**EVALUATING THE USE OF TOW PLOWS IN MICHIGAN**

**MDOT RESEARCH PROJECT NO. OR14-006**

**MDOT CONTRACT NO. 2013-0065**


**By**

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**Definitions and Acronyms for Winter Maintenance Equipment**

The following definitions and acronyms are introduced for readers to understand the terms used throughout this report.

1. Winter Maintenance Truck (WMT) - A single or tandem winter maintenance truck with an underbody blade and/or wing plow. Also denoted as a regular plow truck or plow truck. A typical WMT is shown in the following figure.

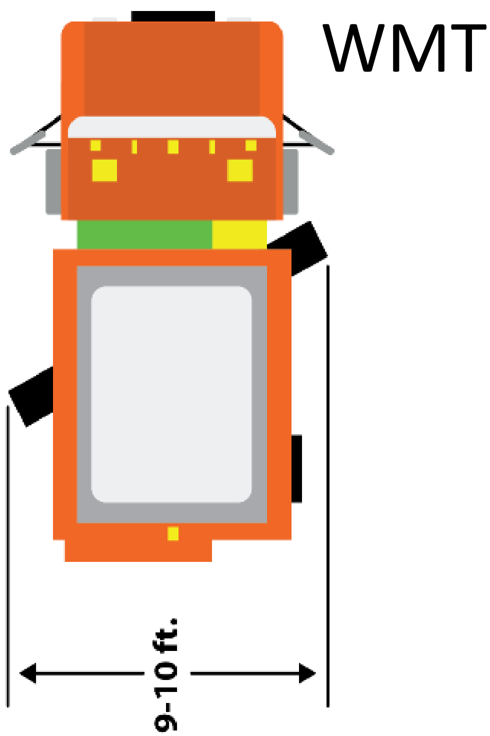



**Figure 1: Typical Winter Maintenance Truck (WMT)[1]**

2. Tow Plow (TP) - Only the Tow Plow trailer unit without the regular WMT used as the tow vehicle. Acronym TP is used in the friction evaluation section of the report since pavement friction data were collected behind the TP and WMT (tow vehicle).
3. Tow Plow Combo Unit (WMTP) - A Tow Plow trailer with a tandem winter maintenance truck (WMT) as the tow vehicle. This combination can clear two lanes in one pass. A typical WMTP is shown in the following figure.

[1] Graphics provided by MDOT

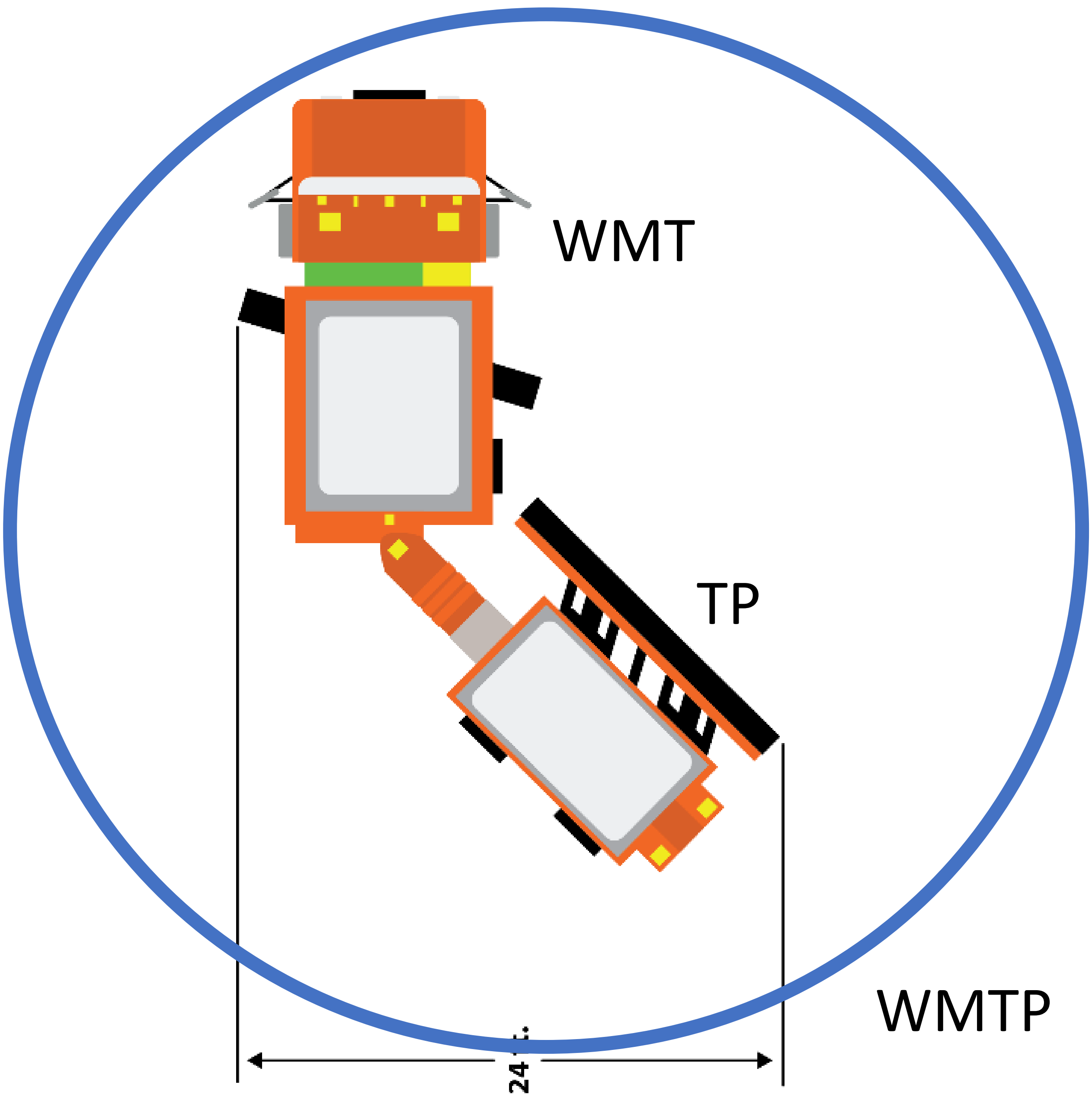



**Figure 2: Typical Tow Plow Combo Unit (WMTP)[2]**

[2] Graphics provided by MDOT.

# EXECUTIVE SUMMARY


The Michigan Department of Transportation (MDOT) purchased several TPs for winter maintenance operations. These units combined, with regular plow trucks (Tow Plow Combo Units or WMTPs), were distributed among numerous maintenance garages that started operating the plows beginning in late 2012. The main goal of this research study was to estimate the cost-benefits of incorporating WMTPs in the winter maintenance equipment fleet in addition to determining the most effective way of using them in terms of overall cost, mobility challenges, and the safety of the traveling public.

The research project was divided into several tasks: perform a literature review, implement a "Tow Plow usage survey" among highways agencies located the snowy regions of the United States and Canada, carry out a field evaluation of TP usage, and analyze winter maintenance cost data. Based on these tasks, the research team was able to determine the benefits of using TPs for winter maintenance activities as well as the most effective ways of using them in the equipment fleet.

Our research also provided additional information relative to winter performance measures as the project came to a close. The measures included winter pavement condition monitoring, pavement friction analysis, and collection of winter travel data. These performance measures can be further refined by highway agencies to estimate the effectiveness of winter maintenance practices and methods.

The initial comparison of visual pavement condition data and pavement friction data collected behind TPs and regular WMTs during winter storms showed no statistically significant difference in pavement friction values. This observation demonstrates that there was no measurable difference in snow removal capabilities between WMTPs and regular WMTs. The only difference observed was an increase in traffic congestion behind WMTPs when compared to regular WMTs during winter maintenance operations. However, the delay cost analysis during winter storm events showed the total delay cost due to a storm event was reduced when a WMTP was used in the snow removal maintenance fleet.

Several relationships between winter maintenance cost elements (labor, salt, equipment and travel delay) and snowstorm severity (in terms of snow amount) were developed for two equipment fleet configurations. These configurations included WMTPs present in the equipment fleet and WMTPs absent in the equipment fleet. Analysis of these two equipment configurations identified the benefits of using WMTPs in the equipment fleet for certain roadway types and at certain winter storm severity levels. The developed relationships also showed that regular WMT to WMTP equivalency varies with snowstorm severities. These relationships were used to develop the most effective equipment fleet configurations for different MDOT snow routes. Finally, an implementation guideline with recommended equipment configurations for different MDOT snow routes was developed and presented to MDOT winter maintenance engineers.

Based on the cost-benefit analysis of using 12 WMTP units[3] on six-lane and four-lane expressways, MDOT can save approximately $1.35 million annually by using the recommended equipment configuration. The above analysis was based on the direct cost of winter maintenance such as equipment rental rates, salt cost and labor cost. If the total cost of winter maintenance also included travel delay costs, the cost savings of using WMTPs was substantially higher than the direct cost savings.

Savings can also be obtained when using WMTP units in the current equipment configuration. When applying the analysis of four-lane and six-lane expressway cost data, the total cost (direct cost and travel delay cost) savings are 62.5%. Sixty-five percent of this savings comes from four-lane expressway winter maintenance while 27% comes from six-lane expressway winter maintenance.

The purchase of three more TPs together with new/retrofitted tandem WMTs to service MDOT-maintained expressways in seven MDOT regions is recommended. This purchase will increase the total WMTP fleet to 17 units. By using the recommended equipment configurations for four-lane and six-lane expressways, the expected annual direct cost savings is $1.9 million. Since MDOT only maintains 30% of the expressways in the state, even greater savings can be realized if WMTPs are used by county maintenance agencies. The total direct cost savings for county-maintained expressways will yield an annual savings of $4.8 million if the county agencies purchase 42 WMTP units and follow recommended equipment configurations.

[3] While MDOT has 14 WMTPs, only 12 were utilized last year.

# CHAPTER 1: INTRODUCTION

Over 70% of highways in the United States, including those in Michigan, are located in snowy regions. According to the Federal Highway Administration's Road Weather Management Program, 70% of the nation's population is concentrated in these same regions. For the State Departments of Transportation (DOT) in these regions, the clearing of snow and ice accounts for more than 20% - 30% of their maintenance budget. Last winter in Michigan, the average cost per lane mile for winter maintenance was $3,100 for snow plowing and salting. Due to the rising costs of winter maintenance, as well as environmental concerns related to the use of salt, MDOT has implemented a number of innovative approaches to enhance winter maintenance operations. These include pre-wetting roadways, applying alternative de-icing and anti-icing products, utilizing Road Weather Information Systems (RWIS), etc. Another potential tool is the TP which has been evaluated by other state DOTs and Canadian provinces. The TP is a trailer-mounted snowplow with a 26-foot blade. When attached to a traditional snow plow with a 12-foot front plow, the combination can clear a 25-foot wide path. Recently MDOT purchased several TPs and is assessing the effectiveness of the TP in terms of efficiency, cost-effectiveness, and safety.

The TP, the brainchild of a Missouri Department of Transportation employee, is now commercially manufactured by Ontario-based Viking-Cives Ltd.  It is a trailer with a 26-foot snow blade that is towed behind a traditional WMT.  The operator of the WMT can steer the TP to the right of the truck thus enabling the operator to clear a second lane while plowing/clearing snow in the driving lane. In combination with a front/underbody snow plow, the TP can clear a 25-foot wide path when operating at a 30-degree angle. The operator can hydraulically steer and control the blade using in-cab controls.  For optimal performance, the TP needs ballast on the trailer wheels. Based on the user needs, this is accomplished by adding 1000 gallons of liquid (into a poly tank) or eight cubic yards of material (into a hopper).

According to the manufacturer, the TP is ideally suited for multilane highways.  Instead of making four to five passes using a traditional WMT, the TP paired with the traditional WMT (WMTP) can clear the highways in only two to three passes. The manufacturer estimates this will save approximately 30% of the snow maintenance costs while improving service.  The effectiveness of the WMTPs can be measured against traditional WMTs by comparing route cycle times, time needed to meet a defined level of service, mobility of public during plowing operations, and performance of snow plowing based on measured friction values.

## 1.1 Research Approach

The overall goal of this research project is to evaluate the effectiveness of the WMTP relative to conventional snow removal techniques. The scope of work of this project includes:

1. Understand the current state of practice for TPs across the nation.

2. Learn the benefits/drawbacks of utilizing a TP.
3. Understand the most efficient use of TPs in Michigan.
4. Develop training materials for operators on the safe and effective use of TPs.

The following work plan was developed to achieve the above objectives.

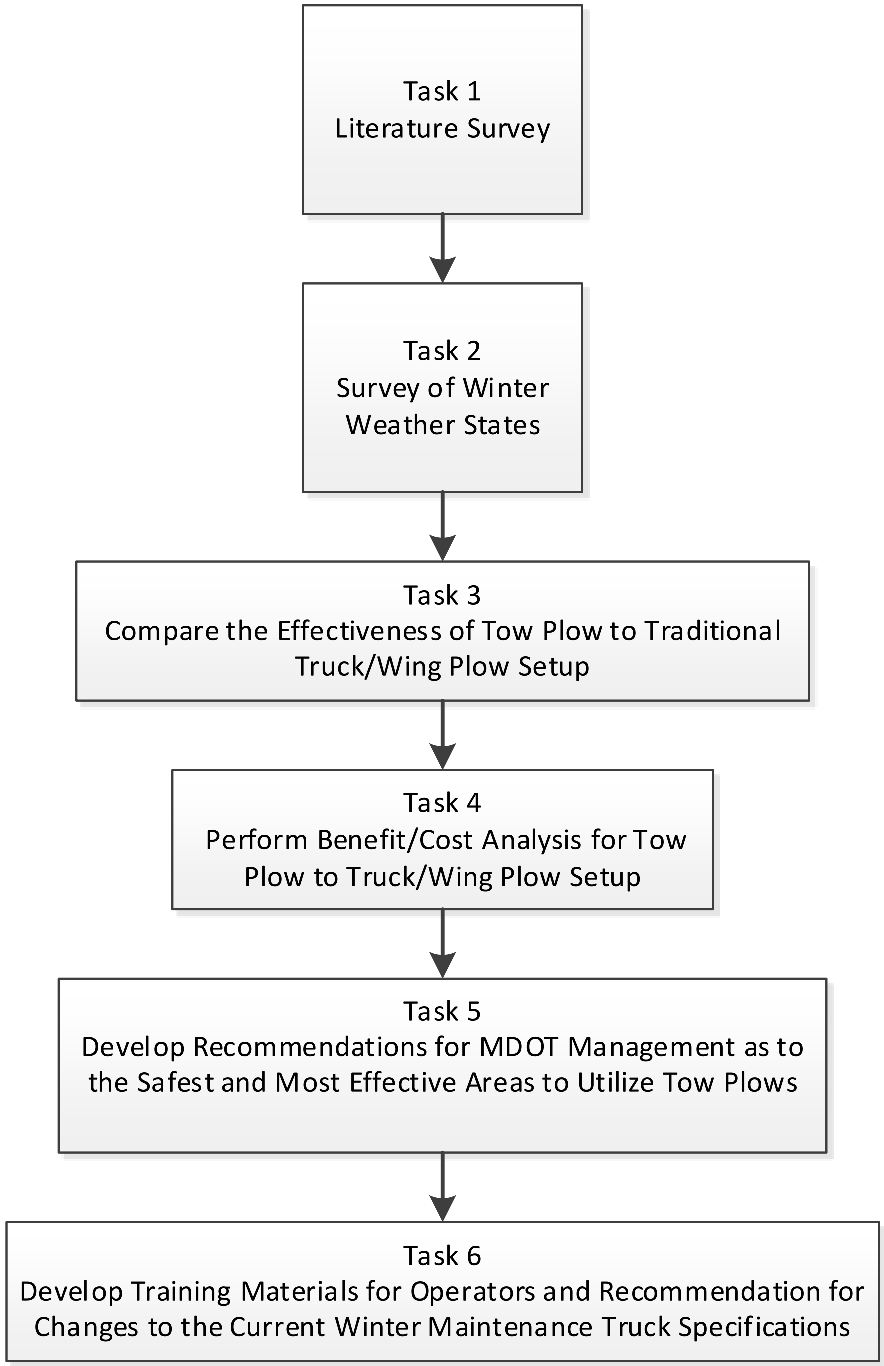



**Figure 1.1: Project Work Plan**

# CHAPTER 2: LITERATURE REVIEW

To obtain state-of-the-practice information on TP technology, as well as performance measurement and cost-benefit analysis data of winter maintenance, a literature review was performed during this study. The details of the literature review results were divided into three subtopics: TP Implementation, Performance Measurement of Winter Maintenance Operations and Cost-Benefit Analysis of Winter Maintenance Operations.

## 2.1 Tow Plow (TP) Implementation

### 2.1.1 AASHTO Closeout Report

The American Association of State Highway and Transportation Officials (AASHTO) Technical Implementation Group (TIG) selected the TP as a focus technology (*TIG Closeout Report*, AASHTO, 2012). A Lead States Team (LST) was identified and charged with the responsibility of providing transportation agencies with enough information about TPs to allow these agencies to soundly implement this technology. A follow-up survey carried out by the LST showed an increase in the number of agencies recognizing the substantial benefits associated with TP usage. From 2010 to 2012, the number of TP owners increased from 76 to 113, further highlighting acceptance and implementation of this technology. There were, however, some states that were unlikely to adopt the use of TPs. They cited the following factors:

- The initial cost of the TP is prohibitively high.
- TPs are limited solely to snow removal.
- Snowfall is minimal and traditional WMTs offer more versatility.

Those agencies likely to adopt the technology highlighted cost savings, safety, mobility and operational improvements as advantages of using the TP for winter maintenance. As the Tow Plow Combo Unit (WMTP) can clear two lanes in a single pass, the cost efficiency feedback included the ability to:

- Maintain the same level of service with less staff.
- Clear more miles of roadway with existing staff.
- Decrease snow removal cycle times.

Safety measures provided by the WMTP include:

- A reduction in the number of snow removal cycles providing the public with more driving hours on safer roads.
- The ability to better navigate around obstacles as compared to the fixed plows.
- A reduction in operator fatigue as a result of fewer passes for snow removal.

The WMTP reduces delays and increases mobility as it can operate at faster speeds when compared to the traditional plow truck (WMT). Since WMTPs clear more snow per cycle than traditional WMTs, less fuel will be used thus lowering the carbon footprint per cycle per weather event.

Operational improvements reported in the survey include:

- Decreased WMTP cycle time due to one pass clearing a wider path.
- Potentially higher operating speeds.
- The ability to quickly reposition or relocate the snow removal equipment in preparation for an event.
- Increased reliability due to the TP's long service life (estimated at 30 years or twice the life of an average WMT).
- Extended plow blade life due to reduced down force.
- Fewer snow removal trucks on the road.
- Fewer truck unit trips to resupply treatment materials.

WMTPs also offer advantages in congested urban areas with left turn lanes, islands and commercial entrances, as one less pass is needed due to the width and maneuverability of the TP. On rural divided four-lane highways, one WMTP and one traditional WMT can clear both the driving and passing lanes and the shoulder in a single pass. On two-lane roadways with paved shoulders, one WMTP can clear the driving lane and the shoulder. The WMTP's ability to clear 25 feet in one pass also lowers the chances of snow being redeposited because the snow is pushed further off the road. If equipped with liquid tanks or granular spreaders, the WMTP can be used as an anti-icing or de-icing treatment device.

Answers to some of the frequently asked questions by the states are given below.

*Does the use of the Tow Plow require any special training for my operator?*

> The use of a Tow Plow does not require special training; however, some training is needed. Operators should familiarize themselves with the equipment in a controlled area prior to taking it on the highway. The Missouri DOT has developed a 12-hour Tow Plow training class.

