0
	0	0	7	0	0	6	0	0	5	0	0	5

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

Table 15 - Spreading results for Crew 310 with the Sand Hill Yard

Area Super 33: Glenn Holzlohner Crew Super: John Mateyka							**Crew: 310 - Sand Hill**					
Recommended Spreading Speed: 20 mph (Lower Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 16.3 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	4	0	0	4	0	0	4	0	0	4
2	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	4	0	0	4	0	0	4	0	0	4
3	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	4	0	0	4	0	0	4	0	0	4

Recommended Spreading Speed: 25 mph (Upper Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 16.3 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	4	0	0	3
2	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
3	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	4	0	0	4	0	0	3	0	0	3

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

Table 16 - Spreading results for Crew 428 with the Middle Twp. Yard

Area Super 47: Dave Pusey Crew Super: Jim Iapalucci							**Crew: 428 - Middle Twp.**					
Recommended Spreading Speed: 20 mph (Lower Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 17.9 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
2	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
3	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
Recommended Spreading Speed: 25 mph (Upper Bound)												
Spreading Rate 250lb/Lane Mile, Estimated Quantity of Salt 17.9 Tons												
TP* / SI*	AM			MD			PM			NT		
	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T	2.5T	6T	10T
1	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
2	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3
3	6	0	0	6	0	0	6	0	0	6	0	0
	0	4	0	0	4	0	0	4	0	0	4	0
	0	0	3	0	0	3	0	0	3	0	0	3

*: TP (Time Period) AM: 6 AM - 9 AM; MD: 9 AM - 3 PM; PM: 3 PM - 6 PM; NT: 6 PM - 6 AM
SI (Snow Intensity) 1: 0 - 0.5 in/hr; 2: 0.5 - 1.0 in/hr; 3: 1.0 -2.0 in/hr

6.4 Results

According to the plowing results presented in Tables 11-13, at the plowing speed of 15 mph, the required number of plowing trucks is not affected by the snow intensity in all time periods since 5th percentile traffic speed is higher than 15 mph. However, while plowing speed increases to 20 mph, it requires more trucks for some snow sections (e.g., 5225265 and 5310262, etc.) at snow intensity level 3 during AM peak and MD time period denoting it is affected by the slow traffic flow (speeds below 20 mph) under this condition. It can be inferred that by employing higher plowing speed, the required number of plowing trucks will vary more significantly due to weather and slow traffic impacts. By further comparing the required fleet size for plowing at two different operating speeds, it can be observed that an increase of 5 MPH in operating speed leads to significant decrease of the total required fleet size, which can be used as basis for further analysis on winter maintenance resource optimization.

According to the spreading results presented in Tables 14-16, there are no variances of the required number of spreading trucks under different snow intensity levels during various time periods at lower spreading speed of 20 mph. However, at higher spreading speed of 25 mph, the impact of slow traffic flow (speeds below 25 mph) on spreading results become obvious and this is special the case for large capacity trucks. This is because, for spreading with large trucks (i.e. 10-T), the service time constraint is the primary factor affecting the required fleet size under this situation, hence, it is sensitive to the weather conditions (i.e. snow intensity). However, for small trucks (i.e. 6-T), the fleet size is mainly dictated by the total amount of spreading salt and capacity of the truck. 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.

Spreading rate, which may vary depending on geometry and weather conditions, is also a critical factor affecting the required fleet size for spreading operation. The fleet size, in general, increases as the spreading rate increases for all different types of spreading trucks. 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.

7 IMPLEMENTATION OF THE PROPOSED MODEL

The developed snow model (including spreading and plowing) can be applied to all snow sections in New Jersey. According to the data provided by NJDOT, there are 75 crews responsible for spreading operation with total centerline mile of 2340 miles, and total lane miles including both mainline and ramps are 9105 miles. The snow section data for plowing operation are extracted from 2012 Bid Sheet for plowing (PRICE LINES-SNOW REMOVAL SECTIONS 13-X-22591). There are 278 snow sections with 100, 107, and 71 sections in North, Central, and South Regions, respectively. The total centerline mile for plowing is 2424 miles, and the total number of lane miles, including ramps, is 9710.