*How does the public respond to a Tow Plow? Are you experiencing accidents involving Tow Plow operations?*

> The Minnesota and Utah DOTs have been running the Tow Plow for two and three winter seasons, respectively, and have not experienced any Tow Plow-related accidents or problems.

*We are a state that uses wings. Are there any benefits for us to add a Tow Plow?*

There are various benefits the Tow Plow has over the wing plows, some of which include:

- Fewer controls than the wing plow.
- Wider clearing path.
- Faster operating speeds.
- Treatment of multilane highway with salt/brine while clearing snow with the same pass.

*Do I need any special truck horsepower, hydraulic, or cooling requirement to pull a Tow Plow?*

A larger truck with a minimum of 350 hp and available hydraulic circuits to operate the Tow Plow are required. Some states use a horsepower rating of 450 hp.

*I can see value on multilane roads, but are there benefits to using a Tow Plow on a two-lane/two-way highway?*

Tow Plow truck use is beneficial on two-lane roadways where shoulders, auxiliary climbing, or alternating passing lanes need clearing. On these kinds of roads, the truck allows for wider sections to be cleared with limited passing.

### 2.1.2 Ohio Department of Transportation Tow Plow (TP) Evaluation Report

For testing during the 2010-2011 winter season, Viking-Cives, Ltd., loaned a TP to the Ohio Department of Transportation (ODOT)'s Ashtabula County (Viking-Cives, Ltd., *Tow Plow Evaluation, Ohio Department of Transportation*, May 2011). The county utilized the TP on three different routes throughout the winter: State Route 11 (SR 11), Interstate 90 (I-90), and US Highway 20 (US-20). All three routes are similar in that they are multilane, but each route has a unique characteristic that presented a wide range of testing scenarios and challenges. The following was reported:

- There were no noticeable challenges on SR 11 due to low volume of traffic.
- Challenges on I-90 included:
  - The inability to turnaround at the normal crossover location because of the length of the TP.
  - Difficulty in viewing traffic behind the TP.
  - The camera behind the tow vehicle was rendered useless because it was covered in snow.
- Challenges on US-20 included:
  - Difficulty maneuvering the TP through obstacles.
  - Keeping the TP off the curbs.

The tow vehicle utilized by Ashtabula County was modified to accommodate the TP and help the driver operate the system safely. Modifications to the tow vehicle included: purchasing a truck with added horsepower and torque to increase towing performance, clearly identifying the hydraulic lines for easier trailer connection, and moving the material spreader under the truck frame behind the cab to enhance material application coverage (the current application is altered by the trailer tongue).

Other modifications to the TP included the addition or installation of: a poly tank for pre-wetting salt, a laser alignment system to define the edge of the plow, a camera at the rear end of the TP to view traffic behind the unit, and a hub-odometer on the trailer wheel to track the TP's usage.

The drivers of the WMTP underwent extensive individual training which included: learning the general aspects of towing and controlling the unit in a closed parking lot, two to three-day dry run training on routes where the TP was to be utilized, and being accompanied by a manger during the first operation in snow and ice conditions.

Some of the driver feedback after operations included:

- The in-cab controls for the TP are simple to operate and do not interfere with other controls.
- The weight of the TP does not jerk the tow vehicle from side to side.
- The TP is clearly visible via the passenger side mirror and camera.
- The traffic behind the unit can be difficult to see.
- The WMTP was faster than the regular WMT and very efficient.

As the public recognized the effectiveness of the WMTP to improve road conditions, their opinion of it was very positive.

Ashtabula County successfully incorporated the TP into their snow and ice operations. With the aid of the TP, the county more efficiently plowed and treated the roadways, thereby reducing overall usage of fuel, labor, and material resources while providing a higher level of service and safer pavement conditions for the traveling public.

### 2.1.3 Summary of the Use of Tow Plows (TPs) on an Arterial Highway in Northern New Brunswick

Brun-Way Highway Operations (Brun-Way), Inc., integrated the TP in their echelon plow train (*Tow Plows-One Operator: The Use of Tow Plows in an Arterial Highway in Northern New Brunswick*, Mike Corbett, Romes Poitras, Annual Conference of the Transportation Association of Canada, 2009). In order to be considered compliant with the New Brunswick Department of Transportation (NBDOT) vehicle licensing and safety requirements, Brun-Way WMTPs required several modifications. Other modifications were also made to suit Brun-Way snow and ice control processes. Brun-Way actively practices anti-icing, pre-wetting, and other salt-reduction strategies, so the TPs were retrofitted to be used in these circumstances. Following are the modifications required by Brun-Way:

- Fenders - During deployment, the tires of the TP were not adequately covered by the fenders, as the wheels skewed and the fenders stayed in place. Cycle fenders were added and modified to move with the wheels.
- Lighting - In addition to the normal lighting required when the unit was in “trailer mode,” two additional high-mounted strobe lights were added.
- Rear Bumper - The rear bumper was chamfered at 30 degrees on both sides to address collision concerns while the unit was deployed.
- Deflectors - Hard plastic deflectors were installed on the top edge of the plow blades to reduce snow “kick up.”
- TP Light Bracket - When deployed, a light bracket on the side of the TP became a point of potential impact for vehicles encroaching on the TP. This mount was remanufactured to become “break away” if hit.
- Mold Boards - The back end of some of the plow mold boards were cut off at an angle to allow the blade to come closer to the guiderail when plowing.

For safe and efficient operations, Brun-Way also implemented training programs for their operators.

Dynamic performance of the TP was questioned, specifically whether it was prone to rollover when deployed. The TP was compared to a tandem axle gravel end-dump pony trailer (the most common pony trailer). The following were noted:

- The tare weight of the two trailers is comparable, but the tare center of gravity of the TP is about 0.74 meters above the ground, while that of a gravel pony trailer is about 1.52 meters.
- The gravel pony has a payload of approximately 12 tons at a center of gravity of about 1.73 meters, while a TP with two brine tanks (Brun-Way configuration) would have a payload of approximately 9 tons at a center of gravity about 1.52 meters.
- The TP has single tires which give a greater effective track width than the dual wheels on a pony trailer.
- The TP has no suspension while the gravel pony has a flexible suspension.

All these factors favored the TP for dynamic performance.

In past winters (2008-2009), Brun-Way instituted new plow routes designed to shorten cycle times and optimize equipment use. In addition, a strategy for intense storms was introduced, whereby many of the routes were shortened and additional enhanced routes were added to ensure the winter operational standards were met. Brun-Way utilized echelon plowing (plowing of both lanes and shoulders in one pass). With increased experience in varying conditions, operators found various ways to improve the TP such as:

- Lower the brine nozzles closer to the road surface to reduce misting of the brine.
- Add two adjustable fire hose-style nozzles on the left side to improve brine application.
- Add a higher capacity brine pump with an application rate of 100 liters per lane kilometer.
- Connect the two brine tanks with a shut-off valve between them.
- Utilize the TPs for hauling water and add a pump and fire hose for use in bridge washing operations in the spring.
- Add an arm to the rear of the TP that deploys similarly to a school bus arm, to prevent vehicles coming into the area between the truck and the TP when the TP is deployed.

The Brun-Way training program for staff and sub-contractors consists of:

- Brun-Way Quality/Safety/Environmental (QSE) awareness that discusses quality, safety and environmental issues as they relate to winter maintenance activities; also covered are an overview of RWIS (Road Weather Information System) and the science of materials used for anti-icing and de-icing.
- Equipment training on the control mechanisms installed in or attached to the plow, loaders and other winter maintenance equipment.
- Safety training related to personal safety and job specific training in accordance with the Brun-Way safety management systems and occupational health and safety act and regulations.
- Brine production system training which includes training staff in the manufacturing and monitoring process for brine.
- Automated vehicle location/GPS training and record keeping.
- RWIS training on data interpretation and forecasting for decision makers.
- Snow and ice control training which includes a detailed analysis of anti-icing, de-icing techniques and abrasive application.
- Traffic control training.
- Safe driving practices training.

As the public is not familiar with the TP, there are issues the operator of the WMTP may face during operations. Some of these issues are:

- Road users attempting to pass around the WMTP during operation.
- Vehicles potentially losing control from large windrows generated by the TP.
- Road users unaware that the TP often shifts from tracking mode to trailer mode.

To proactively address these issues, Brun-Way has attempted to educate the public through the local media. Some of the ways in which it achieved this include:

- Appearing on local radio stations during storms to provide updates on road conditions and to caution drivers to go slow and stay behind the WMTP.
- Providing local newspapers with media kits discussing the Brun-Way snow and ice control methods and a plea for road users to be patient and cautious during winter conditions.
- Providing the opportunity for local reporter to ride behind the WMTP and WMTs during operations to get an understanding of the winter operations.
- Meeting with truck companies and the Atlantic Provinces Trucking Association to convey the message.

Some of the benefits realized with the TP include:

- Fuel savings, albeit minimal as a result of the hilly terrain of western New Brunswick.
- Cutting edges on the TP last for the entire winter season while those of standard plows need to be changed at least twice a season.

Opportunities for improvement include:

- Incentives are required to ensure that more operators are interested in using the TP. The TP needs to be more user-friendly.
- Actual savings need to be identified. This should include fuel and maintenance costs for two WMTs versus the TP.
- The visibility of the TP for the operator requires improvement so that the operator can see the TP in all conditions.
- Improvements to the hydraulic cylinders were planned for the 2009-2010 winter to ensure quicker response to the deployment of the plow in order to avoid hitting guiderail end treatments.
- Investigate methods to ensure that following vehicles stay behind the WMTP and do not go behind or beside the WMTP when the TP is deployed.
- On plow routes containing vertical alignments with more than a 4% grade and in storm conditions with heavy, wet snow, more horsepower and torque are required in order to maintain an acceptable speed.

### 2.1.4 Summary of the Evaluation of the Performance of Automatic Vehicle Location (AVL) and Tow Plow (TP) for Winter Maintenance Operations in Wisconsin

The significant increase in winter maintenance costs since the 2006-2007 winter motivated the Wisconsin Department of Transportation (WisDOT) to implement new technologies for winter maintenance operations (*Evaluation of the Performance of AVL and Tow Plow for Winter*

*Maintenance Operation in Wisconsin*, Transportation Research Board Annual Meeting, 2012). During the 2009-2010 winter season, WisDOT started implementing new technologies, two of which are the TP and AVL. Only the details related to the TP evaluation are presented below.

WMTPs are currently used by over a dozen states in the United States as well as in Canada. Some of the benefits of this new technology include their ability to:

- Carry extra treatment material such as granular salt or liquid brine.
- Clean an extra lane of highway without the need for an additional WMT.
- Alleviate some of the problems of gang plowing, i.e. having multiple WMTs travelling next to each other to clean a highway segment in one pass.
- Reduce capital costs by eliminating the need to acquire new WMTs.

Qualitative evaluations performed with the driver of the WMTP and the Marquette County highway commissioner highlighted the following concerns:

- The negative reaction of highway users to the WMTP.
- Increased mental workload as a result of the driver being more vigilant than usual because of the weight of the TP.
- Poor maneuverability at median crossovers and the inability to perform ramp cleanups.
- Increased fuel consumption as a result of the weight of the TP.
- Impacted the type of truck used due to the weight of the TP. In Eau Claire County, the TP was operated using a tandem axle 330 hp truck.
- Reduced travel distance when treating roads with granular salts as a result of the TP having a smaller salt container.
- Reduced speeds of about 5 mph when compared to the traditional WMTs.

A comparison of fuel and labor costs required for snow removal of a lane of the same width using a WMTP was $71.67/hour and a regular WMT was $125.60/hour. The resulting cost per hour of using a WMTP was 43% lower than that of a regular WMT.

### 2.1.5 Iowa Department of Transportation Tow Plow (TP) Evaluation Report

The Iowa Department of Transportation (DOT) deployed three WMTPs as a pilot project in the Des Moines, Waterloo, and Sioux City areas during the 2010-2011 winter season (http://www.iowadot.gov/maintenance/TowPlows.html#, accessed July 12, 2013). The benefits of the WMTP, based on Iowa DOT's evaluation, included: more lanes plowed without adding additional WMTs and operators, improved productivity, reduced labor cost and fuel usage, anticipated 10-30% projected total savings based on other state usage, and extended plow blade life due to reduced down force.

The Iowa DOT's estimated cost of a TP was $73,000 when compared to $150,000 for a new WMT on the same route. A net operational cost savings of 34% was achieved for every hour the TP was operated. This conclusion was based on the fact that two WMT and two operators cost $115.04 per hour while one WMT, increased fuel costs, one operator, and one TP costs $78.22 per hour.

Based on the results of this evaluation, estimates indicated that the TP generally pays for itself in 1 to 5 years. However, this estimate may vary for other agencies based on the actual clearing path per pass, the frequency of and duration of snowstorms per year, as well as labor and actual fuel costs.

This evaluation suggested that no *special* training was required; however, *basic* training was required. Operators should become familiar with the TP in a controlled area prior to using it on the highway. The Iowa DOT is considering implementing the Missouri DOT 12-hour TP training class.

Most trucks that pulled the TPs were tandem axle plow trucks with a minimum of 350 hp and available hydraulic circuits needed to operate the TP. Some states use a horsepower rating of 450 hp.

### 2.1.6 Maine DOT's Second Year Evaluation of the Viking-Cives, Ltd., Tow Plow (TP)

In February 2009, the Maine Department of Transportation (DOT) entered into an agreement with Viking-Cives USA to evaluate the TP and provide feedback to Viking-Cives (*Technical Brief 10-4, Maine Department of Transportation, 2010*). The first year of this evaluation took place during the 2008-2009 winter season. The second evaluation took place during the 2009-2010 winter season. The same 2009 Volvo wheeler used in 2008-2009 for towing the TP was used during the 2009-2010 winter season. The TP-designated plow route was Route 1A, a two-lane highway with 32 miles of travel lanes and 5 miles of truck lanes. Overall the TP performed very well as a primary vehicle and needed only minimum assistance during one storm event.

Some of the concerns and observations highlighted in the evaluation include:

- The TP did not clean the pavement well when it was not fully extended compared to when it was in the fully deployed position (observations from both the operator and supervisor).
- According to the maintenance supervisor, the TP might have the most value in a more rural, interstate setting.
- Granular salt was distributed from the hopper on the TP at a rate of approximately 500 pounds per lane mile. The spinner was located about mid-point of the TP. When the plow was fully articulated, the position of the spinner was approximately 6 to 8 feet off centerline. Setting the spinner to rotate at a moderate rate, salt was applied to the travel lane at an acceptable level.

- Salt was not distributed from the tow truck (WMT) hopper when the TP was utilized. This salt was kept in reserve as ballast.
- Utilization of the TP on secondary, two-lane roadways created potential issues for the travelling public because traffic cannot pass due to the slow speeds of the TP (15 to 25 mph). However, one of the advantages of the slow moving traffic was that the salt stayed in place better and quickly created a bare and wet pavement surface.
- The biggest issue experienced was the time it took to hook up and remove the TP from the WMT (approximately 30 minutes for each operation).

Recommendations:

- Improve the salt application capability of the WMTP.
- Improve the pre-wetting system.
- Enable salt application from both the TP and WMT for interstate applications.
- Improve the hook up and removal procedures.
- Consider purchasing a laser alignment system.
- Increase the maximum horsepower of the WMT.

#### 2.1.7 Pennsylvania Department of Transportation (PennDOT) Innovation Information – Tow Plow (TP)

PennDOT evaluated the TP using the Experimental Project Process (*Innovation Information-Tow Plow*, Report No. 11B-10-36, Pennsylvania Department of Transportation, 2010). District 2-0 tested the plow on I-99 near the end of the 2009-2010 winter season. The TP showed potential during only one storm event. District 11-0 joined District 2-0 in testing the TP during the 2010-2011 season.

Benefits of the TP as reported by PennDOT include:

- The added weight of the TP increased truck fuel consumption by about 10-15%; however, when compared to using two WMTs to do the same job, this was a fuel savings of 85-90%.
- The TP can be used in a plow train in place of a truck that could be deployed on a different route, thus increasing overall level of service.
- The TP required standard plow and trailer maintenance – a savings compared to maintenance that a second truck and plow require.
- The TP can be used strictly for spreading/antiskid applications when plowing is not necessary.
- During non-winter months, the TP can be used as a water tank.

Points to consider when making a TP investment:

- The cost of a TP purchased through PennDOT's Plow contract was $73,790.
- Required WMT modifications costing $15,500 included a rear hitch module, hydraulic upgrade, and two in-cab controls; no engine or transmission changes were necessary.
- If the tow vehicle goes down for maintenance, then the TP is out of service unless another truck with the required modifications is available.
- The TP can be configured for anti-icing at a cost of $25,820, or with an 8-cubic yard granular material hopper at a cost of $18,184.
- Operators require overview and familiarization training, provided by the vendor.
- The TP should probably not be deployed in urban areas during periods of high traffic volume.

### 2.1.8 Ohio DOT (ODOT) Trailer Plow (TP) Evaluation for Winter Maintenance

Based on the positive results obtained during the 2011 pilot evaluation, ODOT conducted further research to compare the cost-effectiveness of using a TP when compared to traditional equipment used for winter operations (*Evaluation of the Viking-Cives Tow Plow for Winter Maintenance*, Schneider IV et al, 2014). The research was focused on collecting three main areas of data: weather, TP utilization, and travel speed in three counties that used a TP during the 2013-2014 winter season.

Using weather data obtained from National Oceanic and Atmospheric Administration (NOAA)'s three weather stations located in selected counties, winter storms were divided into five categories:

1. No snowfall
2. Trace snowfall - Less than 0.1 inch of total accumulation with peak snowfall rates less than 0.1 inches per hour.
3. Light snowfall - Between 0.1 and 2 inches of total accumulation with peak snowfall rates between 0.10 and 0.25 inches per hour.
4. Moderate snowfall - Between 2 and 6 inches of total accumulation with peak snowfall rates between 0.25 and 0.75 inches per hour.
5. Heavy snowfall - Greater than 6 inches of total accumulation with peak snowfall rates greater than 0.75 inches per hour.

If the snow event fell between two categories, the storm was placed in the higher category.

The TP utilization data were collected from installed video cameras along with a GPS unit and a digital video recorder (DVR) on two plows. These data were compared to a standard WMT equipped with a GPS-AVL system.

Vehicle speed data were collected using Bluetooth Nodes (BTN) placed along selected routes. To compare the effectiveness of the WMTP to a traditional WMT, a roadway (I-76) was divided into two treatment routes with the WMTP treating one side of the road while the traditional WMT treated the other side. The Bluetooth technology allowed for a controlled experiment and the research team was able to collect traffic speed data for each truck individually as well as the Level of Service (LOS) provided by each truck.

Using Monte Carlo simulation modeling on the collected data, the following annualized costs were obtained for the WMTP and the standard WMT.

**Table 2.1: Annualized Cost Summary (ODOT TP Evaluation Study, Schneider IV et al, 2014)**

| Equipment | Annualized Average Cost | Standard Deviation |
|---|---|---|
| WMTP (includes the truck towing the TP) | $83,629 | $12,568 |
| One Standard WMT (with a wing) | $62,212 | $10,865 |
| Equivalent Standard WMT (1.7 with wings) | $106,180 | $11,210 |

Note: The number of standard WMTs needed to match one WMTP (based on utilization data) is 1.7.

## 2.2 Performance Measurement of Winter Maintenance Operations

### 2.2.1 Performance Measures for Snow and Ice Control Operations

The purpose of this research was to identify and assess the measures used to evaluate the performance of winter maintenance activities and to recommend the most promising measures for further development (NCHRP Web-Only Document 136, Transportation Research Board, December 2007). The first part of this research entailed a comprehensive review of performance measures that have been and are currently being used by transportation agencies. The second part identified the most promising performance measures.

Agencies currently measure winter maintenance performance from one of three basic perspectives.