7.1 Summary of the Results

The estimated results for spreading and plowing operations are presented in Appendices A and B, respectively. For spreading, the outputs indicate the estimated quantity of salt for each crew at different spreading rates 250 *lb/ln-mi*, 350 *lb/ln-mi* and 450 *lb/ln-mi*. For plowing, the estimated fleet size for snow plowing in each snow section is included, considering 15-mph and 2-hour service time. The results are compared with those listed in the Bid Sheet (2012). Other outputs including fleet sizes for spreading and plowing operations under different time periods and snow intensities are suggested in the final report package.

8 SUMMARY AND CONCLUSIONS

This project developed a new snow model (including spreading and plowing) and a working database (integrating geometric, weather, and traffic data) for NJDOT, so that the number of plowing trucks and amounts of spreading salt could be estimated accordingly by considering service time constraint and plowing/spreading patterns. Spreading rates and vehicle capacity were also considered in spreading model. The model is sustainable and can be further enhanced by periodically updating the working database.

The main features of the developed model lies in adapting complicate roadway geometry, different spreading/plowing patterns, weather and time dependent traffic speed, as well as the use of mixed sizes of spreaders and plows. The geometric database of road sections was developed. Considering actual plowing operation on a varying pavement width, the maximum pavement width and centerline miles were applied. The acceleration/deceleration lanes were extracted from SLD (2009) and were treated by trucks carrying ramp service. The actual plowing and spreading speed was considered as a function of highway types, snow intensity, time period of a day, day of a week (i.e., weekday, weekend). A dynamic speed matrix was developed by correlating the traffic data and weather data during different time periods. If the traffic speed is greater than the operating speed, the later one will apply in the developed snow model.

The developed model has been applied to three maintenance crews and the results were discussed in the case study. It was found that the spreading rate apparently had a direct effect on the total required salt amount during spreading operation. The higher the spreading rate, the more amount of salt was required, which laid the potential basis for the resource management under different weather and traffic conditions. For both the spreading and plowing operations, two different ranges of operating speeds were employed (20 mph to 25 mph for spreading; 15 mph to 20 mph for plowing). It was observed that at lower operating speed (i.e. 15 mph for plowing and 20 mph for spreading), the fleet sizes did not vary under different weather conditions during different time periods. However, the fleet sizes were slightly reduced as the operating speeds increase. The implementation of the new snow model to all snow sections in New Jersey was also performed which was expected to assist managers in determining the required number of contractor trucks before the start of a snow season, considering the worst case situation including weather and geometry conditions and the corresponding traffic speed. Additionally, it can be employed to calculate the required number of spreading trucks/plows to call out during/after each winter storm subject to the forecasted weather and expected traffic.

9 RECOMMENDATIONS

The research team identified various areas that are worthy of further research, which are listed below:

- In this study, only 19 snow events in 2010~2011 were applied to quantify the impact of snow intensity and time of a day to operating speeds for plowing and spreading. More efforts shall be paid for continuously collecting the weather/traffic data to enhance the accuracy of the speed matrix.
- To improve the accuracy of fleet size (i.e. number of trucks) estimation for plowing and spreading, the actual operating speeds under different weather/traffic conditions can be obtained via processing data collected by the "MARVLIS" system instead of traffic speed matrix developed in this study.
- There are discrepancies between road geometry of snow sections (e.g., lane miles, lane number, pavement width and etc.) and the current NJDOT SLD (2009), which shall be corrected for improving the accuracy of fleet size estimation.
- Based on the developed snow model, a cost and benefit analysis shall be conducted to determine the model efficiency in reducing the winter maintenance cost by decreasing the number of trucks for snow plowing and salt spreading operation.
- The current snow sections shall be re-defined (i.e. change beginning and ending point) and/or re-organized (i.e. justify crew responsible sections), so that the needed trucks for winter road maintenance may be further reduced.
- The spreading worksheets of different regions should be unified (i.e. Central and South regions are suggested to follow the format of North region's Spreading Deployment Plan Worksheet).
- The relationship between snow model and MDSS (Maintenance Decision Support System) may be explored to provide more efficient use of maintenance resources, reduce operating costs and increase safety, reliability and mobility on roadways.
- In case the road geometry, weather, and traffic data changes, the snow model working database should be well maintained.