- Inputs - Input measures represent the resources spent or utilized to perform snow and ice control operations. These include fuel usage, labor hours, machinery or equipment hours, and units of anti-icing materials or abrasives. The level of inputs is directly proportional to agency costs.
- Outputs - Outputs quantify the resulting physical accomplishment of work performed using resources in winter maintenance. These include lane miles plowed or sanded, the number of lane miles to which de-icing materials were applied, lane miles to which anti–icing brine were applied, and other accomplishments of the maintenance process in units of work.
- Outcomes - Outcomes generally attempt to assess the effectiveness of the winter maintenance activity, very often from the perspective of the user or customer. Desired

outcomes of winter maintenance might include the improvement of safety, mobility, and/or user satisfaction, bare pavement regain time, duration and frequency of closure, advanced warning time to customers, and customer satisfaction indicated by customer satisfaction surveys.

Some of the notable performance measures included:

- Friction - There are different methods for measuring friction. Several different measuring friction devices can be mounted under a WMT or towed by a supervisor's vehicle.
- Bare pavement - The time to bare pavement is the most common measure of performance in the United States. State DOTs measure the time to reach bare pavement throughout the state trunk highway system and have different levels of satisfactory performance depending on the level of traffic at the time.

The survey of winter maintenance findings highlighted that most performance measures cited by respondents are tied to their accounting and management systems. These measures included lane-miles plowed, personnel and/or overtime hours, tons of material used, amounts of equipment deployed, cost of operations, time to bare pavement, time to return to a reasonably near-normal condition, length of road closures, and customer satisfaction. Budget and staffing constraints make experimenting with new technology difficult for agencies.

To identify measures and approaches that warrant further study, the following criteria were applied to the measures and approaches.

- Measure Criteria:
    - Does the measure directly quantify safety, mobility, or public satisfaction?
    - Does the measure improve snow and ice control?
    - Is the measure mapped to roadway segments?
    - Is the measure reported for garages or districts?
    - Is the measure sensitive to storm characteristics?
- Approach Criteria:
    - Is the approach quantitative?
    - Is the approach stable across observers?
    - Is the technology likely to improve?
    - Is a major capital or operational investment required?
    - Can the approach be piggybacked on another system to reduce installation costs?
- Measure: Degree of clear pavement
    - Approach: Manual observation
    - Approach: Camera-assisted observation
- Measure: Traffic flow
    - Approach: Detectors – speed, volume, and occupancy

    - Approach: Road closure
- Measure: Crash Risk
    - Approach: Friction (or slipperiness)
    - Approach: Reported crashes

A more effective and reliable winter maintenance program will be developed as more winter maintenance agencies adopt performance measurement practices. New technologies such as the automated vehicle location (AVL), global positioning system (GPS), friction meters, road weather information systems (RWIS) will help aid in obtaining the additional data required to enhance measuring performance.

### 2.2.2 Survey of State Practice Prepared by CTC & Associates LLC

Level of Service (LOS) is a measure used by transportation agencies to develop guidelines, classify routes, and coordinate winter maintenance activities (Wisconsin Department of Transportation Research and Library Unit, 2009). The Clear Roads winter maintenance pooled fund was interested in learning how snowy states use LOS to provide motorist safety and to effectively use limited resources. A brief survey was conducted of three groups: SNOW-ICE Listserv members, Clear Roads technical advisory committee representatives, and attendees of the 2007 National Winter Maintenance Peer Exchange. The survey results are as follows broken down by state:

**Table 2.2: Summary Survey Results**

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| Indiana | Class I = Interstate routes and roadways with ADT > 10,000 vehicles per day.<br><br>Class II = Routes between 5,000 and 10,000 ADT.<br><br>Class III = Routes with traffic volume less than 5,000 ADT. | No set performance measure standard. | No set procedure; however, it is up to the unit foreman, district and sub-district managers. | No set time devoted. |
| Iowa | Class I = Interstate routes and roadways with ADT > 10,000 vehicles per day.<br><br>Class II = Routes between 5,000 and 10,000 ADT.<br><br>Class III = Routes with traffic volume less than 5,000 ADT. | A and B level - Return to near normal winter conditions within 24 hours of storm end.<br><br>C level - Bare wheel path within 24 hours of storm end, return to near normal winter conditions within three days. | Self-reported by maintenance supervisors at each garage. | Monitoring of operations is done by garage supervisors, district personnel and central office during winter storms. |

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| Kansas | Category I Routes - Multilane highways and two-lane highways with AADT >3,000.<br>Category II Routes - Two-lane highways with AADT 1,000 to 3,000.<br><br>Category III Routes - Two-lane highways with AADT near or under 1,000. | None | Field personnel monitor road conditions and enter data into the Road Condition Reporting System (RCRS) | LOS on routes is monitored during each event. |
| Maine | Priority 1+ = Urban interstate over 20,000 winter ADT.<br><br>Priority 1 = Other interstate and major arterials.<br><br>Priority 2 = Lower volume arterials and high volume collectors.<br><br>Priority 3 = All remaining collectors. | Time until bare pavement. Also dependent on priority levels. | Observation by managers. | Varies from at least a few hours per storm for probably a dozen people. |

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| Maryland | Bare Pavement | Bare pavement on all interstate and primary roads within four hours. | Routes are monitored for a LOS at the maintenance shop level and data from all shops fighting winter storms are recorded in the Maryland State Highway Administration (SHA) Emergency Operation System (EORS). | The SHA's Office of Maintenance (OOM) spends several hours after a storm has ended reviewing shop data. OOM also utilizes RWIS data to help identify and resolve any data that appears out of range. |
| Massachusetts | Level I: Bare almost all the time.<br><br>Level II: Less than Level I. | Feedback from customers | Constant supervision by Massachusetts highway's personnel. | The whole time is spent monitoring in the most congested areas and areas where problems usually arise. |

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| Michigan | One to five categories based on corridor of significance to the State of Michigan. | Visual observations.<br><br>Priority #1 Orange routes: Pavement surface over its entire width generally bare of ice and snow.<br><br>Priority #2 Blue Route: Pavement surface generally bare of ice and snow wide enough for one-wheel track in each direction. | Garage supervisors are responsible for LOS being met on all corridors within the area. | Time devoted is dependent on the storm duration and severity. |
| Minnesota | Super Commuter, Urban Commuter, Rural Commuter, Primary and Secondary are determined by AADT's for each road segment. | Bare lane | After every snow event, post-storm meetings are held to discuss material usage and regain time. Reports are generated using Work Management System (WMS) to compare regain times to material usage per mile for all plow routes | See the comment on the monitoring method. |

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| Missouri | Clear, Partly Covered, Covered and Closed | Priority 1 routes are to be returned to a clear condition as soon as possible after the end of a storm.<br><br>Priority 2 routes are to be plowed open to two-way traffic and treated with salt and/or abrasives on hills, curves, intersections and other areas as needed as soon as possible after the end of a storm. | District maintenance personnel and supervisors monitor and report on the performance objectives. | Unknown |
| New Jersey (Township of Hamilton) | Primary and Secondary | Time (how long it took to complete spreading and/or plowing) and visual verification are utilized. | Geographic Information System (GIS) is utilized to monitor winter operations. Also, a supervisor report as visual verification that the quality of the job was satisfactory is utilized. | The duration of the event |

| State | Survey Question | | | |
|---|---|---|---|---|
| | Service Level Classification | Performance Measures | How are Routes Monitored? | Time Devoted to Monitoring? |
| New York | Regular LOS and Modified LOS. | Goal is to have roadways cleared shoulder-to-shoulder within two hours of end of storm. | Patrols by highway maintenance supervisors and radio reports from plow operators. | Patrols are done as time permits. |
| North Dakota | Urban Areas, Rural Interstate, Interregional, State Corridor, District Corridor, District Collector. | Desired recovery times are used. | The routes are monitored by our supervisors; it is a visual assessment. | There is no set time, but we monitor each storm event. |

### 2.2.3 Transportation Synthesis Report

Incorporating real-time road surface friction measurements into maintenance activities has the potential to increase efficiency and allow agencies to concentrate on areas experiencing the worst driving conditions (*Using Friction Measurements to Gauge Winter Maintenance Performance*, Wisconsin Department of Transportation Research and Library Unit, 2007). Highway agencies in Japan and Europe have been using this technology to evaluate winter road conditions and maintenance performances for many years. As the lead state for the Clear Roads pooled fund, the Wisconsin DOT Research and Communication Services Section carried out a study to identify whether friction measurements could be used as a realistic, effective and reliable maintenance performance indicator.

#### 2.2.3.1 State DOT's Experiences with Real Time Traction Tool (RT3)

The RT3 measures road surface friction under winter conditions using an auxiliary wheel that attaches to a truck undercarriage or can be towed behind a vehicle. The friction reading is presented to the operator as a colored light on a display. Green indicates safe driving conditions, yellow indicates where caution is needed, and red indicates dangerous areas where immediate attention is needed. Five agencies were interviewed about their experiences with the RT3. The Agencies included: Ohio DOT, Utah DOT, Virginia DOT, Wyoming DOT, and the Ontario Ministry of Transportation. These agencies have all utilized the RT3 technology as either a research testing instrument or as a winter maintenance performance monitor. All operators were confident that the collected data accurately represented the surface conditions.

#### 2.2.3.2 U.S. and International Research

**Feasibility of Using Friction Indicators to Improve Winter Maintenance Operations and Mobility.**

This research reviewed domestic and foreign practices on the use of friction indicators for winter maintenance, operations decision making and performance evaluation, and for providing information to motorists (NCHRP Web Document 53, 2002).

**Methods for Measuring and Reporting Winter Maintenance Activities**

Norway's winter friction project used several standards and measures, including a friction standard, to evaluate the performance of different friction improvement methods (such as salting and sanding) (T. Vaa, Transportation Research Record No. 1741 2001).

**The Potential of Friction as a Tool for Winter Maintenance**

This study explored the possibility of using friction as an operational tool in winter maintenance, with a focus on the relationship of friction to traffic volume, traffic speeds and accident rates (Final Report of Project TR 400, Iowa DOT, 1998).

**On-line Estimation of Friction Coefficients of Winter Road Surfaces Using Unscented Kalman Filter**

The authors of this study developed an online system that utilized an unscented Kalman filter to estimate the friction coefficient of winter road surfaces. The filter detected vehicular motion via a probe that was attached to a vehicle equipped with a GPS device and motion sensor (T.Nakatsuji, P.Ranjitkar, I.Hayashi, Hitachi Ltd.; T. Shirakawa and A. Kawamura, Transportation Research Board Annual Meeting, 2007).

**Joint Winter Runway Friction Program Accomplishments**

The program aims to standardize ground vehicle friction measurements and to establish reliable correlations between ground vehicle friction measurements and aircraft braking performance (Thomas Yager et al., Pavement Evaluation 2002 Conference, 2002).

### 2.3 Cost-Benefit Analysis of Winter Maintenance Operations

#### 2.3.1 Quantifying Safety Benefit of Winter Road Maintenance: Accident Frequency Modeling

Winter road safety is a source of concern for transportation officials in countries, such as Canada and the United States, that routinely deal experience severe weather conditions (Taimur Usmana, Liping Fua, Luis F. Miranda-Morenob, Accident Analysis and Prevention 42 (2010) 1878–1887). Driving conditions in winter can deteriorate very dramatically due to snowfall and ice formation, causing significant reductions in pavement friction that can increase the risk of accidents. The total cost of weather-related injuries in Canada is estimated at $1 billion[4] per year. Moreover, costs for winter road maintenance are estimated in Canada at $1 billion and over $2 billion in the United States. The substantial direct and indirect costs associated with winter road maintenance have stimulated significant interest in quantifying the safety and mobility benefits of winter road maintenance in terms of a systematic cost-benefit assessment. This research aims to investigate the effect of road surface conditions on accident occurrences under adverse winter weather conditions.

[4] US Dollars

To quantify the relationship between road safety and factors that could cause road accidents during snowstorms, an event-based modeling approach was used to explain the variation of accident frequencies across individual storm events. The proposed methodology included the following steps:

- Selection of study sites and data sources.

  Study sites:
  - 401-R1: Hwy 400 to Morning Side Ave (28.0 km)
  - 401-R2: Trafalgar Road to Hwy 400 (31.1 km)
  - QEW-R1: Burloak Drive to Erin Mills Parkway (17.4 km)
  - QEW-R2: Erin Mills Parkway to East Mall (13.1 km)

  Data sources:
  - Traffic volume data
  - Traffic accident data
  - Road condition weather information system (RCWIS) data
  - Road weather information system (RWIS) data
  - Environment Canada (EC) data

- Data processing:

  Once the five types of available data of each selected study site were obtained, they were pre-processed for merging and integration.

- Modeling of road surface conditions:

  The road surface condition index (RSI), a surrogate measure of the commonly used friction level, was introduced to represent different RSC (Road Surface Conditions) classes described in RCWIS (Road Conditions Weather Information System). RSI values for major road surface classes are given below.

**Table 2.3: Road Surface Condition Index (RSI) Range**

| Road Surface Condition Classes | RSI Range |
|---|---|
| Bare and Dry | 0.90 – 1.00 |
| Bare and wet | 0.80 – 0.89 |
| Partly snow covered | 0.50 – 0.79 |
| Snow covered | 0.25 – 0.49 |
| Snow packed | 0.20 – 0.24 |
| Slushy | 0.16 – 0.19 |
| Icy | 0.10 – 0.15 |

- Generation of an event-based dataset:

  An event-based dataset was generated by aggregating the hourly data over individual data events. An important step in this data aggregation step was to identify the individual events with the available hourly data records. Each event was identified with the following constraints:

  - An event starts at the time when snow/freezing rain is observed.
  - An event ends when snow/freezing rain stops and a certain predefined road surface condition is achieved after that time.
  - Precipitation must be greater than zero.
  - Air temperature must be less than 5° Celsius.
  - The road surface conditions index value must not be equal to bare dry conditions.

- Model Development:

  In this research, the Negative Binomial (NB) model, along with its extensions, was first evaluated for its performance in capturing observed and unobserved accident variations among individual snowstorms. The second model, commonly referred as the Generalized Negative Binomial (GNB), overcame the shortcomings of the NB model. The third model considered in this research was called the Zero Inflated NB (ZINB) model.

  - The RSI was found to be a statistically significant factor influencing road safety across all sites.
  - Visibility was also found to have a statistically significant effect on accident frequency during a snowstorm.
  - Exposure, defined as total vehicle kilometers traveled, was found to be significant, suggesting that an increase in traffic volume, storm duration, or route length would lead to an increased number of accidents.
  - Both air temperature and precipitation amount had a statistically insignificant effect on accident frequency.
  - Exploratory analysis also found that maintenance was correlated with road surface conditions and was not statistically significant after road surface conditions were accounted for.

  The results of this modeling approach aimed at explaining the variation of road accidents over different snowstorm events. This approach also explored the relationship of winter road safety to some direct road surface condition measures. Also assessed were the safety benefits of alternative winter road maintenance goals under different weather and traffic conditions.

### 2.3.2 Methods for Estimating the Benefits of Winter Maintenance Operations

This study estimated the benefits of winter maintenance operations (AASHTO Standing Committee on Highways, NCHRP Project 20-07 (300), 2007). Although several non-quantifiable benefits were identified, the three major quantifiable benefits of winter maintenance operations are as follows:

- Safety Improvements - The changes (ideally reductions) in crashes and realized financial savings as a result of winter maintenance.
- Travel Time Savings - Travel time savings resulting from differences in travel speeds over road segments under different levels of winter maintenance.
- Fuel Usage - The differences between vehicle fuel usage under storm conditions where maintenance was performed or not performed.

The developed framework for determining winter maintenance benefits and costs is shown in the figure below.

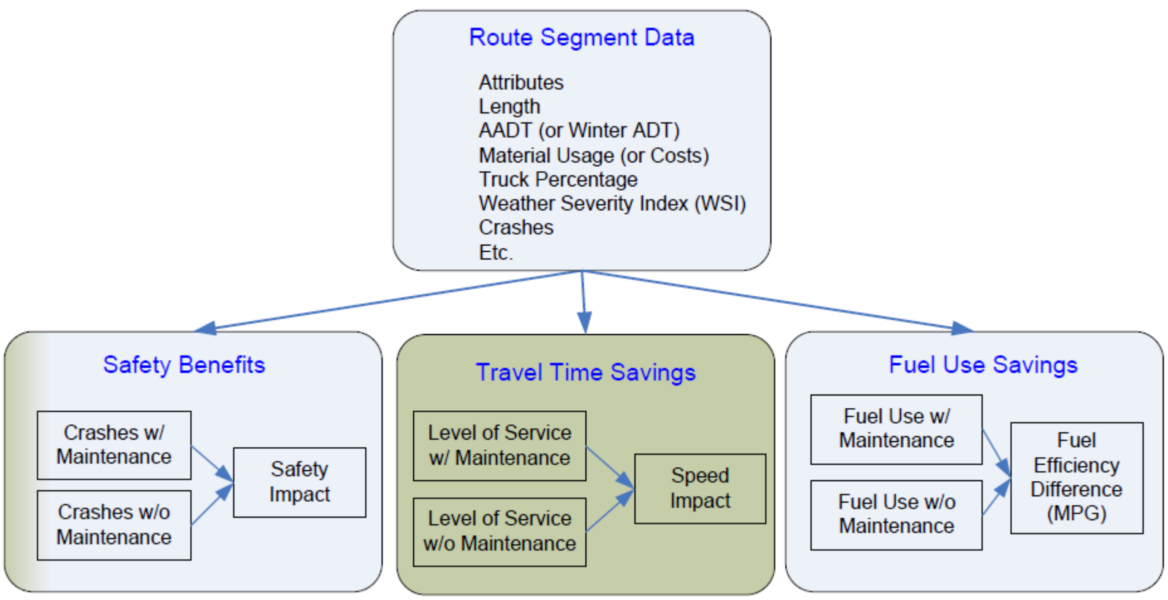



**Figure 2.1: Framework for Winter Maintenance Benefit Estimation**

The safety benefits were estimated using a negative binomial model by predicting the number of crashes that could occur under different winter maintenance scenarios. Then the reduction in crashes and the financial savings were estimated using the cost of different types of crashes for the whole highway network.

Travel time savings are gained through improved vehicle speeds and reduction in user delay. Travel speeds for different winter conditions were calculated using speed reduction factors for the prevailing pavement condition (snow covered, slushy, etc.) with or without winter maintenance. To use this method, it is necessary to know the length of each winter storm during the study period.

Previous studies in the United States and Canada have suggested that fuel usage for vehicles travelling on snow packed roadways increases by 30-50%. In this study, fuel usage under different winter maintenance conditions (no maintenance and completely cleared condition) was calculated for different types of vehicles.

The developed methodologies were demonstrated using winter maintenance data from the Minnesota Department of Transportation. The following variables were used to calculate the winter maintenance benefits in three categories: safety, travel time, and fuel usage.

- Attributes:
    - The route, the district a maintenance segment belongs to, speed limit, number of lanes, maintenance job number.
- Length:
    - The length of the segment will be used in the calculation of both safety benefits and travel time savings.
- Annual Average Daily Traffic (AADT) or Winter Average Daily Traffic:
    - This information will be used for estimating safety benefits and travel time savings.
- Truck Percentage:
    - The percentage of trucks in the traffic stream.
    - This information will be used for calculating benefits resulting from travel time and fuel savings.
- Material usage/costs:
    - Costs or usage of materials for each winter season.
    - Will be used in estimating safety benefits.
- Crashes:
    - Number of crashes that occurred during a winter season.
- Weather Severity Index (WSI):
    - Road Weather Information System (RWIS) and the National Weather Service (NWS) are the common resources for collecting and analyzing weather data.

### 2.3.3 Development of a Toolkit for Cost-Benefit Analysis of Specific Winter Maintenance Practices, Equipment and Operations

The purpose of this research was to develop a toolkit which would facilitate a cost-benefit analysis for a series of winter maintenance practices, equipment, and operations (Wisconsin Department of Transportation and the Clear Roads Program, 2010). With the availability of this toolkit, maintenance managers should be able to more efficiently use scarce financial resources. This includes identifying a set of best practices employed by an agency to apply the right type and amount of materials in the right place at the right time for winter maintenance activities.