10 REFERENCES

1. Agarwal, M., Maze, T. H., and Souleyrette, R. (2005). "Impact of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity." Final Technical Report, (http://www.ctre.iastate.edu/reports/weather_impacts.pdf, accessed Aug., 2012).
2. Cifelli, N. J., Cunningham, W. B., Dunn Jr, J. F., Kee, O. D., Keller, G. F., Kjetsaa, M. B., Webber, R. C., Willever, L. J. (1979). "New Jersey Department of Transportation Model for Winter Equipment and Manpower Allocations." *Transportation Research Board Special Report*, Vol. 185, pp. 82-84.
3. Chien, S. I., and Schonfeld, P. (2001). "Optimal Work Zone Lengths for Four-lane Highways." *Journal of Transportation* Engineering, ASCE, 127(2): 124-131.
4. Chien, S. I., Tang, Y., and Schonfeld, P. (2002). "Optimizing Work Zones for Two-lane Highway Maintenance Projects." *Journal of Transportation Engineering, ASCE*, 128 (2): 145-155.
5. Chien, S. I., Kolluri, K. K. (2010). "Evaluation of Freeway Travel Time Variability and Reliability under Adverse Weather with TRANSMIT Data." *TRB meeting 2010*, 10-3214.
6. Dalta, S. and Sharma S. (2010). "Variation of the Impact of Cold Temperature, Snowfall and their Interaction on Traffic Volumes." *TRB meeting 2010*, 10-3182.
7. Daniel, J. and Chien, S. I. (2009). "Impact of Adverse Weather on Freeway Speeds and Flows." *TRB meeting 2009*, 09-2837.
8. Federal Highway Administration (2010). "Data mining and gap analysis for weather responsive traffic management studies." Report No. FHWA-JPO-11-037, http://ntl.bts.gov/lib/38000/38100/38165/HTML/dmga.pdf, accessed in Dec. 2012.
9. Federal Highway Administration (2011), "How do weather events impact roads?" Available at: http://www.ops.fhwa.dot.gov/weather/q1_roadimpact.htm, accessed in Dec. 2012.
10. Federal Highway Administration (2012). "Guidelines for the use of variable speed limit systems in wet weatehr." Report No. FHWA-SA-12-022, http://safety.fhwa.dot.gov/speedmgt/ref_mats/fhwasa12022/fhwasa12022.pdf, accessed in Dec. 2012.
11. Federal Highway Administration (2012). "Best Practices for Road Weather Management, Version 3.0." Report No. FHWA-HOP-12-046, http://ops.fhwa.dot.gov/publications/fhwahop12046/fhwahop12046.pdf, accessed in Dec. 2012.
12. Han, L. D., Chin, S. and Hwang, H. (2003). "Estimating Adverse Weather Impacts on Major US Highway Network." *TRB 2003 Annual Meeting* CD-ROM.
13. Hanbali, R. M. (1994). "Economic Impact of Winter Road Maintenance on Road Users." *Transportation Research Record,* 1442: 151-161.
14. *INRIX Inc*., http://www.inrix.com/default.asp, accessed in Aug. 2012.
15. Knapp, K. K., Kroeger, D., and Glese, K. (2000). "Mobility and Safety Impacts of Winter Storm Events in A Freeway Environment." *FINAL REPORT*, Iowa State University, February 2000 (http://www.intrans.iastate.edu/reports/winstorm.pdf, accessed in Aug. 2012).
16. Lannert Robert Glenn (2008). "Plowing Wider and Faster on 21st-Century Highways by Using 14-ft Front Plows and Trailer Plows Effectively." *Transportation Research*

E-Circular, E-C126, pp. 261-266.

17. Liang, W. L., Kyte, M., Kitchener, F., and Shannon, P. (1998). “Effect of Environmental Factors on Driver Speed: A Case Study.” *Transportation Research Record*, 1635: 155-161.
18. New York State Department of Transportation (2006). “Highway maintenance guidelines: snow and ice control.” (https://www.dot.ny.gov/divisions/operating/oom/transportation-maintenance/repository/HMG%20Section5.pdf, accessed in Aug. 2012)
19. Padget, E. D., Knapp, K. K. and Thomas, G. B. (2001). “Investigation of winter-weather speed variability in sport utility vehicles, pickup trucks, and passenger cars. Traffic Safety 2001: Americans with Disabilities Act; Driver and Vehicle Modeling; Situation Awareness; Licensing; Driver Behavior; Enforcement; Trucks; and Motorcycles.” *Transportation Research Board National research Council*, Washington, 116-124
20. Perrier, N., Langevin, A., and Campbell, J. (2007). “A survey of models and algorithms for winter road maintenance. Part IV: Vehicle routing and fleet sizing for plowing and snow disposal.” *Computers & Operations Research*, 34 (1), 258-294.
21. Shahdah, U. and Fu, L. (2010). “Quantifying the mobility benefits of winter road maintenance - A simulation based analysis.” *TRB Annual Meeting* CD-ROM (http://www.civil.uwaterloo.ca/wpti/documents/Quantifying%20the%20Mobility%20Benefits%20of%20Winter%20Road%20Maintenance.pdf, accessed in Aug. 2012).
22. *Surface Transportation Weather Research Center*, http://stwrc.und.edu/undclarus.php, Accessed in Aug. 2012.
23. The California Department of Transportation (2009). “Snow removal operations and general information.” (http://www.dot.ca.gov/dist3/departments/mtce/documents/SnowRemovalOps.pdf, accessed in Aug. 2012)
24. Wilson, M. C., Dadie-Amoah, K. and Zhang, Y. (2003). “Snowplow operations and resource management.” Final report summited to Minnesota Department of Transportation (http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=962, accessed in Aug. 2012).

APPENDICES

A. Estimated Quantity of Spreading Salt

Region	Crew No.	2009 SLD				NJDOT Deployment Plan (2012)				Lane Miles Difference*	Salt Tons Difference**
		Lane Miles	Salt Tons Needed			Lane Miles	Salt Tons Needed				
			250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi		250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi	350 lb/ln-mi	350 lb/ln-mi
North	210	68.3	8.5	12.0	15.4	81	10.1	14.2	18.2	12.7	2.2
	211	165.6	20.7	29.0	37.3	244	30.5	42.7	54.9	78.4	13.7
	212	88.4	11.0	15.5	19.9	90.4	11.3	15.82	20.3	2.0	0.4
	213	184.7	23.1	32.3	41.6	306	38.3	43.1	68.9	121.3	10.8
	214	101.0	12.6	17.7	22.7	175.3	21.9	30.7	39.4	74.3	13.0
	215	115.5	14.4	20.2	26.0	238	29.8	41.7	53.6	122.5	21.5
	216	152.2	19.0	26.6	34.2	237.45	29.7	41.6	53.4	85.3	15.0
	217	167.4	20.9	29.3	37.7	225.6	28.2	39.5	50.8	58.2	10.2
	218	134.1	16.8	23.5	30.2	157.6	19.7	27.6	35.5	23.5	4.1
	219	191.0	23.9	33.4	43.0	250.8	31.4	26.25	56.4	59.8	-7.2
	220	219.7	27.5	38.4	49.4	177.3	22.2	31	39.9	-42.4	-7.4
	221	156.0	19.5	27.3	35.1	245.5	30.7	43	55.2	89.5	15.7
	222	106.5	13.3	18.6	24.0	120	15.0	12.2	27.0	13.5	-6.4
	223	127.6	15.9	22.3	28.7	223.34	27.9	39.1	50.3	95.8	16.8
	224	67.9	8.5	11.9	15.3	71.6	9.0	10.1	16.1	3.7	-1.8
	225	153.3	19.2	26.8	34.5	174.2	21.8	30.5	39.2	20.9	3.7
	226	157.9	19.7	27.6	35.5	227.6	28.5	45.6	51.2	69.7	18.0
	227	110.7	13.8	19.4	24.9	187	23.4	32.7	42.1	76.3	13.3
	228	151.2	18.9	26.5	34.0	212.9	26.6	37.3	47.9	61.7	10.8
	229	74.3	9.3	13.0	16.7	78.5	9.8	8.9	17.7	4.2	-4.1
	230	79.3	9.9	13.9	17.9	80.6	10.1	14.1	18.1	1.3	0.2
	231	89.1	11.1	15.6	20.0	116.7	14.6	20.4	26.3	27.6	4.8
	245	88.1	11.0	15.4	19.8	117.8	14.7	20.6	26.5	29.7	5.2
	246	44.1	5.5	7.7	9.9	40.9	5.1	7.2	9.2	-3.2	-0.5
	250	85.0	10.6	14.9	19.1	140.5	17.6	24.6	31.6	55.5	9.7
	256	60.2	7.5	10.5	13.6	88.4	11.1	15.5	19.9	28.2	5.0
	265	67.1	8.4	11.7	15.1	84	10.5	14.7	18.9	16.9	3.0