The toolkit includes the following input variables:

- Anti-icing
- De-icing
- Carbide blades
- Front plows
- Underbody plows
- Zero velocity spreader
- Maintenance Decision Support Systems (MDSS)
- Automatic Vehicle Location and Geography Positioning Systems (AVL/GPS)
- Road Weather Information Systems (RWIS)
- Mobile pavement or air/pavement temperature sensors

A survey was conducted among highway agencies to gather information on their winter maintenance tools, equipment, and procedures. The main objective of the survey was to identify the top ten winter maintenance tools, procedures, and practices and to prioritize them for inclusion in the cost-benefit toolkit.

The web-based toolkit was built in a manner that walks the user through a cost-benefit analysis in a series of steps. Based on the practice, equipment, or operation selected, the user will be presented with a series of web pages that represent the steps of cost-benefit analysis. The steps include:

- Step 1 – Define Project Parameters: The user will provide specific parameters related to the application of the item they plan to analyze at their agency.
- Step 2 – Enter Costs: The user will enter initial and annual costs specific to the agency.
- Step 3 – Benefits: No input is required on this page. Rather, it presents the user with a list of quantified and non-quantified benefits that may be achieved by the agency, user, and/or society through the use of the item being examined.
- Step 4 – Benefit Quantification: The user will enter the values related to the determination of benefits of using a winter maintenance method or material.
- Step 5 – Results: The results will be presented in the final page.

As in any cost-benefit analysis approach, costs were easily identifiable but monetary values for benefits were hard to establish for many winter maintenance items. In the toolkit, both tangible and intangible benefits were identified and only the tangible benefits were used in the analysis. However, intangible benefits were presented to the user in the toolkit.

When financial values were assigned to the costs and benefits, a cost-benefit ratio can be computed. However, since many of the items under consideration for winter maintenance have present (initial capital expenditure) and future (annual maintenance) costs, a Present Value (PV) method was employed to bring all future costs to a present value.

# CHAPTER 3: SURVEY OF WINTER WEATHER STATES

## 3.1 Survey Distribution List

Included in Appendix A of this report, a survey distribution list was compiled based on discussions with the MDOT Project Manager and Research Advisory Panel. This distribution list included TP owners, the Clear Roads pooled fund study members, and highway agencies in the snowy regions of United States and Canada. The survey was also posted on AASHTO SNOW-ICE listserv.

## 3.2 Results of the Tow Plow (TP) Usage Survey

The TP Usage survey, included in Appendix A of this report, was deployed through the "Survey Monkey" online survey tool. At the end of the survey period, 48 valid survey responses were received. Table 3.1 lists the agencies that responded to the survey.

**Table 3.1: Agencies Responding to the Survey**

| Agency | Number of Responses |
|---|---|
| Colorado Department of Transportation | 2 |
| Illinois Department of Transportation | 1 |
| Pennsylvania Department of Transportation | 3 |
| West Virginia Division of Highways | 1 |
| Massachusetts Department of Transportation | 1 |
| Nebraska Department of Roads | 1 |
| Kansas Department of Transportation | 3 |
| Brunway Highway Operations, Inc. | 2 |
| Kansas Turnpike Authority | 1 |
| Kentucky Transportation Cabinet | 1 |
| Montana Department of Transportation | 2 |
| North Dakota Department of Transportation | 3 |
| Virginia Department of Transportation | 1 |
| Snow King Technologies | 1 |
| New York State Department of Transportation | 1 |
| Utah Department of Transportation | 4 |
| Ohio Department of Transportation | 1 |
| Minnesota Department of Transportation | 1 |
| Rhode Island Department Transportation | 1 |
| Michigan Department of Transportation | 2 |
| Washington State Department Transportation | 2 |
| Missouri Department of Transportation | 3 |
| Tennessee Department of Transportation | 1 |

| Agency | Number of Responses |
|---|---|
| Nevada Department of Transportation | 1 |
| Ohio Turnpike | 1 |
| New Hampshire Department of Transportation, Bureau of Turnpike | 1 |
| Laserline | 1 |
| Alaska Department of Transportation and Public Facilities | 1 |
| Transfield Services | 1 |
| Maine Department Transportation | 1 |
| Iowa Department of Transportation | 1 |
| Eau Clair County Highway Department | 1 |

As shown, 48 responses were received from 32 agencies. The agencies included 24 state highways departments, one county department of transportation, three turnpike authorities, two private contractors and two equipment manufacturers. Figure 3.1 shows the geographic distribution of the survey respondents.

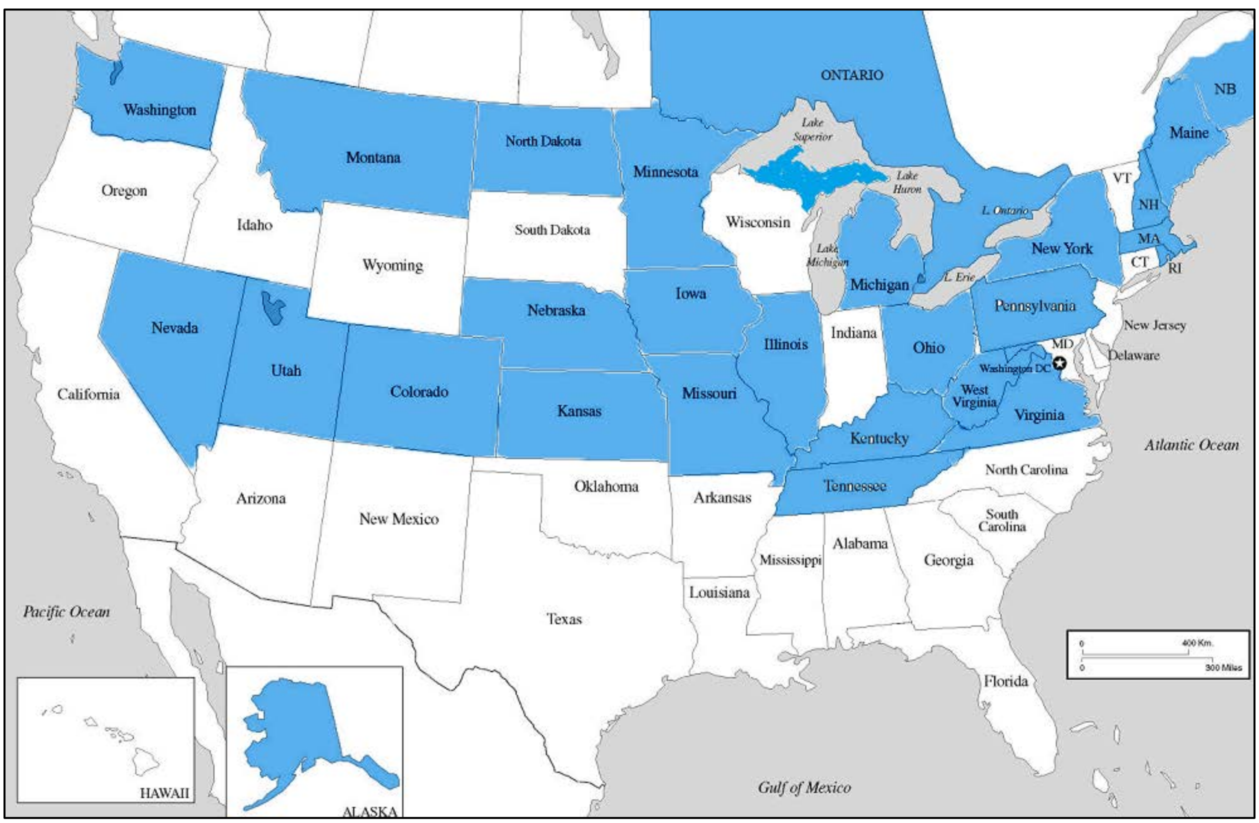
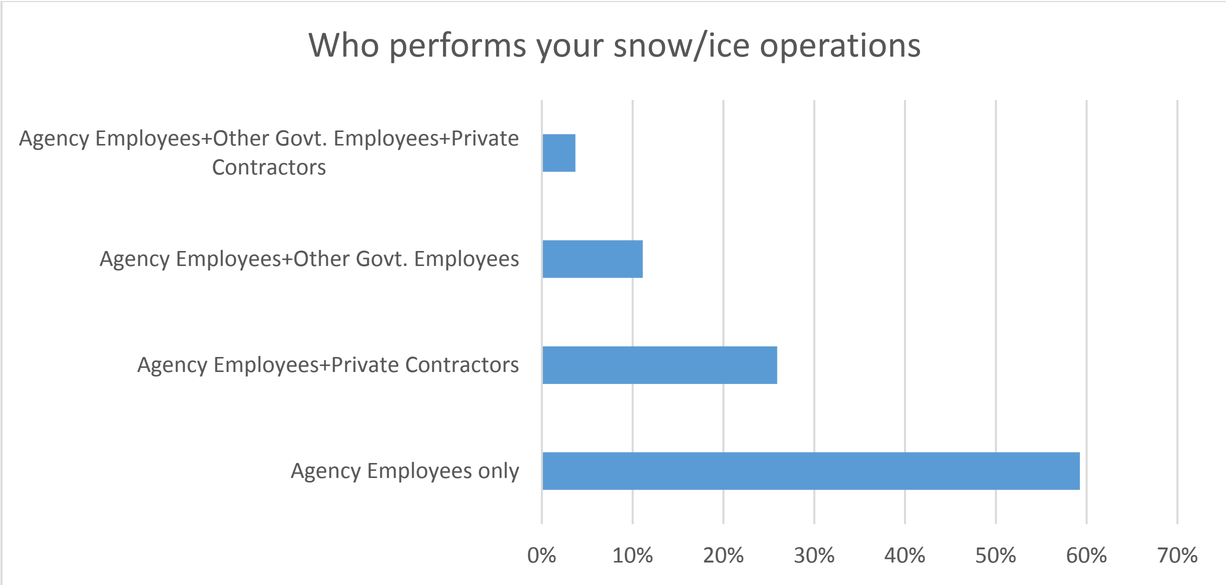



**Figure 3.1: Geographic Distribution of the Survey Respondents**

The summary of survey responses is presented below.

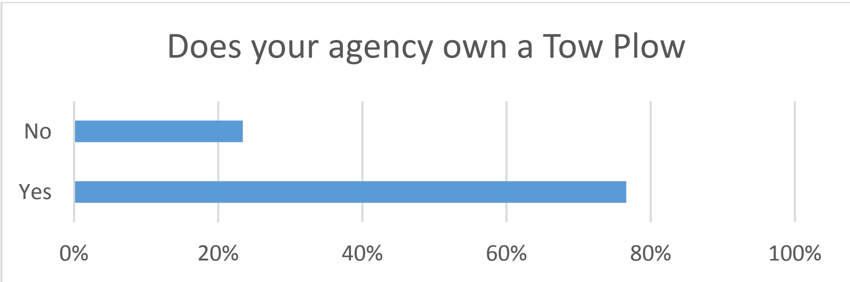
1. *Who performs the snow and ice operations?*




2. *Are you familiar with the Tow Plow Technology?*

   100% of the survey respondents answered "Yes" to this question.

3. *Does your agency own a Tow Plow?*



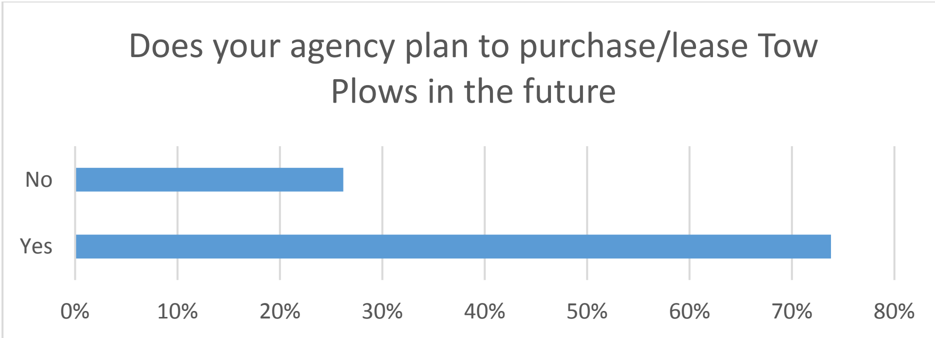

   *How many Units?*

   The number of Tow Plow units owned by the respondents varied from 1 to 79 (Missouri DOT). The total number of Tow Plows owned by the survey respondents was 198 units.

4. *If your employees do not perform snow/ice operations, does your contractor use Tow Plows?*

   100% of the respondents to this question answered "No" to this question. Only two contractors from Canada responded to the survey.

5. *Does your agency plan to purchase/lease Tow Plows in the future?*




*How many units?*

This number varied from unknown to 32 (in 10 years).

6. *Towing Truck Type?*

Towing truck types included the following brands:

- International/IHC – 43%
- Freightliner – 19%
- Mack – 14%
- Peterbilt – 5%
- Western Star – 5%
- Sterling – 5%

Ten percent of the respondents answered "Tandem Axle".

7. *Engine Make/Model/Year of Each Tow Truck?*

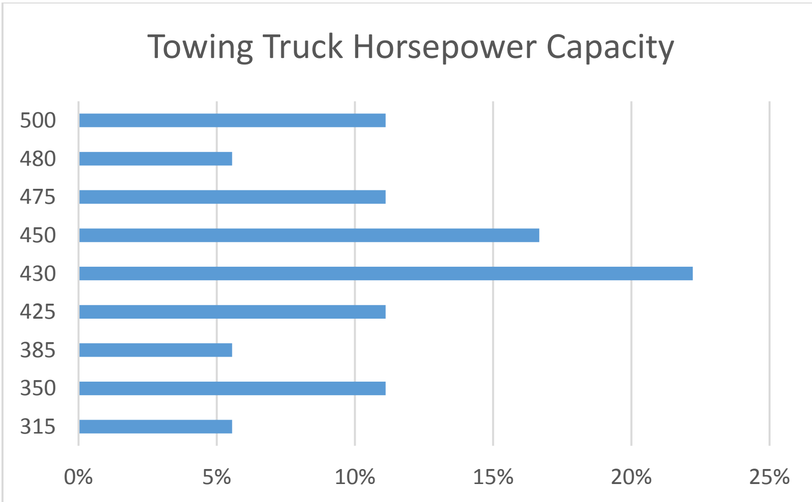
Most of the respondents answered with the truck manufacturer's brand name for this question.

8. *Transmission Make/Model?*

Interestingly all the survey respondents to this question answered, "Allison brand transmission."

9. *Towing Truck Horsepower Capacity?*

Towing truck horsepower capacity ranged from 315 hp to 500 hp with the majority of respondents indicating 430 hp capacity.




*10. Towing Truck Hydraulic Capacity?*

Most of the respondents stated that they are unaware of the hydraulic capacity of the tow truck. Based on the few responses, most agencies have 20 to 28 gpm systems. Some even has 40 gpm systems. If the Tow Plow is equipped with a spreader, a reserve hydraulic capacity of 18 gpm is recommended.

*11. Hitch plate capacity?*

The hitch capacity of tow trucks varied from 20 to 60-ton trailer capacity with 18,000 lb. to 20,000 lb. vertical load capacity. The majority of the trucks had 50-ton trailer capacity.

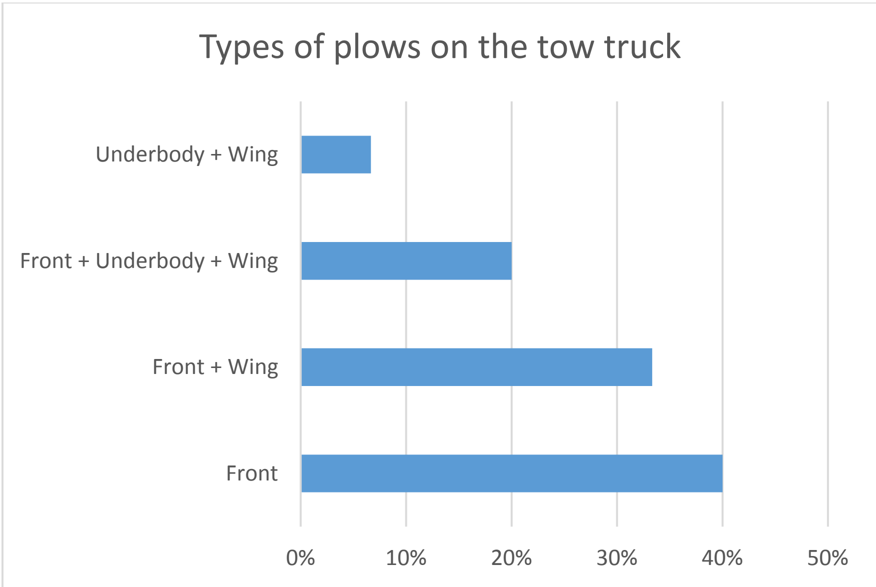
*12. Salt distribution system of the tow truck?*

The following types of salt distribution systems were identified from the survey:

- V-box spreaders
- U-body spreaders (Canadian respondents)
- Tailgate Spreaders
- Auger spreaders
- Radial dump box with chain
- Live bottom and cross auger spreaders
- Granular spinners

*13. Type of plows on the tow truck?*

The majority of respondents indicated that they use either Front Plows or Front and Wing plows with the tow truck used with the Tow Plow.




*14. Type of cutting edges used in the plow truck?*

More than 90% of the respondents use carbide cutting edges. The remaining few agencies use rubber, steel and rubber molded ceramic inserts.

*15. Modifications to the tow truck, approximate cost and who performed the modifications?*

The modifications to the tow truck include: hydraulic system upgrade with plumbing, hitch plate upgrade to a heavier pintle plate, spreader control system upgrade with relocating the spreader chute to the opposite side of the Tow Plow, light system upgrade to add rear elimination, and adding arrow boards. The costs of modifications varied from $330 to $16,000 with an average cost of $7,500. The majority of the modification were performed by an outside garage or truck vendor.

*16. Availability of a poly tank for pre-wetting salt on the truck?*

The majority of Tow Plow owners stated that they have a poly tank on the tow truck. The capacity of these poly tanks varied from 120 to 300 gallons.

*17. Availability of a hopper with a spreader on the tow truck?*

The majority of Tow Plow owners stated that they have a hopper with a spreader on the tow truck. The capacity of these hoppers varied from 2 to 16 cubic yards.

*18. Availability of a rear-view camera to observe traffic behind Tow Plow and their usefulness?*

The majority of survey respondents stated that they have not used a rear view camera. The few agencies who used them stated their usefulness is minimal due to snowfog. One agency stated their Tow Plow operators find the cameras useful.

19. *Availability of a laser alignment system used by the Tow Plow operator to define the edge of the plow?*

    Two-thirds of the respondents stated that they have not used a laser alignment system. A few respondents stated they have used/tried it before but did not continue to use it. Approximately one-third of respondents still use them.

20. *Availability of a hub-odometer or other system for tracking Tow Plow usage?*

    Approximately three-fourth of the respondents have not used any system for tracking Tow Plow usage. The remaining one-fourth of respondents use them.

21. *Type of cutting edges used on the Tow Plow?*

    More than 90% of the respondents use carbide cutting edges. The remaining few agencies use rubber and rubber molded ceramic inserts.

22. *Modifications to the Tow Plow, approximate cost and who performed the modifications?*

    Only few modifications were completed by responding agencies. These include some hydraulic system upgrades, hitch upgrades and the light system upgrades. One agency installed proximity sensors at the back and side of the Tow Plow for a cost of $2,000. The costs of modifications varied from $2,000 to $8,000. The majority of the modification were performed by the agency employees.

23. *Average fuel efficiency of the tow truck + Tow Plow combination?*

    The reported fuel efficiency of the tow truck + Tow Plow combination varies from 3 to 8 miles/gallon with an average value of 4.8 mpg. Only five agencies responded to this question and others stated they do not have sufficient data to calculate the fuel efficiency.

24. *Operational Speed of the tow truck + Tow Plow combination?*

    The reported operational speed of the tow truck + Tow Plow combination varies from 23.5 to 50 miles/hour with an average value of 35.5 mph. Only seven agencies responded to this question. One agency reported they are operating the Tow Plow at a higher speed than a regular plow in order to not to leave a ridge of snow.

25. *Average fuel efficiency of the regular plow?*

    The reported fuel efficiency of the regular plow varies from 4 to 6.2 miles/gallon with an average value of 4.8 mpg. Only four agencies responded to this question.

26. *Operational Speed of the regular plow?*

    The reported operational speed of the regular plow from 23.5 to 40 miles/hour with an average value of 31.4 mph. Only six agencies responded to this question.

*27. Maintenance costs of tow truck + Tow Plow combination?*

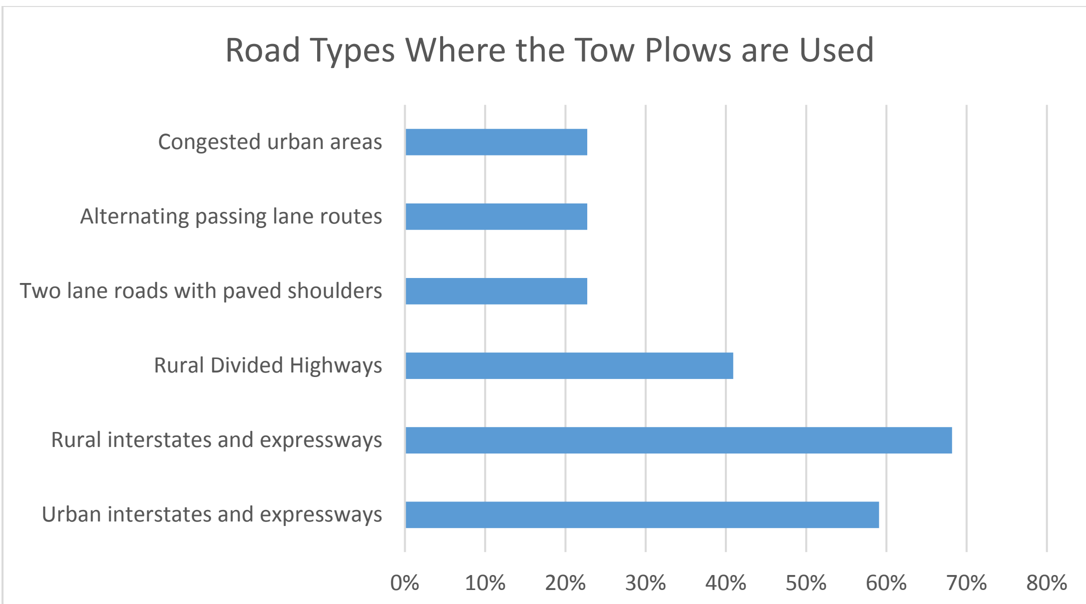
Only two respondents answered with an approximate yearly cost of $3,000. No one has provided a list of maintenance cost items.

*28. Maintenance costs of regular plow?*

Only two respondents answered with an approximate yearly cost of $500 and $1,500. No one has provided a list of maintenance cost items.

*29. Types of Roads the Tow Plows are used on?*

The following chart shows the type of roads the Tow Plows are used on.




*30. Restrictions on Tow Plow usage?*

Only two agencies answered with restrictions, one with concerns for mountain usage and the other with plowing ramps.

*31. Training activities for Tow Plow operators?*

Only one agency stated they do not have any training program. The Missouri DOT has developed a comprehensive training program which was later adopted by other agencies. North Dakota Department of Transportation (NDDOT also has developed a yearly training school for Tow Plow operators.

*32. Plow operator's opinion of the Tow Plow?*

Most of the agencies reported "efficient and cost effective", "good investment" and "expensive" as the opinions of their Tow Plow operators.

*33. Public complaints related to Tow Plow usage?*

One agency reported that they received one complaint stating traffic was being backed up. All others responded "No" to this question.

*34. Research on Tow Plow usage?*

Two-thirds of the respondents stated they have conducted or currently are conducting research studies. These research studies range from initial field trails to university research studies.

*35. Any other information related to Tow Plow experience?*

All compiled information is included in the Appendix A of this report.

# CHAPTER 4: COMPARE THE EFFECTIVENESS OF THE TOW PLOW (TP) TO A TRADITIONAL WINTER MAINTENANCE TRUCK (WMT)

A field data collection program was developed to perform a comparison of the effectiveness of the TP relative to a WMT. The following field data were used to evaluate the effectiveness:

1. Visual pavement condition observed behind the TP and the WMT.
2. Pavement friction condition measured behind the two respective truck units.
3. Operating speed of each truck unit.

When the research project was initiated, MDOT had purchased only one TP and housed it at the MDOT Brighton maintenance garage. The field data collection program was designed to capture field performance results along roadways in the Brighton maintenance garage area. During the second year of evaluation (2014-2015 winter season), more TPs were added to the MDOT winter maintenance equipment fleet. While the field evaluation program was mainly limited to the Brighton maintenance garage area, a few data collection cycles were conducted in the adjacent Williamston maintenance garage area during the 2014-2015 winter season. Winter maintenance routes for both areas are shown in Figures 4.1 and 4.2. Descriptions of each route are listed in Tables 4.1 and 4.2.

**Table 4.1: Brighton Maintenance Garage Winter Maintenance Routes**

| Route | Description | Lane Miles |
|---|---|---|
| 8WRUN0/42 | I-96 from 1st turnaround west of M-59 to Oakland County line. | 121.0 |
| 8NORTH/42 | US-23 from Clyde Road to Owen Road in Genesse County, includes ramps. | 48.0 |
| 8SEAST/42 | US-23 from Washtenaw County line to 1st turnaround north of garage and I-96 from Oakland County line to Spencer Road, includes ramps. | 40.5 |
| 8INTER/42 | Interchange at I-96 and US-23 from Lee Road to 1st turnaround north of garage. From 1st turnaround on I-96 at barrier wall east of US-23 to Spencer Road at I-96, includes ramps. | 45.2 |
| 8WM590/42 | M-59 from I-96 to Old US-23. | 43.0 |
| 8EM590/42 | M-59 from Old US-23 to Oakland County line. | 27.8 |
| 8BLOOP/42 | BL-96 from M-59 through city of Howell to Exit 141. Also includes M-155 Michigan Avenue south of Grand River Avenue to High Hill Crest Road. | 40.5 |
| 8M3600/42 | M-36 from US-23 to Gregory Road. | 40.3 |
| 59SPUI/42 | US-23 from Lee Road to Clyde Road, includes ramps and eastbound rest area. | 50.0 |

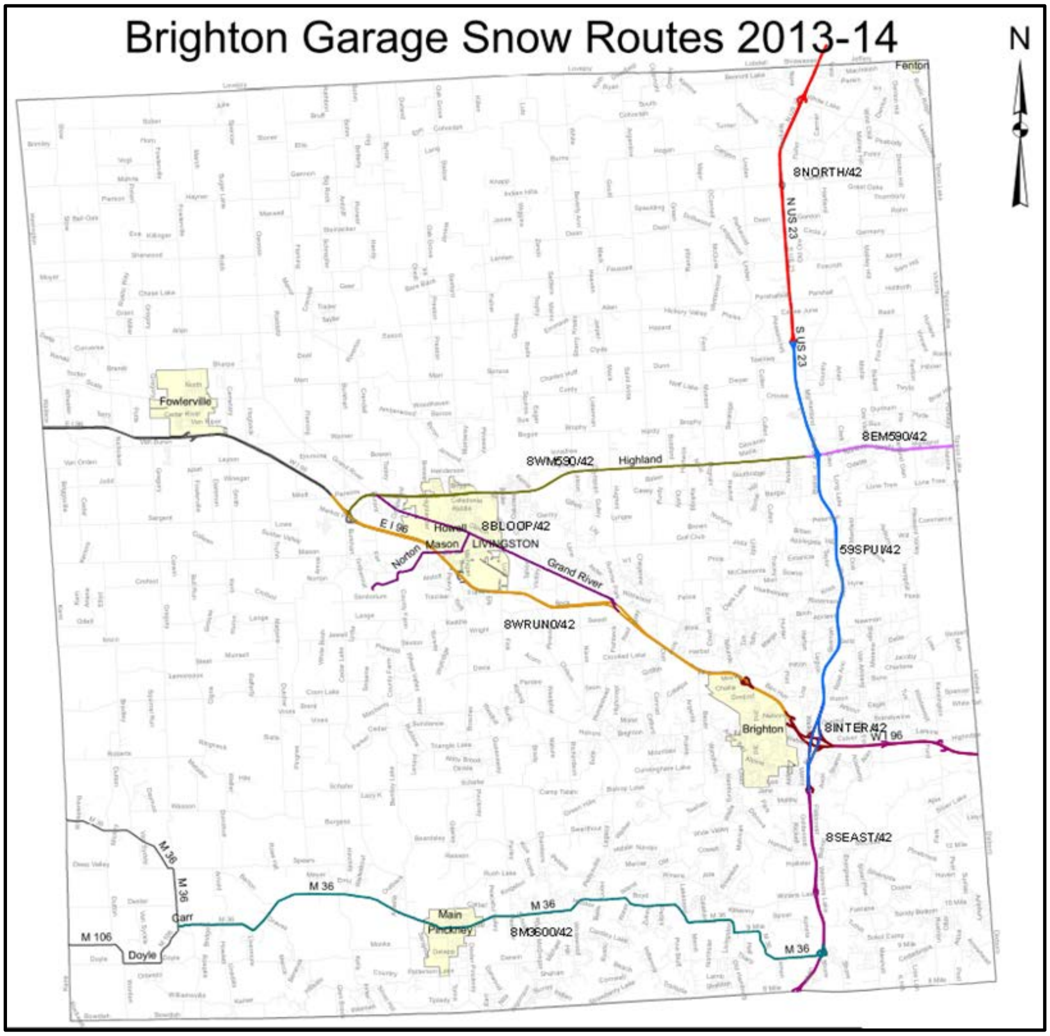



**Figure 4.1: Map of Brighton Maintenance Garage Winter Operation Routes**

**Table 4.2: Williamston Maintenance Garage Winter Maintenance Routes**

| Route | Description | Lane Miles |
|---|---|---|
| OI0069-19 | Purple Run – I-69 between I-127 and east of the I-96 Business Loop | 33.1 |
| 8BLRUN-12 | Green Run – I-69 Business Loop (Saginaw Street) in East Lansing | 22.6 |
| 843RUN-12 | Blue Run – M-43 between East Lansing and M-52 | 43.8 |
| 896WST-12 | Pink Run – I-96 between Hagadorn Road and Williamston Road | 46.3 |
| 852RUN-12 | Yellow Run – M-52 between county border and M-36 | 35.1 |
| 896EST-12 | Red Run – I-96 between Williamston Road to Burkhart Road (I-96 Business Loop) | 70.8 |
| 8LOOP0-12 | Orange Run M-36/M-52 to M-106 near Stockbridge | 41.8 |

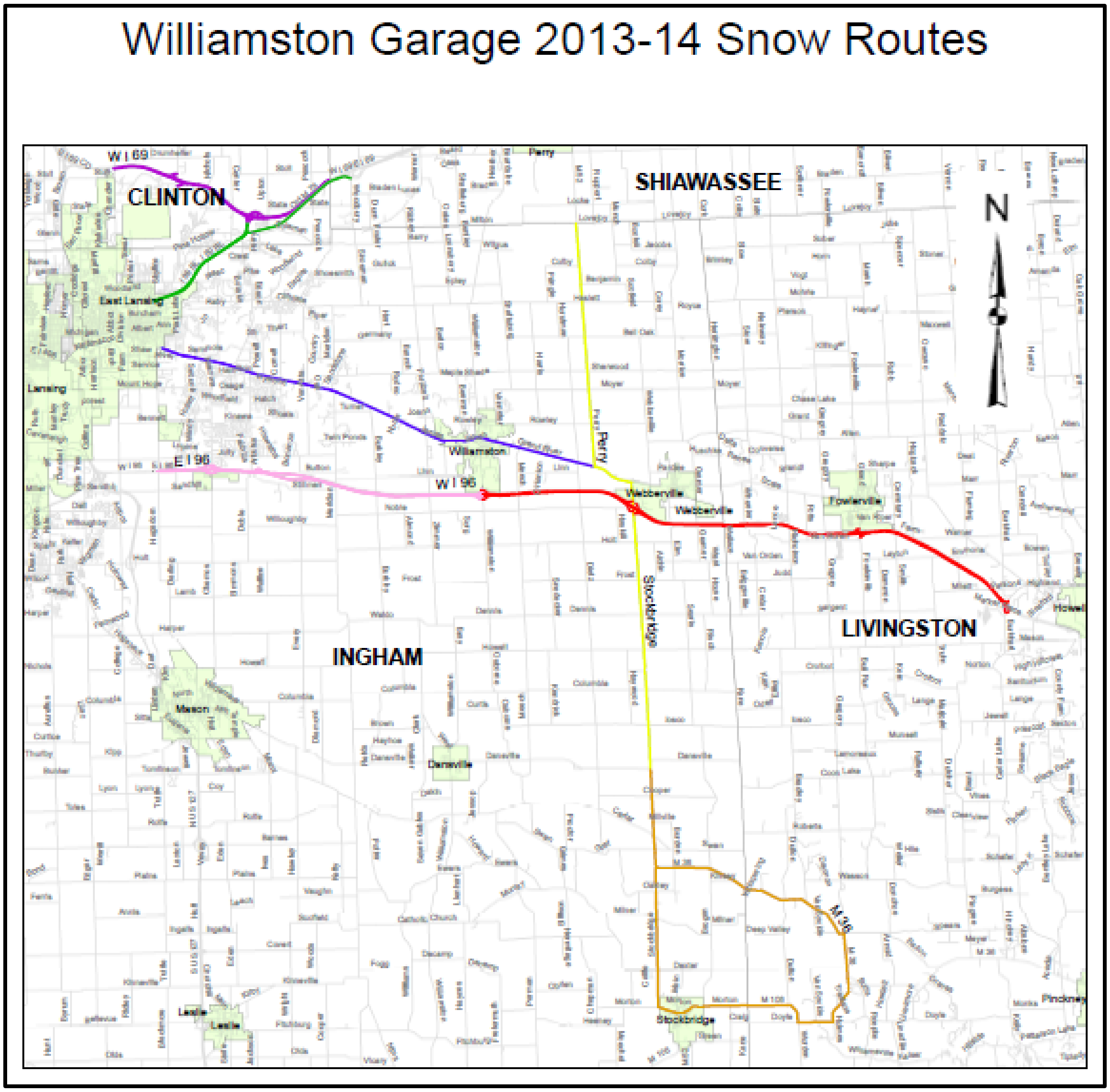



**Figure 4.2: Map of Williamston Maintenance Garage Winter Operation Routes**

Data were collected during different types of snowstorms. The snowstorms were categorized into four classes as shown below.

- Trace Snow - Less than 0.5 inches of total accumulation, and peak snowfall rate of less than 0.1 inches per hour.
- Light Snow - Between 0.5 and 1.5 inches of total accumulation, and peak snowfall rates between 0.10 and 0.25 inches per hour.
- Moderate Snow - Between 1.5 and 5.5 inches of total accumulation, and peak snowplow rates between 0.25 and 0.75 per hour.
- Heavy Snow - More than 5.5 inches of total accumulation, and snowfall rates more than 0.75 inches per hour.

## 4.1 Field Data Collection

### 4.1.1 Visual Pavement Condition

Based on discussions with the MDOT Project Manager (PM) and RAP members, a field data collection sheet was developed to record the visual pavement condition after TP usage. The Dynatest "SURVEY" field data collection program was configured to include pavement conditions defined in the field data collection form. Figure 4.3 shows the sample field data collection form used during this study. At predefined intervals (528 feet), pictures of the surface conditions were taken and stored for future use. These pictures were used to supplement surface condition data collected during snow events. Based on the visual pavement condition of each 528-foot segment, percentage area of different pavement surface condition was estimated.

| Surface Condition | Description | Picture |
|---|---|---|
| Bare (B) | Bare Pavement. |  |
| Centerline Bare (CLB) | Entire lane is cleared of snow, ice and slush. |  |
| Wheel Track Bare (WTB) | Only wheel tracks are bare, snow/ice/slush are in the other areas. |  |
| Loose Snow/Slush (LS) | Loose snow/slush-covered. |  |
| Snow Covered (S) | Entire roadway is covered with packed snow and ice |  |

**Figure 4.3: Field Data Collection Form**

### 4.1.2 Pavement Friction and Operating Speed of Snow Plows

A Dynatest Highway Friction Tester (HFT), equipped with a camera and a "Survey" data collection program, was utilized during each data collection cycle. This tester uses a two-axis force transducer mounted on a retractable fifth wheel located under the vehicle bed adjacent to the left rear wheel of the vehicle. A picture of the Dynatest HFT is shown in Figure 4.4 below.


**Figure 4.4: Dynatest 6875 Highway Friction Tester**

HFT is a continuous friction tester. They are categorized as fixed-slip testers and generally measure the maximum friction value between the test tire and pavement. A graphical representation of this process is shown in the following figure. The maximum or peak friction value simulates ABS braking action.

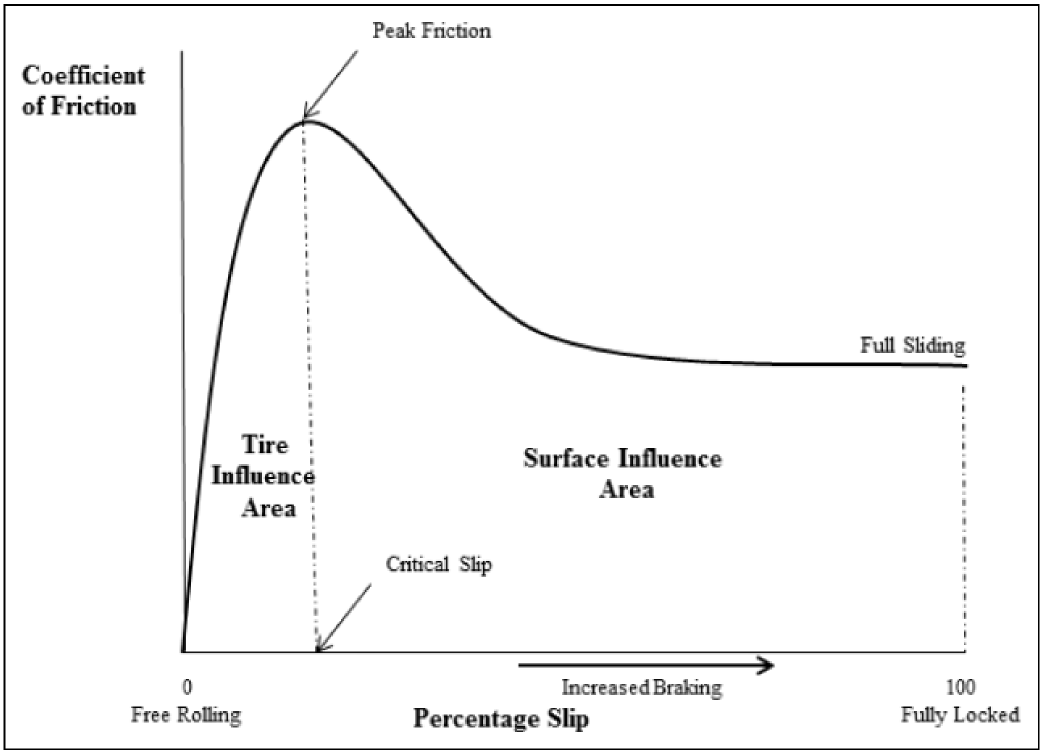



**Figure 4.5: Friction vs. Slip (Little Book of Friction, 2012)**

Friction values between the road surface and test tire were measured for a length of 500 feet at 1000-foot intervals. The average friction values for each 500-foot test section were recorded and summarized. TP/WMT operating speed was recorded based on the average testing speed of the friction tester.