*: The lane miles from NJDOT Deployment Plan (2012) minus the lane miles in SLD (2009).

**: The salt tons needed from NJDOT Deployment Plan (2012) minus the salt tons needed based on SLD (2009).

Region	Crew No.	2009 SLD				NJDOT Deployment Plan (2012)				Lane Miles Difference*	Salt Tons Difference**
		Lane Miles	Salt Tons Needed			Lane Miles	Salt Tons Needed				
			250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi		250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi	350 lb/ln-mi	350 lb/ln-mi
Central	310	130.6	16.3	22.9	29.4	89.5	11.2	15.7	20.1	-41.1	-7.2
	311	126.3	15.8	22.1	28.4	59.47	7.4	10.4	13.4	-66.8	-11.7
	312	86.8	10.9	15.2	19.5	34	4.3	6	7.7	-52.8	-9.2
	313	129.2	16.2	22.6	29.1	78.21	9.8	13.7	17.6	-51.0	-8.9
	314	123.4	15.4	21.6	27.8	90.05	11.3	15.76	20.3	-33.3	-5.8
	316	155.1	19.4	27.1	34.9	66.72	8.3	11.68	15.0	-88.3	-15.5
	317	86.3	10.8	15.1	19.4	90.29	11.3	15.8	20.3	4.0	0.7
	318	132.8	16.6	23.2	29.9	100.59	12.6	17.6	22.6	-32.2	-5.6
	319	133.1	16.6	23.3	29.9	97.58	12.2	17.1	22.0	-35.5	-6.2
	320	174.5	21.8	30.5	39.3	129.57	16.2	22.7	29.2	-44.9	-7.8
	321	174.6	21.8	30.6	39.3	110.32	13.8	19.3	24.8	-64.3	-11.3
	324	129.9	16.2	22.7	29.2	71.38	8.9	12.5	16.1	-58.5	-10.2
	325	34.3	4.3	6.0	7.7	14.79	1.8	2.6	3.3	-19.5	-3.4
	327	121.7	15.2	21.3	27.4	95.81	12.0	16.8	21.6	-25.9	-4.5
	329	118.2	14.8	20.7	26.6	82.5	10.3	14.4	18.6	-35.7	-6.3
	330	111.0	13.9	19.4	25.0	83.65	10.5	14.6	18.8	-27.4	-4.8
	331	67.2	8.4	11.8	15.1	37.92	4.7	6.6	8.5	-29.2	-5.2
	332	144.9	18.1	25.4	32.6	97.87	12.2	17.1	22.0	-47.1	-8.3
	333	47.2	5.9	8.3	10.6	45.36	5.7	7.9	10.2	-1.9	-0.4
	334	86.8	10.8	15.2	19.5	135.48	16.9	23.7	30.5	48.7	8.5
	335	160.9	20.1	28.1	36.2	100.1	12.5	17.5	22.5	-60.7	-10.6
	336	125.4	15.7	21.9	28.2	150.2	18.8	26.3	33.8	24.8	4.4
	337	147.0	18.4	25.7	33.1	117.9	14.7	20.6	26.5	-29.1	-5.1
	338	194.8	24.3	34.1	43.8	163.97	20.5	28.7	36.9	-30.8	-5.4
	339	162.6	20.3	28.5	36.6	224.42	28.1	39.3	50.5	61.8	10.8
	345	30.5	3.8	5.3	6.9	25.44	3.2	4.5	5.7	-5.1	-0.8
	346	23.2	2.9	4.1	5.2	22.66	2.8	4	5.1	-0.6	-0.1
	356	64.8	8.1	11.3	14.6	41.98	5.2	7.3	9.4	-22.9	-4.0
	357	96.4	12.0	16.9	21.7	94.88	11.9	16.6	21.3	-1.5	-0.3
	369	28.9	3.6	5.1	6.5	19.28	2.4	3.4	4.3	-9.6	-1.7

*: The lane miles from NJDOT Deployment Plan (2012) minus the lane miles in SLD (2009).