## 4.2 Collected Field Data

A summary of the data collected during selected snowstorms is shown in this section. A sample of the collected data is included in Appendix B of this report.

The summary data includes:

- Winter storm date, winter storm type or condition.
- Lane plowed and type of plowed used.
- Resulting surface condition and area.
- Average friction value and standard deviation of friction value.

Sample data also includes data collection starting and ending points, operating speeds, and photographs of the pavement surface conditions.

**Table 4.3: Summary of Collected Data**

| Winter Storm Event Data | Winter Storm Condition | Lane/Plow Type | Pavement Surface Condition | Area (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|---|---|---|
| 1/1/2014 | Moderate Snow (5.3 inches of snow) | WB I-96 Middle Lane/WMT | WTB | 94 | N/A | N/A |
| | | | LS | 6 | N/A | N/A |
| | | WB I-96 Slow Lane/TP | WTB | 94 | 0.34 | 0.12 |
| | | | LS | 6 | 0.16 | 0.01 |
| | | EB I-96 Fast Lane/WMT | WTB | 85 | 0.28 | 0.11 |
| | | | LS | 15 | 0.16 | 0.03 |
| 1/5/2014 | Heavy Snow (10.2 inches of snow) | WB I-96 Slow Lane/WMT | WTB | 100 | 0.18 | 0.05 |
| | | WB I-96 Shoulder/TP | CLB | 14 | N/A | N/A |
| | | | WTB | 43 | N/A | N/A |
| | | | LS | 43 | N/A | N/A |
| | | EB I-96 Fast Lane/WMT | LS | 100 | 0.15 | 0.02 |
| 2/1/2014 | Heavy Snow (7.4 inches of snow) | WB I-96 Slow Lane/WMT | WTB | 28 | 0.15 | 0.03 |
| | | | LS | 72 | 0.12 | 0.03 |
| | | WB I-96 Outside Shoulder/ TP | LS | 100 | N/A | N/A |
| | | EB I-96 Middle Lane/WMT | WTB | 26 | N/A | N/A |
| | | | LS | 74 | N/A | N/A |
| | | EB I-96 Slow Lane/TP | WTB | 10 | 0.14 | 0.01 |
| | | | LS | 90 | 0.11 | 0.02 |
| | | WB I-96 Fast Lane/WMT | WTB | 16 | 0.12 | 0.01 |
| | | | LS | 84 | 0.11 | 0.02 |
| | | EB I-96 Fast Lane/WMT | LS | 100 | 0.11 | 0.02 |
| 1/21/2015 | Moderate Snow (2.5 inches of snow) | WB I-96 Slow Lane/TP | B | 72 | 0.40 | 0.16 |
| | | | CLB | 8 | 0.31 | 0.15 |
| | | | WTB | 20 | 0.10 | 0.02 |
| | | EB I-96 Slow Lane/TP | B | 48 | 0.72 | 0.23 |
| | | | CLB | 22 | 0.25 | 0.09 |
| | | | WTB | 10 | 0.14 | 0.03 |
| | | | LS | 20 | 0.11 | 0.03 |

| Winter Storm Event Data | Winter Storm Condition | Lane/Plow Type | Pavement Surface Condition | Area (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|---|---|---|
| 2/1/2015 | Heavy Snow (17 inches of snow in 2 days) | EB I-96 Slow Lane, TP | CLB | 15 | 0.24 | 0.06 |
| | | | WTB | 85 | 0.22 | 0.04 |
| | | EB I-96 Middle Lane, WMT | WTB | 89 | N/A | N/A |
| | | | LS | 1 | N/A | N/A |
| | | EB I-96 Slow Lane, WMT | WTB | 40 | 0.20 | 0.05 |
| | | | LS | 60 | 0.16 | 0.03 |
| | | EB I-96 Shoulder, TP | LS | 100 | N/A | N/A |
| | | WB I-96, Slow Lane (Williamston), WMT | CLB | 43 | 0.23 | 0.03 |
| | | | WTB | 57 | 0.23 | 0.03 |
| | | WB I-96, Shoulder (Williamston), TP | LS | 100 | N/A | N/A |
| 2/14/2015 | Moderate Snow (2.2 inches of snow) | NB US-23 Slow Lane, WMT | CLB | 32 | 0.38 | 0.13 |
| | | | WTB | 68 | 0.26 | 0.07 |
| | | NB US-23 Shoulder, TP | WTB | 100 | N/A | N/A |
| 3/3/2015 | Light Snow (1.1 inches of snow) | WB I-96, Middle Lane, WMT | CLB | 11 | N/A | N/A |
| | | | LS | 89 | N/A | N/A |
| | | WB I-96, Slow Lane, TP | CLB | 13 | N/A | N/A |
| | | | LS | 87 | N/A | N/A |
| | | NB US-23, Slow Lane, WMT | CLB | 14 | N/A | N/A |
| | | | WTB | 48 | N/A | N/A |
| | | | LS | 37 | N/A | N/A |
| | | NB US-23, Shoulder, TP | WTB | 8 | N/A | N/A |
| | | | LS | 92 | N/A | N/A |
| | | SB US-23, Slow Lane, TP | CLB | 76 | N/A | N/A |
| | | | WTB | 11 | N/A | N/A |
| | | | LS | 13 | N/A | N/A |
| | | SB US-23, Slow Lane, TP | CLB | 3 | N/A | N/A |
| | | | WTB | 29 | N/A | N/A |
| | | | LS | 68 | N/A | N/A |

N/A – Not available

## 4.3 Comparison of Pavement Conditions and Friction Levels behind Tow Plows (TPs) and Regular Plows (WMTs)

One of the main objectives of this study was to evaluate any differences in snow clearing capabilities between the TPs and WMTs. This objective was achieved by performing winter pavement condition evaluations and friction testing behind both the TPs and the WMTs during different snow events. Collected behind the various plow units, pavement visual condition data and friction data were analyzed to obtain various relationships described in the following sections and in Appendix C of this report. The main goal of these analyses was to determine if there was a significant difference in pavement visual condition and pavement friction relative to WMT and TP usage.

As seen in Table 4.3, different pavement conditions and related friction values were observed behind WMTs and TPs. In order to compare the differences in friction values behind the TPs and WMTs for each pavement condition, average friction values were calculated from the friction measurements collected behind the TPs and WMTs and are shown in Table 4.4.

**Table 4.4: Friction Statistics for Different Winter Surface Conditions behind TP and WMT**

| Winter Surface Condition | WMT | | | TP | | |
|---|---|---|---|---|---|---|
| | Average μ | Standard Deviation of μ | Number of Observations | Average μ | Standard Deviation of μ | Number of Observations |
| Bare (B) | No data | No data | No data | 0.53 | 0.25 | 61 |
| Centerline Bare (CLB) | 0.34 | 0.13 | 37 | 0.26 | 0.09 | 20 |
| Wheel Track Bare (WTB) | 0.25 | 0.09 | 148 | 0.26 | 0.13 | 94 |
| Loose Snow (LS) | 0.13 | 0.03 | 81 | 0.12 | 0.03 | 60 |
| Snow Covered (S) | No data | No data | No data | No data | No data | No data |

A statistical analysis was performed by comparing the absolute difference between average friction values against the product of the standard deviation, in terms of the average friction values, and the Z factor for a given confidence level.

If the averages between mean friction values are significantly different, the following relationship should be satisfied.

$$\left|\overline{\mu_1} - \overline{\mu_2}\right| > ZS_d$$

$$S_d = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

Where,

$\overline{\mu_1}$ = average friction value for the first winter pavement condition

$\overline{\mu_2}$ = average friction value for the second winter pavement condition

$S_1$ = standard deviation of friction values for the first winter pavement condition

$S_2$ = standard deviation of friction values for the second winter pavement condition

$n_1$ = sample size of friction values for the first winter pavement condition

$n_2$ = sample size of friction values for the second winter pavement condition

Z = Z factor for a given confidence level

Since "Bare" and "Snow Covered" pavement conditions did not have a sufficient amount of data for a statistical analysis, only friction values related to "Centerline Bare," Wheel Track Bare," and "Loose Snow" were compared.

**Table 4.5: Statistical Analysis Results for Average Friction Values and Winter Pavement Conditions**

| Variable | Centerline Bare | | Wheel Track Bare | | Loose Snow | |
|---|---|---|---|---|---|---|
| | TP | WMT | TP | WMT | TP | WMT |
| μ | 0.26 | 0.34 | 0.26 | 0.25 | 0.12 | 0.13 |
| Std. Dev (S) | 0.09 | 0.13 | 0.13 | 0.09 | 0.03 | 0.03 |
| Sample size (n) | 20 | 37 | 94 | 148 | 60 | 81 |
| $S_d$ | 0.029 | | 0.015 | | 0.005 | |
| $\lvert\overline{\mu_1} - \overline{\mu_2}\rvert$ | 0.08 | | 0.01 | | 0.01 | |
| $ZS_d$ | 0.0575 | | 0.0298 | | 0.01002 | |
| Result | Different | | Not Different | | Not Different | |

The analysis showed there were no statistically significant differences in friction values for "Wheel Track Bare" and "Loose Snow" conditions at the 95% confidence level behind a TP and a WMT. However, friction values related to the "Centerline Bare" pavement condition showed statistically significant differences at a 95% confidence level behind a TP and a WMT. This may be due to the limited number of friction test results that were available behind both a TP and a WMT under "Centerline Bare" conditions. Generally, under the "Centerline Bare" condition, higher friction values were observed behind both a TP and a WMT; hence driving safety is not compromised by these differences.

Various byproduct-type relationships were developed based on the above collected data and are included in Appendix C of this report. These include:

- Winter maintenance performance measures based on winter pavement condition and pavement friction.
- Winter driving speed limit recommendations based on pavement friction.

## CHAPTER 5: PERFORM COST-BENEFIT ANALYSIS FOR TOW PLOW COMBO UNIT (WMTP) TO REGULAR PLOW (WMT)

### 5.1 Cost-Benefit Analysis Methodology

As replicated in the following figure, the NCHRP study 20-07 (2012) presented an overall framework for estimating the cost and benefits of winter maintenance at a *statewide* level.

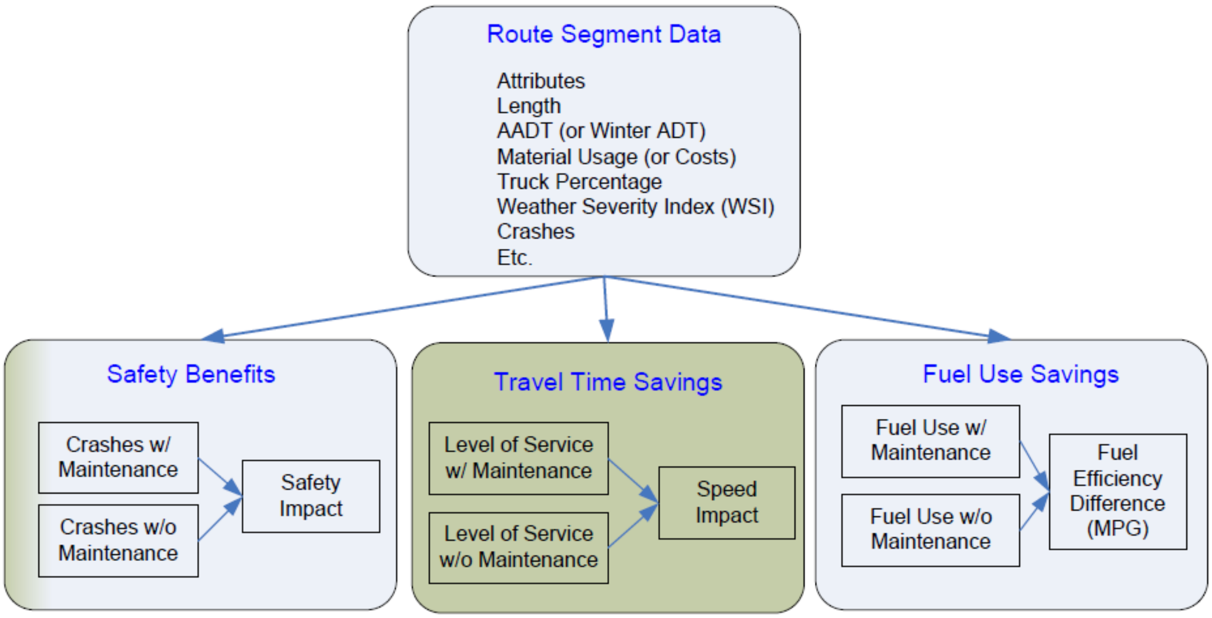



**Figure 5.1: Framework for Cost-Benefit Estimation of Winter Maintenance (NCHRP, 2007)**

Our study was smaller in scale and aimed at developing cost-benefit ratios when comparing two different winter maintenance equipment options (WMTP vs. WMT) at the *maintenance segment* level. Once the ratio for each selected winter maintenance equipment option per each maintenance segment was established, the most efficient winter maintenance strategy for each maintenance segment can be employed thus increasing efficiency and cost effectiveness.

The above framework identified three major quantifiable benefits of winter maintenance:

1. Safety Benefits – Crash frequencies are reduced as a result of winter maintenance. If the selected equipment option clears the snow faster on the traveled roadways, the frequency of winter weather-related accidents should be reduced more quickly.
2. Travel Time Savings – Vehicles can travel with reduced travel delay times on clearer roadways. If the selected equipment option clears the snow faster, travel times will decrease.

3. Fuel Use Savings – Previous studies suggested that fuel consumption increases when vehicles travel on snow-packed or icy roadways when compared to vehicles traveling on clear roadways. The average increase in fuel usage varied from 33% to as much as 50% (NCHRP, 2007). Therefore, if the selected equipment option clears the roadway more quickly, savings are realized due to reduced fuel usage.

Winter maintenance costs include materials, labor, and equipment including capital and maintenance costs. There are other indirect costs such as vehicle delay cost, productivity loss due to fatigue, etc. Except for vehicle delay cost, other societal costs are hard to quantify and were neglected in this analysis.

When estimating the cost and benefit of winter maintenance using any equipment option, the following types of data were needed for each maintenance segment.

- Segment Attributes:
  - Road name
  - Road number
  - Maintenance job number
  - Road class
  - Length
  - Number of lanes
  - Annual Average Daily Traffic (AADT) or Winter ADT
- Crash Data - The number of crashes for different crash types:
  - K - Fatal
  - A - Incapacitating injury
  - B - Non-incapacitating injury
  - C - Possible injury
  - O - No injury
- Weather Data - The average duration (or weather severity index) and number of different types of winter storms:
  - Freezing rain
  - Light snow - <2 inches
  - Medium snow - 2 inches to 6 inches
  - Heavy snow - > 6 inches

When estimating the winter maintenance costs per each maintenance segment, the following data were needed:

- Capital Equipment Costs
  - WMTPs with upgrades
  - WMTs

        - Estimated service life
- Maintenance Labor Costs
    - Salary
    - Benefits
    - Overhead
    - Percentage overtime
- Equipment Operating Costs
    - Depreciation of the equipment
    - Operating costs of the equipment
        - Fuel
        - Lubricants
        - Tires
        - Repairs
    - Material Costs – Based on total material (salt, sand, and/or brine) consumption for different winter seasons for each maintenance segment
- Typical Maintenance Truck Routes and Maintenance Priority Classifications
    - Maintenance priority classification
    - ADT
    - Lane-miles per maintenance truck
    - Average truck speed
    - Cycle time
    - Treatment coverage time (hrs/day)

### 5.1.1 Winter Maintenance Direct Cost Estimation

In this project, the winter maintenance direct cost per each maintenance segment was estimated as shown below.

$$WMC_j = \sum_{k=1}^{n} \left( CEC_{jk}, MLC_{jk}, MC_{jk} \right)$$

Where,

$WMC_j$ = winter maintenance cost for the $j^{th}$ maintenance segment per winter storm

$CEC_{jk}$ = equipment rental rates including all attachments (wings, spreader, and TP) for the $j^{th}$ maintenance segment per winter season for the $k^{th}$ type of equipment

$MLC_{jk}$ = maintenance labor cost including any overtime costs for the $j^{th}$ maintenance segment per winter season for the $k^{th}$ type of equipment

$MC_{jk}$ = winter maintenance material costs for the $j^{th}$ maintenance segment per winter season for the $k^{th}$ type of equipment

### 5.1.2 Safety Benefit Estimation

As previous studies suggest, a relationship between crash frequency and explanatory variables, such as weather condition, AADT, and maintenance efforts, is needed to estimate the safety benefit of winter roadway maintenance. NCHRP project 20-07 referred to this relationship as the Safety Performance Function (SPF) and is shown below.

$$Crash = f(Length, AADT, Weather\ Condition, maintenance\ efforts, \ldots .)$$

The most commonly used approach for modeling accident frequency is the Negative Binomial (NB) regression model. The NB regression model consists of two parts: the distribution function and the link function as shown below (NCHRP 20-07, 2012).

Distribution function:

$$Y_{it}/u_{it} \sim Poisson(u_{it})$$

Link function:

$$u_{it} = f(X;\beta)\exp(e_{it})$$

Where,

$Y_{it}$ = the number of crashes at the $i^{th}$ entity and $t^{th}$ time period
$u_{it}$ = the mean of the Poisson distribution
$\beta$ = the coefficients of covariates
$e_{it}$ = the model error independent of covariates

The distribution function estimates the number of crashes ($Y_{it}$) for the $i^{th}$ road segment at time period $t$. This is conditional to $u_{it}$, the mean of the Poisson distribution. In the link function, it is assumed that $\exp(e_{it})$ is independent and gamma distributed with a mean equal to 1 and variance $1/\emptyset, \emptyset > 0$. The probability distribution function of $Y_{it}$ is Poisson-gamma and the parameter $f$ is the inverse dispersion parameter of the NB distribution as shown in the equation below (NCHRP 20-07, 2012).

$$\Pr(Y_{it} = y_{it}) = f(y_{it}; u_{it}; \phi) = \frac{\Gamma(y_{it} + \phi)}{\Gamma(y_{it} + 1)\Gamma(\phi)} \left(\frac{u_{it}}{u_{it} + \phi}\right)^{y_{it}} \left(\frac{\phi}{u_{it} + \phi}\right)^{\phi}$$

The mean and variance of $Y_{it}$ are:

$$E(Y_{it}) = u_{it}$$

and

$$Var(Y_{it}) = u_{it} + u_{it}^2/\phi$$

respectively.

The functional form of the link function, usually developed using crash data modeling, describes the relationship between crash frequency and explanatory variables.