**: The salt tons needed from NJDOT Deployment Plan (2012) minus the salt tons needed based on SLD (2009).

Region	Crew No.	2009 SLD				NJDOT Deployment Plan (2012)				Lane Miles Difference*	Salt Tons Difference**
		Lane Miles	Salt Tons Needed			Lane Miles	Salt Tons Needed				
			250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi		250 lb/ln-mi	350 lb/ln-mi	450 lb/ln-mi	350 lb/ln-mi	350 lb/ln-mi
South	410	193.0	24.1	33.8	43.4	90.9	11.4	15.9	20.5	-102.1	-17.9
	411	133.7	16.7	23.4	30.1	193.1	24.1	33.8	43.4	59.4	10.4
	413	166.9	20.9	29.2	37.5	179.6	22.5	31.4	40.4	12.7	2.2
	414	102.6	12.8	18.0	23.1	134.94	16.9	23.6	30.4	32.3	5.6
	430	190.8	23.8	33.4	42.9	214.7	26.8	37.6	48.3	23.9	4.2
	445	104.0	13.0	18.2	23.4	94.9	11.9	16.6	21.4	-9.1	-1.6
	420	159.7	20.0	28.0	35.9	146	18.3	25.5	32.9	-13.7	-2.5
	421	152.6	19.1	26.7	34.3	163.7	20.5	31.8	36.8	11.1	5.1
	434	121.1	15.1	21.2	27.2	104.3	13.0	20.6	23.5	-16.8	-0.6
	468	69.3	8.7	12.1	15.6	66.7	8.3	11.7	15.0	-2.6	-0.4
	416	192.5	24.1	33.7	43.3	284.4	35.6	49.8	64.0	91.9	16.1
	417	132.1	16.5	23.1	29.7	186.8	23.4	23.4	42.0	54.7	0.3
	425	104.8	13.1	18.3	23.6	108.1	13.5	18.9	24.3	3.3	0.6
	415	171.7	21.5	30.1	38.6	177.7	22.2	31.1	40.0	6.0	1.0
	423	150.8	18.9	26.4	33.9	140.1	17.5	24.5	31.5	-10.7	-1.9
	426	175.1	21.9	30.6	39.4	203	25.4	35.5	45.7	27.9	4.9
	428	143.2	17.9	25.1	32.2	71.59	8.9	12.5	16.1	-71.6	-12.6
	456	86.6	10.8	15.2	19.5	69.38	8.7	12.1	15.6	--17.2	-3.1

*: The lane miles from NJDOT Deployment Plan (2012) minus the lane miles in SLD (2009).

**: The salt tons needed from NJDOT Deployment Plan (2012) minus the salt tons needed based on SLD (2009).

B. Estimated Number of Plowing Trucks

North Region Plowing Worksheet
(Operating Speed: 15 mph, Service Time: 2 hours)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
210	5210261	3	5	2
	5210262	3	5	2
	5210263	3	4	1
211	5211261	5	8	3
	5211262	4	8	4
	5211263	5	8	3
212	5212261	4	5	1
	5212262	3	5	2
	5212263	3	3	0
	5212264	2	3	1
213	5213261	5	8	3
	5213262	5	5	0
	5213263	7	10	3
	5213264	5	6	1
	5213265	3	6	3
214	5214261	5	7	2
	5214262	6	7	1
215	5215261	4	7	3
	5215262	4	11	7
	5215263	3	8	5
	5215264	2	3	1
216	5216261	6	5	-1
	5216262	5	8	3
	5216263	5	8	3
217	5217261	3	5	2
	5217262	3	5	2
	5217263	4	8	4
	5217264	4	11	7
	5217265	4	10	6
218	5218261	4	5	1
	5218262	4	7	3
	5218263	5	7	2
	5218264	4	7	3
219	5219261	5	6	1
	5219262	3	3	0
	5219263	5	6	1
	5219264	4	6	2
	5219265	3	3	0
	5219266	2	4	2
220	5220261	4	8	4
	5220262	6	12	6
	5220263	5	6	1
	5220264	4	4	0
	5220265	5	6	1
221	5221261	4	8	4
	5221262	5	8	3
	5221263	4	4	0
	5221264	4	4	0
	5221265	9	6	-3

*: Information obtained from NJDOT 2012 Bid Sheet.

**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

North Region Plowing Worksheet (Continued)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
222	5222261	3	4	1
	5222262	3	3	0
	5222263	4	5	1
	5222264	4	4	0
223	5223261	6	9	3
	5223262	4	5	1
	5223263	3	4	1
224	5224261	3	3	0
	5224262	3	3	0
	5224263	3	3	0
225	5225261	6	12	6
	5225262	3	7	4
	5225263	4	6	2
	5225264	5	10	5
226	5226261	3	4	1
	5226262	4	7	3
	5226263	3	7	4
	5226264	9	10	1
	5226265	2	6	4
227	5227261	4	5	1
	5227262	3	7	4
	5227263	3	3	0
	5227264	4	7	3
228	5228261	4	13	9
	5228262	4	10	6
	5228263	3	3	0
	5228264	4	5	1
	5228265	3	6	3
229	5229261	3	3	0
	5229262	3	3	0
	5229263	4	4	0
230	5230261	3	4	1
	5230262	2	3	1
	5230263	2	3	1
	5230264	4	3	-1
231	5231261	3	3	0
	5231262	2	3	1
	5231263	3	3	0
	5231264	3	3	0
245	5245261	5	10	5
	5245262	5	8	3
246	5246261	3	3	0
	5246262	4	5	1
250	5250261	5	5	0
	5250262	5	8	3
	5250263	3	6	3
256	5256261	2	3	1
	5256262	2	3	1
	5256263	4	6	2
265	5265261	5	5	0
	5265262	4	5	1

*: Information obtained from NJDOT 2012 Bid Sheet.

**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

Central Region Plowing Worksheet
(Operating Speed: 15 mph, Service Time: 2 hours)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
310	5310261	5	8	3
	5310262	4	8	4
	5310263	3	4	1
	5310264	3	4	1
	5310265	2	4	2
311	5311261	3	10	7
	5311262	3	6	3
	5311263	3	6	3
	5311264	2	5	3
	5311265	3	6	3
312	5312261	3	4	1
	5312262	2	3	1
	5312263	6	8	2
313	5313261	5	5	0
	5313262	4	5	1
	5313263	3	5	2
	5313264	3	5	2
314	5314260	6	6	0
	5314261	4	5	1
	5314262	2	2	0
	5314263	4	3	-1
	5314264	5	7	2
	5314265	4	7	3
	5314266	5	7	2
	5314267	3	3	0
	5314268	3	6	3
	5314269	3	5	2
317	5317261	5	7	2
	5317262	4	4	0
318	5318261	4	3	-1
	5318262	3	3	0
	5318263	3	5	2
	5318264	5	8	3
319	5319261	5	8	3
	5319262	4	6	2
	5319263	3	6	3
	5319264	4	6	2
320	5320261	5	8	3
	5320262	4	6	2
	5320263	4	4	0
	5320264	4	7	3
	5320265	4	6	2
321	5321261	6	6	0
	5321262	5	7	2
	5321263	3	3	0
	5321264	5	6	1

*: Information obtained from NJDOT 2012 Bid Sheet.