In the NCHRP study 20-07, the use of the above modeling approach was demonstrated by using a dataset from the Minnesota Department of Transportation (MnDOT). As seen in the equation below, the following variables were used to estimate crash frequency.

$$crash = f(length, winter\ ADT, Material\ Cost, winter\ severity\ index)$$

The crash frequency $u_i$ was defined by the following equation.

$$u_i = \beta_0 \times L_i \times ADT_i^{\beta_1} \times e^{\beta_2 \times C_i + \beta_3 \times WSI_i}$$

Where,

$u_i$ = crash frequency of the $i^{th}$ segment
$L_i$ = length of the $i^{th}$ segment
$ADT_i$ = winter ADT of the $i^{th}$ segment
$C_i$ = material cost for the $i^{th}$ segment ($/winter season)
$WSI_i$ = winter severity index of the $i^{th}$ segment
$\beta_0, \beta_1, \beta_2, \beta_3$ = coefficients

Using average data values calculated from five winter seasons and 828 maintenance segments, the following regression equation was developed. Note: Having a level of 0.01, $\beta_3$ was considered insignificant and removed from the final equation.

$$u_i = (9.487 \times 10^{-5} \times L_i \times ADT_i^{1.104} \times e^{(-1.959 \times 10^{-6}) \times C_i}$$

This model was used to estimate the safety benefit of winter maintenance by setting maintenance costs for all segments to zero. The predicted crash values represent the number of crashes that would have occurred if no winter maintenance was carried out. When applied, the study showed that winter maintenance reduced the number of crashes for all the segments by 29.4%.[5, 6]

[5] In practice, multiple equipment configurations and options (one or two WMTPs and/or a number of regular WMTs) are utilized on the same route during winter storm events. Therefore, safety benefits for individual equipment options are extremely difficult to estimate. As a result, individual safety benefits relative to regular WMTs and WMTPs were excluded in this cost-benefit estimation.

[6] During this research study, the total number of winter weather-related accidents were analyzed before and after introducing WMTPs to the winter maintenance fleet. Since the historical accident data after introducing the WMTP for winter maintenance is limited (2 years), statistically significant conclusions may not be feasible at this time. The researchers suggest revisiting this item after the WMTPs have been in use for a few more years of winter maintenance in order to generate a more statistically significant dataset for this analysis.

### 5.1.3 Modeling of Travel Time Benefits

Again, the methodology provided in the NCHRP study 20-07 was adopted to estimate travel time savings per maintenance segment. The following study equation was used to calculate these benefits.

$$TTS = Dur \times (\frac{L}{S_1} - \frac{L}{S_2})(VOT_{PC} \times ADT_{PC} + VOT_{truck} \times ADT_{Truck})$$

Where,

$L$ = length of the maintenance segment
$S_1$, $S_2$ = vehicle speed without winter maintenance and with winter maintenance

### 5.1.4 Modeling Fuel Savings

Previous studies performed in the United States and Canada have shown that vehicles can consume 33% to 50% more fuel during winter storms. Since these results were calculated using average values over multiple snow seasons, fuel usage for individual maintenance segments under different winter Level of Service (or winter pavement conditions) scenarios is difficult to estimate. The NCHRP project 20-07 used the following approach to determine fuel savings for winter maintenance conditions.

Initially, the following equation was used to estimate fuel usage with the assumption that no winter maintenance was performed.

$$Fuel_{pcNM} = \frac{MVM_{pc}}{MPG_{pc} \times 0.67} \times \frac{Storm_{hrs}}{24} \times Cost_{Avg}$$

Where,

$Fuel_{pcNM}$ = fuel usage under the no (or limited) winter maintenance condition
$MVM_{pc}$ = million vehicle miles (MVM) traveled for passenger cars per day during the winter season examined in the study area (or maintenance segment)
$MPG_{pc}$ = an average passenger vehicle MPG value
$Storm_{hrs}$ = total storm duration, in hours, per season
$Cost_{Avg}$ = average fuel cost in the area for the winter season
0.67 = adjustment factor to account for 33% reduction in vehicle MPG when no winter maintenance is performed

The same equation was used to calculate the fuel usage for heavy vehicles, again with the assumption that no winter maintenance was performed. Then, after removing the 0.67 adjustment factor, the fuel usage for the winter maintenance condition was calculated. In this project, winter maintenance fuel savings were estimated using only regular WMTs and WMTPs in the snow removal equipment fleet for each maintenance route. The above NCHRP 20-07 equations can be modified and used with only regular WMTs in the snow removal equipment fleet and WMTPs in the fleet for each maintenance route for each winter storm. Fuel usage for passenger cars ($Fuel_{pc\_snowplow}$) and heavy vehicles ($Fuel_{hv\_snowplow}$) traveling during snow events while roads are being maintained using only a WMT in the fleet was estimated by the following equations:

$$Fuel_{pc\_WMT} = \frac{MVM_{pc}}{MPG_{pc} \times 0.67} \times \frac{TB_{WMT}}{24} \times Cost_{Avg}$$
$$Fuel_{hv\_WMT} = \frac{MVM_{hv}}{MPG_{hv} \times 0.67} \times \frac{TB_{WMT}}{24} \times Cost_{Avg}$$

Similarly, the same equations are used to determine fuel usage when WMTPs are employed.

$$Fuel_{pc_{WMTP}} = \frac{MVM_{pc}}{MPG_{pc} \times 0.67} \times \frac{TB_{WMTP}}{24} \times Cost_{Avg}$$
$$Fuel_{hv\_WMTP} = \frac{MVM_{hv}}{MPG_{hv} \times 0.67} \times \frac{TB_{WMTP}}{24} \times Cost_{Avg}$$

The time to bare pavement (*TB*) in hours replaces $Storm_{hrs}$ in these equations. Time to bare pavement (*TB*) can be obtained from analyzing vehicle speed data as described in Section 5.4 of this report.

Estimated from previous research studies, the adjustment factor 0.67 was used here for demonstration purposes only.[7]

## 5.2 Winter Maintenance Direct Costs

As described in Section 5.1.1, winter maintenance costs include winter maintenance equipment costs, maintenance labor costs, and winter maintenance material costs.

### 5.2.1 Winter Maintenance Equipment Costs

Discussions with MDOT winter maintenance personnel revealed that MDOT uses a vehicle/equipment rental rate model for calculating equipment usage costs.  These costs include the use of their own equipment as well as equipment hired from the counties. These rental rates include the hourly cost of using each vehicle/piece of equipment based on the initial cost, salvage value, and operating costs of the equipment. The rental rates use annualized costs of the equipment

[7] More studies to establish MPG values under different snow conditions need to be conducted to predict the fuel usage savings accurately when WMTPs are utilized. The research team recommends conducting future studies with this adjustment factor.

and the annual usage time to calculate the hourly rate for each piece of equipment. This vehicle equipment rental rate model was utilized for this research project. The following tables show the type of winter maintenance equipment and related rental rates for the Brighton, Charlotte, Williamston, Grand Ledge, and Reed City maintenance garages.

**Table 5.1: MDOT Equipment Rental Rates for Brighton Garage**

| Unit Number | Type of Equipment | Wings/TP | Spreader | Hourly Rate ($) |
|---|---|---|---|---|
| 04-1356 | Single | N/A | Yes | 37.26 |
| 04-1476 | Single | N/A | Yes | 37.26 |
| 04-1528 | Tandem | N/A | N/A | 56.09 |
| 04-1565 | Tandem | N/A | N/A | 56.09 |
| 04-1579 | Tandem | Left Wing | N/A | 64.90 |
| 04-1591 | Tandem | N/A | Yes | 59.23 |
| 04-1592 | Tandem | N/A | Yes | 59.23 |
| 04-1625 | Tandem | Right Wing | N/A | 64.90 |
| 04-1692 | Tandem | Right Wing | N/A | 64.90 |
| 04-3024 | Single | N/A | Yes | 37.26 |
| 04-3032 | Single | N/A | N/A | 37.26 |
| 04-4004 | Tandem | Left Wing | N/A | 70.63 |
| 04-4005 | Tandem | Left Wing | N/A | 70.63 |
| 04-4049 | Tandem | TP | N/A | 102.07 |
| 04-4016 | Tandem | N/A | N/A | 59.23 |
| 04-3033 | Single | N/A | N/A | 37.26 |

**Table 5.2: MDOT Equipment Rental Rates for Charlotte Garage**

| Unit Number | Type of Equipment | Wings/TP | Spreader | Hourly Rate ($) |
|---|---|---|---|---|
| 04-1493 | Single | N/A | Yes | 37.26 |
| 04-4058 | Tandem | Yes | Yes | 68.04 |
| 04-1691 | Tandem | Yes | Yes | 68.04 |
| 04-1627 | Tandem | N/A | Yes | 56.09 |
| 04-1461 | Single | N/A | Yes | 37.26 |
| 04-1428 | Single | N/A | Yes | 37.26 |
| 04-3034 | Single | N/A | Yes | 37.26 |
| 04-3047 | Single | N/A | Yes | 37.26 |
| 04-3012 | Single | N/A | Yes | 37.26 |
| 04-4028 | Tandem | Yes | Yes | 68.04 |
| 04-4059 | Tandem | TP | Yes | 110.86 |

**Table 5.3: MDOT Equipment Rental Rates for Williamston Garage**

| Unit Number | Type of Equipment | Wings/TP | Spreader | Hourly Rate ($) |
|---|---|---|---|---|
| 04-1494 | Single | N/A | Yes | 37.26 |
| 04-1516 | Tandem | N/A | N/A | 56.09 |
| 04-1566 | Tandem | Right Wing | Yes | 68.04 |
| 04-1610 | Tandem | Right Wing | N/A | 64.90 |
| 04-1628 | Tandem | N/A | N/A | 56.09 |
| 04-1664 | Tandem | Right Wing | N/A | 64.09 |
| 04-3014 | Single | N/A | Yes | 37.26 |
| 04-4026 | Tandem | Right Wing | Yes | 68.04 |
| 04-4027 | Tandem | Right Wing | Yes | 68.04 |
| 04-4043 | Tandem | Right Wing | Yes | 68.04 |
| 04-4060 | Tandem | TP | Yes | 102.07 |

**Table 5.4: MDOT Equipment Rental Rates for Grand Ledge Garage**

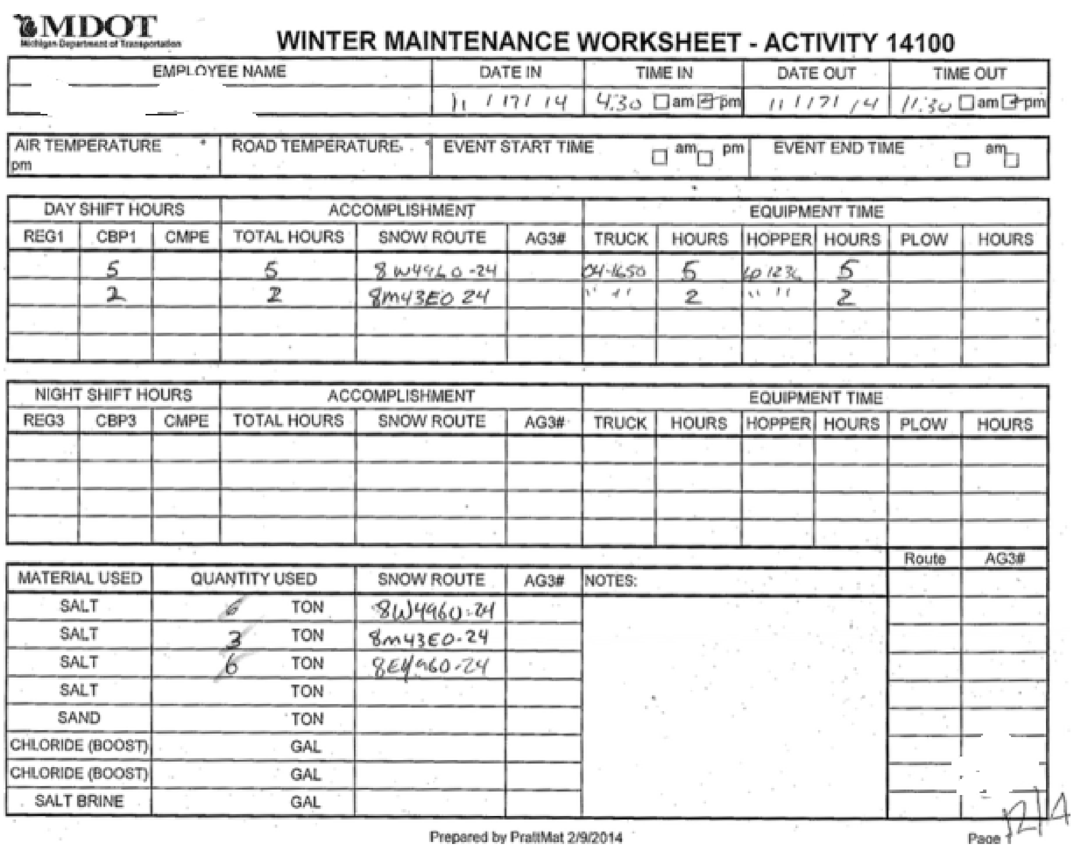
| Unit Number | Type of Equipment | Wings/TP | Spreader | Hourly Rate ($) |
|---|---|---|---|---|
| 04-1436 | Single | N/A | Yes | 37.26 |
| 04-1515 | Tandem | N/A | Yes | 59.23 |
| 04-1521 | Tandem | N/A | Yes | 59.23 |
| 04-1531 | Tandem | N/A | N/A | 56.09 |
| 04-1580 | Tandem | N/A | N/A | 56.09 |
| 04-1590 | Tandem | N/A | N/A | 56.09 |
| 04-1611 | Single | Yes | Yes | 68.04 |
| 04-1646 | Tandem | Yes | Yes | 68.04 |
| 04-1650 | Tandem | Yes | N/A | 64.90 |
| 04-1668 | Tandem | N/A | Yes | 59.23 |
| 04-1688 | Tandem | Yes | Yes | 68.04 |
| 04-3006 | Single | N/A | Yes | 37.26 |
| 04-3007 | Single | N/A | Yes | 37.26 |
| 04-3010 | Single | N/A | Yes | 37.26 |
| 04-3013 | Single | N/A | Yes | 37.26 |
| 04-4024 | Tandem | Yes | Yes | 68.04 |
| 04-4042 | Tandem | Yes/TP | Yes | 110.86 |

**Table 5.5: MDOT Equipment Rental Rates for Reed City Garage**

| Unit Number | Type of Equipment | Wings/TP | Spreader | Hourly Rate ($) |
|---|---|---|---|---|
| 04-1546 | Tandem | Yes | N/A | 64.90 |
| 04-1564 | Tandem | Yes | N/A | 64.90 |
| 04-1655 | Tandem | Yes | Yes | 68.03 |
| 04-1671 | Tandem | N/A | Yes | 59.23 |
| 04-3011 | Single | N/A | Yes | 37.26 |
| 04-3019 | Single | N/A | Yes | 37.26 |
| 04-4034 | Tandem | Yes | N/A | 64.90 |
| 04-4052 | Tandem | Yes | Yes | 68.04 |

### 5.2.2 Winter Maintenance Labor and Materials Costs

For each winter storm, winter maintenance labor and material costs were obtained from MDOT Form 14100. Each MDOT winter maintenance employee completes this form after performing winter maintenance activities on his assigned routes. Employee activities for each winter storm related to respective routes, the number of hours, equipment details and winter maintenance material used, etc., are recorded. A sample form is shown in Figure 5.2.


MDOT Michigan Department of Transportation

WINTER MAINTENANCE WORKSHEET - ACTIVITY 14100

| EMPLOYEE NAME | DATE IN | TIME IN | DATE OUT | TIME OUT |
|---|---|---|---|---|
| | 11 / 17 / 14 | 4:30 am pm | 11 / 17 / 14 | 11:30 am pm |

| AIR TEMPERATURE pm | ROAD TEMPERATURE | EVENT START TIME am pm | EVENT END TIME am |
|---|---|---|---|

| DAY SHIFT HOURS | | | ACCOMPLISHMENT | | | EQUIPMENT TIME | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| REG1 | CBP1 | CMPE | TOTAL HOURS | SNOW ROUTE | AG3# | TRUCK | HOURS | HOPPER | HOURS | PLOW | HOURS |
| | 5 | | 5 | 8W4960-24 | | 04-1650 | 5 | 60123 | 5 | | |
| | 2 | | 2 | 8M43EO 24 | | " " | 2 | " " | 2 | | |

| NIGHT SHIFT HOURS | | | ACCOMPLISHMENT | | | EQUIPMENT TIME | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| REG3 | CBP3 | CMPE | TOTAL HOURS | SNOW ROUTE | AG3# | TRUCK | HOURS | HOPPER | HOURS | PLOW | HOURS |

| MATERIAL USED | QUANTITY USED | | SNOW ROUTE | AG3# | NOTES: | Route | AG3# |
|---|---|---|---|---|---|---|---|
| SALT | 6 | TON | 8W4960-24 | | | | |
| SALT | 3 | TON | 8M43EO-24 | | | | |
| SALT | 6 | TON | 8E4960-24 | | | | |
| SALT | | TON | | | | | |
| SAND | | TON | | | | | |
| CHLORIDE (BOOST) | | GAL | | | | | |
| CHLORIDE (BOOST) | | GAL | | | | | |
| SALT BRINE | | GAL | | | | | |

Prepared by PrattMat 2/9/2014

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**Figure 5.2: Sample MDOT Form 14100**

The research team obtained thousands of these MDOT 14100 forms from different maintenance garages (Brighton, Williamston, Grand Ledge, Reed City and Charlotte) for different years and different winter storms. These forms were analyzed in order to retrieve the following data for each winter storm:

- Labor cost for each maintenance route
- Winter maintenance materials cost for each maintenance route
- Equipment cost for each maintenance route based on equipment rental rates
- Number of trucks used for each maintenance route

A sample set of data for winter maintenance routes in Brighton garage for the winter storm on 1/1/2014 – 1/2/2014 is shown below.

**Table 5.6: Total Hours, Salt Usage and Equipment Usage for Winter Storm on 1/1/2014 – 1/2/2014**

| Snow Route | Total Hours | Total Salt (tons) | Total Number of Snow Plows (WMTs and WMTPs) |
|---|---|---|---|
| 0M0059 | 58.5 | 91.54 | 2.00 |
| 0I0096 | 119.0 | 221.92 | 4.36 |
| 0US023 | 125.0 | 249.96 | 5.16 |
| 0M0036 | 46.0 | 72.18 | 1.00 |
| 0BI096 | 46.0 | 64.50 | 1.48 |

**Table 5.7: Costs for Winter Maintenance for Winter Storm on 1/1/2014 – 1/2/2014**

| Snow Route | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | Total Cost ($) |
|---|---|---|---|---|
| 0M0059 | 2,632.50 | 4,119.30 | 3,210.84 | 9,962.64 |
| 0I0096 | 5,355.00 | 9,986.40 | 8,038.53 | 23,379.93 |
| 0US023 | 5,625.00 | 11,248.20 | 7,054.07 | 23,927.27 |
| 0M0036 | 2,070.00 | 3,248.10 | 3,104.54 | 8,422.64 |
| 0BI096 | 2,070.00 | 2,902.50 | 3,180.22 | 8,152.72 |

By combining snow route and the units responding to this winter storm, the percent utilization for each winter maintenance unit per snow route was generated and is shown in Figure 5.3.

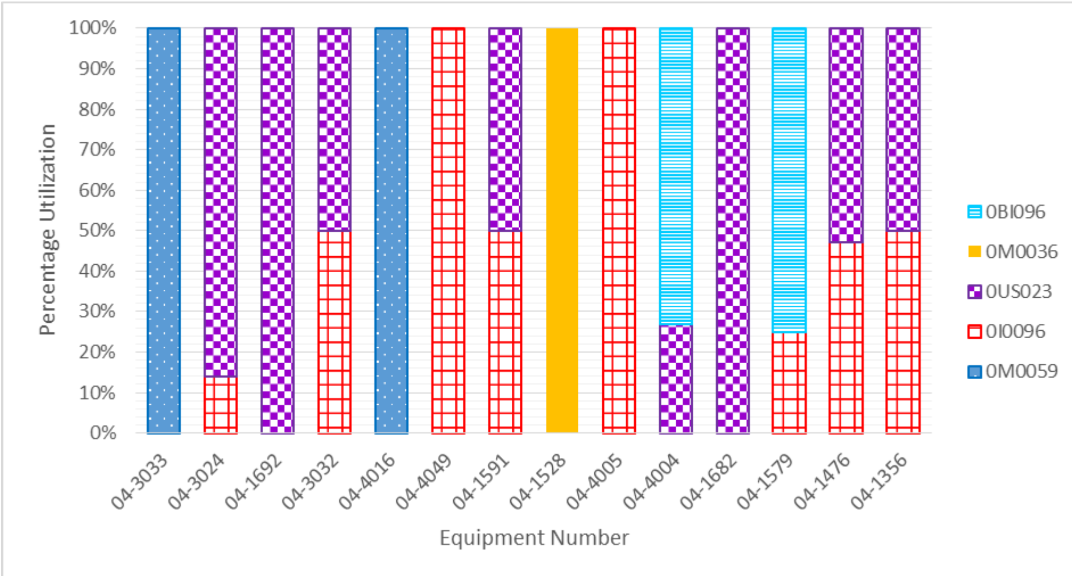


**Figure 5.3: Snow Plow (WMT and WMTP) Utilization for Each Maintenance Route for Winter Storm on 1/1/2014 – 1/2/2014**

Similar analyses were performed for each winter storm event for each maintenance route with WMTP usage in different garages. Appendix D of this report shows the summarized results of the above analysis.