**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

Central Region Plowing Worksheet (Continued)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
324	5324261	4	6	2
	5324262	3	5	2
	5324263	3	6	3
	5324264	4	7	3
	5324265	4	3	-1
	5324266	4	5	1
325	5325261	2	6	4
327	5327261	3	3	0
	5327262	4	5	1
	5327263	4	3	-1
	5327264	4	5	1
	5327265	3	3	0
329	5329261	3	6	3
	5329262	5	7	2
	5329263	4	4	0
	5329264	4	8	4
330	5330261	2	4	2
	5330262	1	5	4
	5330263	3	6	3
	5330264	4	6	2
	5330265	3	3	0
	5330266	3	3	0
331	5331261	2	4	2
	5331262	4	6	2
	5331263	4	6	2
	5331264	1	5	4
332	5332261	3	5	2
	5332262	4	6	2
	5332263	5	8	3
	5332264	5	8	3
	5332265	3	4	1
	5332266	2	4	2
333	5333261	4	5	1
	5333262	6	8	2
	5333263	4	3	-1
334	5334261	4	3	-1
	5334262	2	3	1
	5334263	7	5	-2
335	5335261	5	7	2
	5335262	5	8	3
	5335263	4	6	2
	5335264	2	3	1
	5335265	3	4	1
336	5336261	4	4	0
	5336262	5	7	2
	5336263	4	7	3
	5336264	3	6	3

*: Information obtained from NJDOT 2012 Bid Sheet.

**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

Central Region Plowing Worksheet (Continued)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
337	5337261	4	6	2
	5337262	4	4	0
	5337263	6	7	1
	5337264	3	4	1
338	5338261	8	7	-1
	5338262	5	7	2
	5338263	4	5	1
	5338264	5	5	0
339	5339261	3	4	1
	5339262	5	6	1
	5339263	6	8	2
	5339264	3	6	3
356	5356261	4	6	2
	5356262	5	6	1

*: Information obtained from NJDOT 2012 Bid Sheet.
**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

South Region Plowing Worksheet
(Operating Speed: 15 mph, Service Time: 2 hours)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
410	5410261	6	6	0
	5410262	6	8	2
	5410263	4	6	2
	5410264	5	7	2
411	5411261	4	10	6
	5411262	4	10	6
	5411263	5	10	5
413	5413261	4	5	1
	5413262	5	4	-1
	5413263	3	3	0
	5413264	5	10	5
	5413265	4	10	6
414	5414261	6	5	-1
	5414262	5	6	1
	5414263	5	8	3
	5414264	2	5	3
415	5415261	4	6	2
	5415262	5	6	1
	5415263	3	7	4
	5415264	5	5	0
	5415265	3	5	2
416	5416261	7	6	-1
	5416262	5	8	3
	5416263	5	4	-1
	5416264	2	3	1
	5416265	2	3	1

*: Information obtained from NJDOT 2012 Bid Sheet.
**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).

South Region Plowing Worksheet (Continued)

Crew ID	Snow Section ID	No. of Trucks (Plowing Model)	No. of Trucks (NJDOT)*	Difference**
417	5417261	3	4	1
	5417262	2	4	2
	5417263	2	3	1
	5417264	5	12	7
	5417265	4	5	1
420	5420261	2	2	0
	5420262	5	4	-1
	5420263	4	3	-1
	5420264	2	3	1
	5420265	2	3	1
	5420266	5	6	1
	5420267	2	3	1
421	5421261	4	3	-1
	5421262	4	6	2
	5421263	3	4	1
	5421264	6	5	-1
423	5423261	8	8	0
	5423262	3	5	2
	5423263	4	6	2
425	5425261	4	5	1
	5425262	5	6	1
	5425263	2	4	2
426	5426261	5	8	3
	5426262	4	7	3
	5426263	5	3	-2
	5426264	4	3	-1
	5426265	3	3	0
428	5428261	8	8	0
	5428262	6	7	1
	5428263	2	5	3
430	5430261	4	4	0
	5430262	5	8	3
	5430263	3	6	3
	5430264	5	4	-1
	5430265	4	4	0
434	5434261	1	4	3
	5434262	5	4	-1
	5434263	2	4	2
	5434264	3	3	0
	5434265	3	4	1
456	5456261	4	4	0
	5456262	5	6	1
445	5445261	5	6	1
	5445262	6	6	0
468	5468261	7	8	1

*: Information obtained from NJDOT 2012 Bid Sheet.

**: No. of trucks (NJDOT) minus No. of trucks (Plowing Model).