### 5.3 Winter Maintenance Direct Cost Modeling

Winter maintenance costs for different types of roadways were modeled to estimate the cost-benefit of using a WMTP for winter maintenance. Relationships were developed for different cost elements relative to snowstorms of varying severity (measured as snow amount per storm). The following sections describe the developed models for different types of roadways.

#### 5.3.1 Characteristics of Low Severity Storms

As seen in the following figure, the winter maintenance cost relationships for low severity storms do not necessarily depend on snow severity. The maintenance costs for low severity storms are mostly dependent on the storm characteristics such as the duration of the storm, type of snow, wind condition, etc. However, the cost relationships for high severity storms largely depend on the severity of the snowstorm (amount of snow).

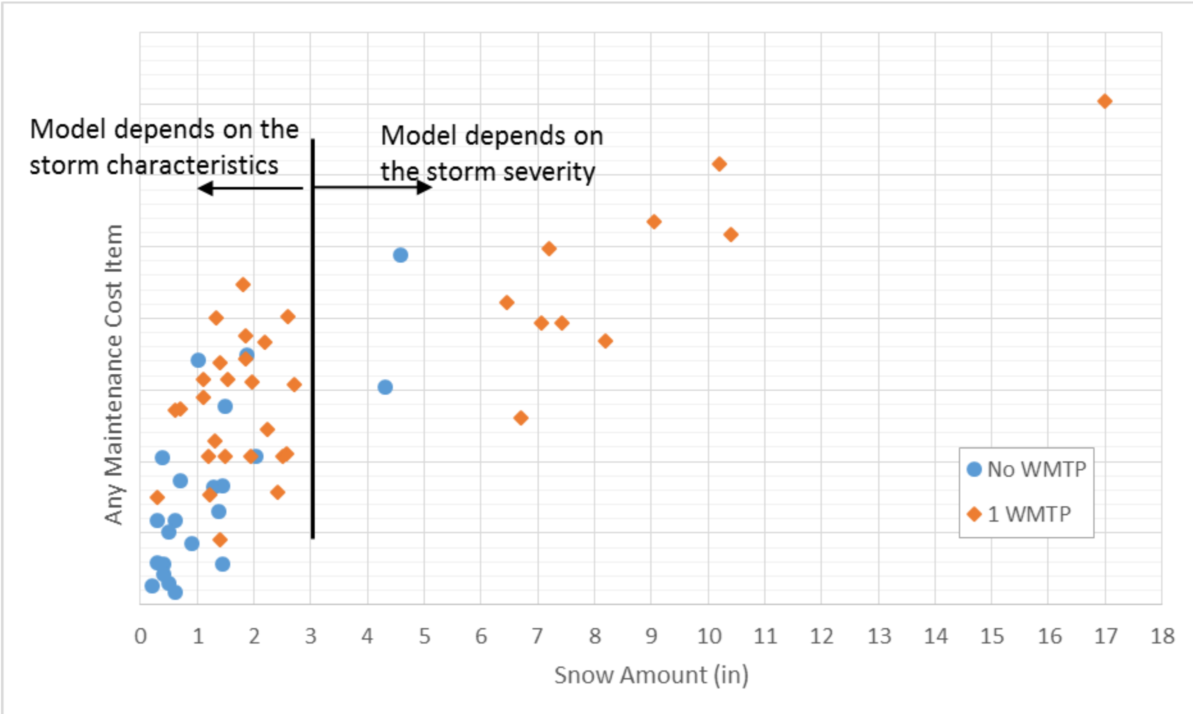


**Figure 5.4: Characteristics of Low Severity Storms**

For the maintenance cost modeling purposes as shown in the proceeding sections, the variability due to storm characteristics of low severity storms was neglected.

### 5.3.2 Modeling of Winter Maintenance Direct Costs for Six-Lane Expressway in a Rural Area (I-96 in Brighton, 121 Lane Miles)

Winter maintenance costs were analyzed using I-96 in Brighton, Michigan. This section of I-96 includes six lanes of expressway. Figures 5.5 to 5.8 show the developed relationships for total labor costs, total salt costs, total equipment costs, and combined total direct costs for different storm types. As seen from the following figures, different relationships were developed when only regular WMTs were in the equipment fleet (no WMTP) and one WMTP was in the equipment fleet (1 WMTP). With the limited data available for the analysis (winter storm events between 2012 and 2015), the "No WMTP" relationship was only valid for winter storms with less than 4.6 inches of snow.

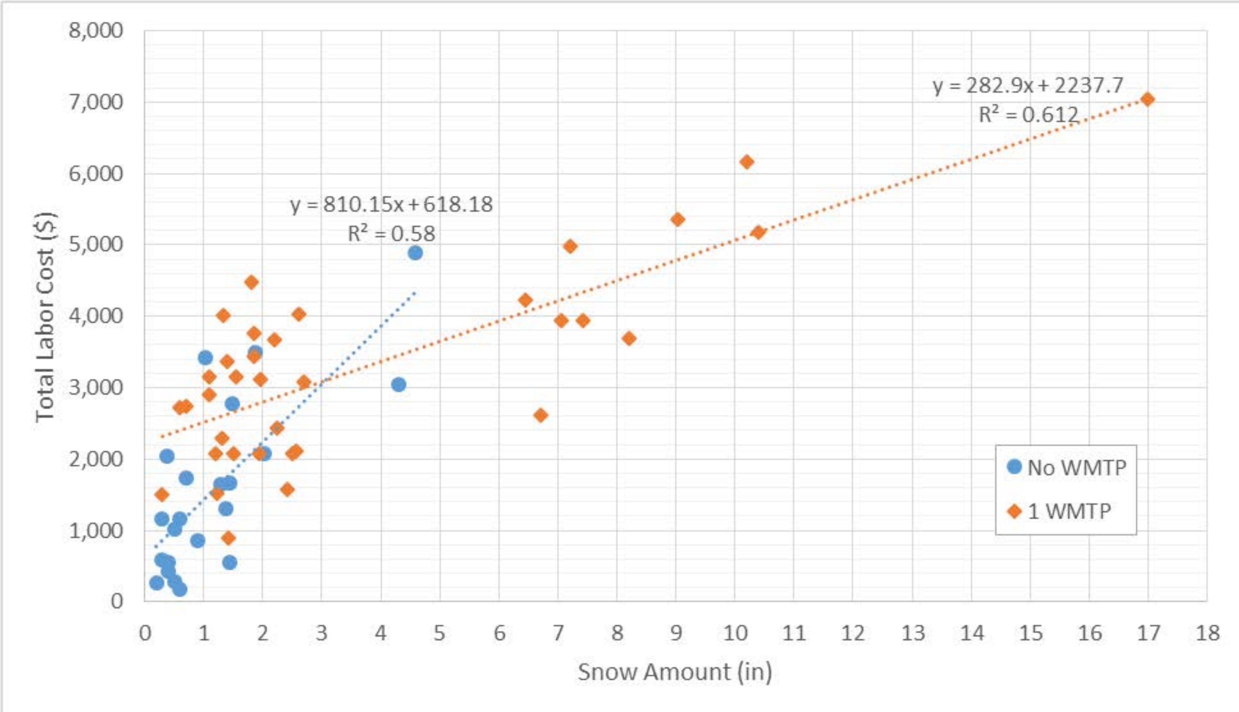


**Figure 5.5: Total Labor Cost with Snowstorm Severity for I-96 in Brighton**

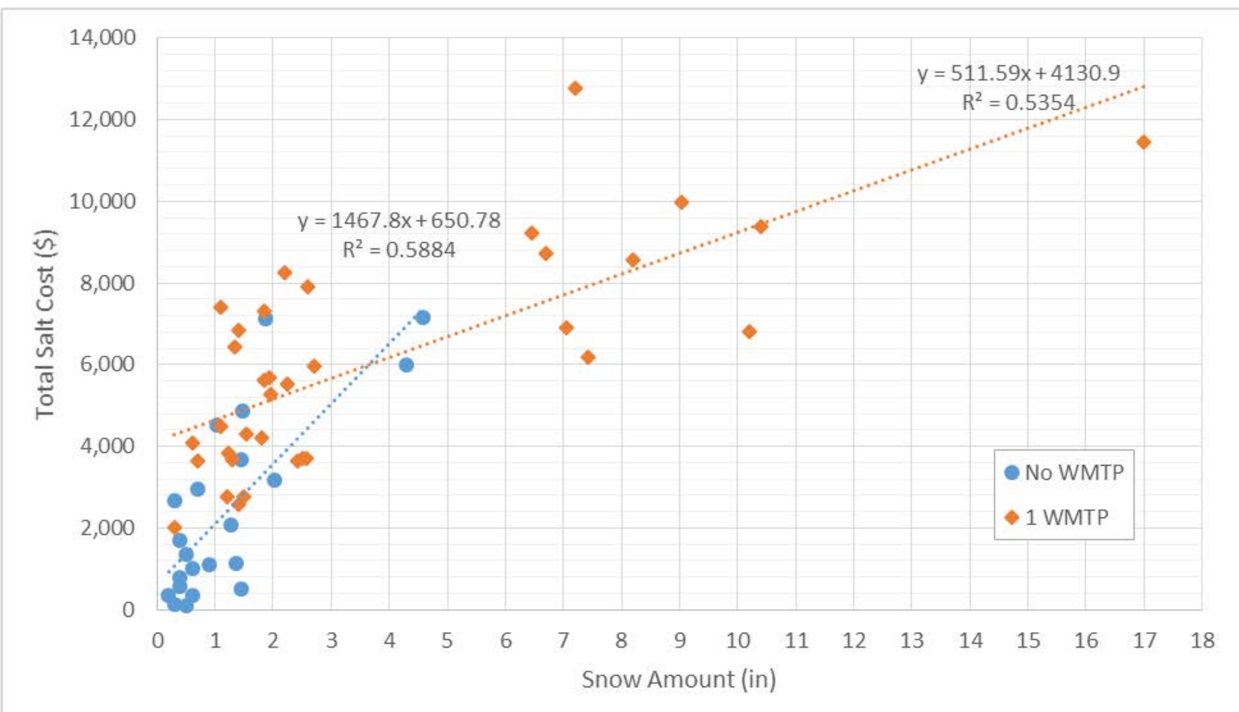


**Figure 5.6: Total Salt Cost with Snowstorm Severity for I-96 in Brighton**

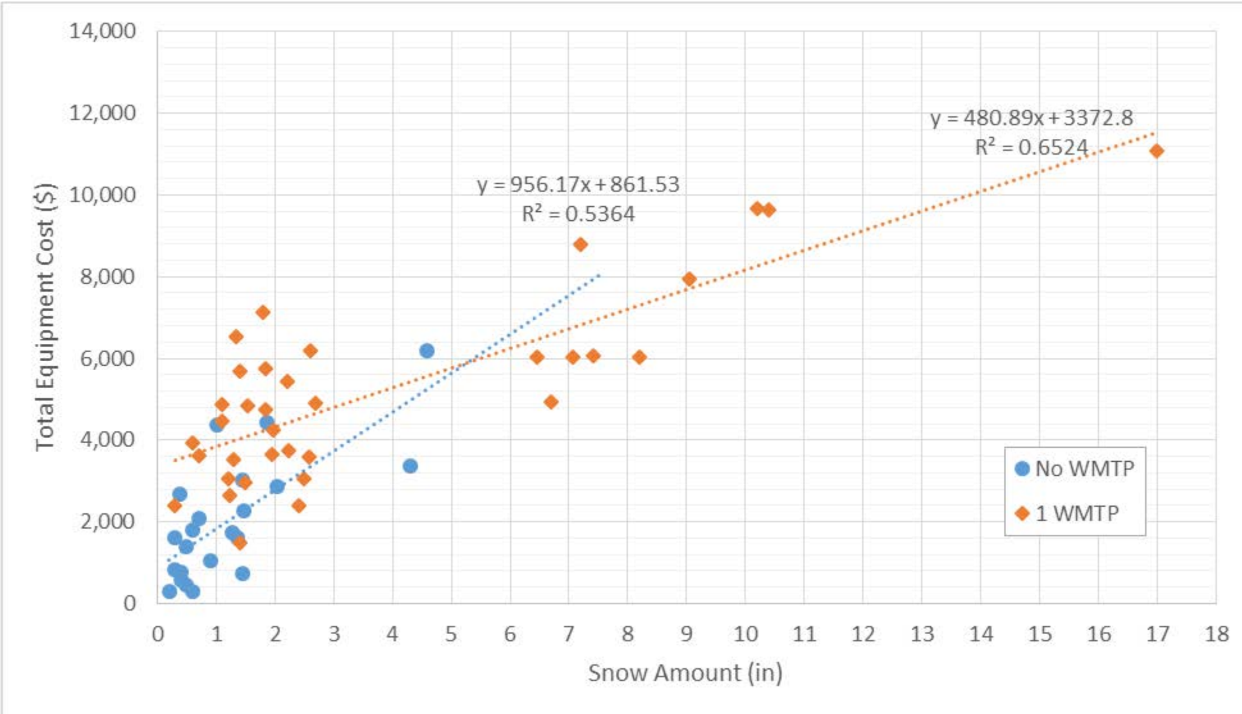


**Figure 5.7: Total Equipment Cost with Snowstorm Severity for I-96 in Brighton**

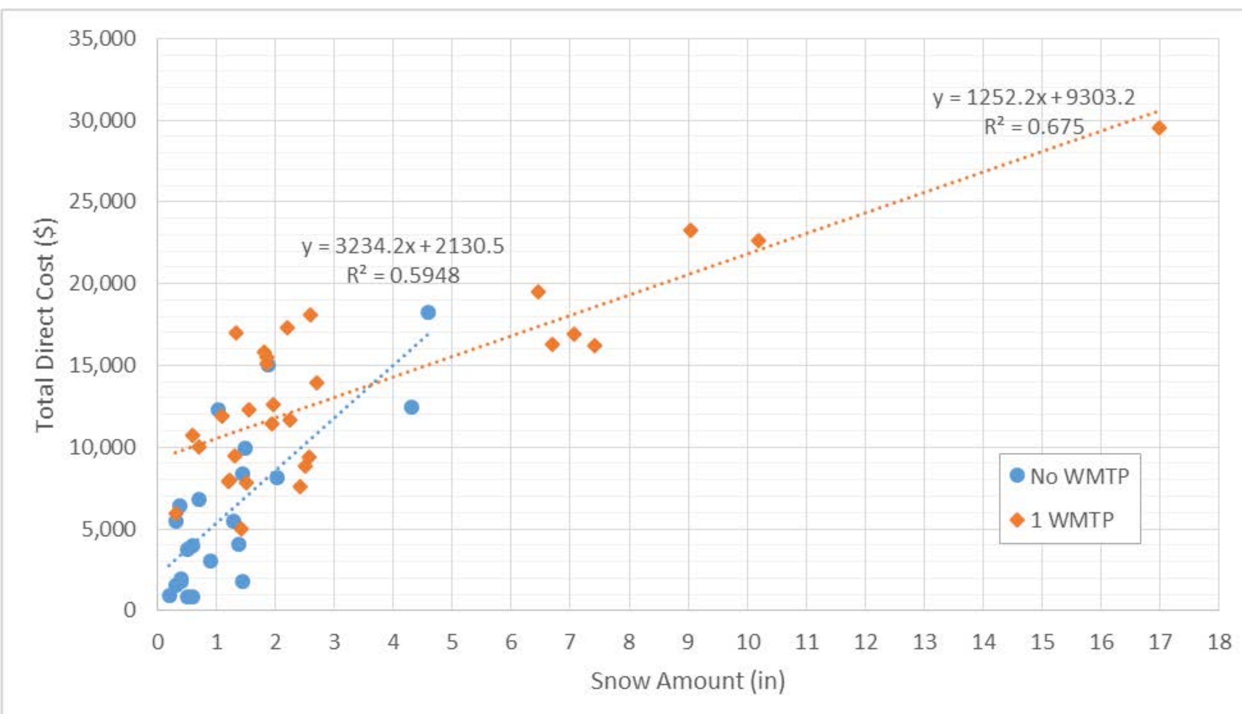


**Figure 5.8: Total Combined Direct Cost with Snowstorm Severity for I-96 in Brighton**

The above-developed relationships are shown in Table 5.8.

**Table 5.8: Total Direct Cost Relationships for Six-Lane Expressway with 121 Lane Miles (I-96, Brighton)**

| Relationship | Type of Plow | Equation | Goodness of Fit ($R^2$) |
|---|---|---|---|
| Total Labor Cost | No WMTPs in the fleet | $Total\ Labor\ Cost = 618.18 + 810.15 \times Snow\ Amount$ | 0.58 |
| | 1 WMTP in the fleet | $Total\ Labor\ Cost = 2237.7 + 282.9 \times Snow\ Amount$ | 0.61 |
| Total Salt Cost | No WMTPs in the fleet | $Total\ Salt\ Cost = 650.78 + 1467.8 \times Snow\ Amount$ | 0.59 |
| | 1 WMTP in the fleet | $Total\ Salt\ Cost = 4130.9 + 511.59 \times Snow\ Amount$ | 0.54 |
| Total Equipment Cost | No WMTPs in the fleet | $Total\ Equipment\ Cost = 861.53 + 956.17 \times Snow\ Amount$ | 0.54 |
| | 1 WMTP in the fleet | $Total\ Equipment\ Cost = 3372.8 + 480.89 \times Snow\ Amount$ | 0.65 |
| Total Combined Direct Cost | No WMTPs in the fleet | $Total\ Combined\ Direct\ Cost = 2130.5 + 3234.2 \times Snow\ Amount$ | 0.59 |
| | 1 WMTP in the fleet | $Total\ Combined\ Direct\ Cost = 9303.2 + 1252.2 \times Snow\ Amount$ | 0.68 |

After a minimum snow severity, the above relationships show when a WMTP is included in the winter maintenance equipment fleet, each cost item (labor, salt, equipment and total combined direct) trends lower than when no WMTPs are included. The breakeven storm severity occurs between 2.5 and 3.5 inches of snow. Based on the above relationships, conclusions indicate that WMTP usage in the equipment fleet is more economical when the snow severity is greater than 3.5 inches if the current equipment configuration is used.

Using the winter maintenance cost data for I-96 in Brighton, the total number of regular WMTs needed per each winter storm, with WMTPs in the fleet and without WMTPs in the fleet, can be calculated using the developed relationships shown below.

**Table 5.9: Number of Regular WMTs for Six-Lane Expressway in a Rural Area (121 Lane Miles)**

| Condition | Equation | Goodness of Fit ($R^2$) |
|---|---|---|
| Without WMTPs in the fleet | $No.of\ WMTs = 3.0377 \times Snow\ Amount^{0.3585}$ | 0.23 |
| With 1 WMTP in the fleet | $No.of\ WMTs = 2.5601 \times Snow\ Amount^{0.1775}$ | 0.22 |

The following figure shows the relationships for a total number of regular WMTs required for winter maintenance during winter storms with different severities.

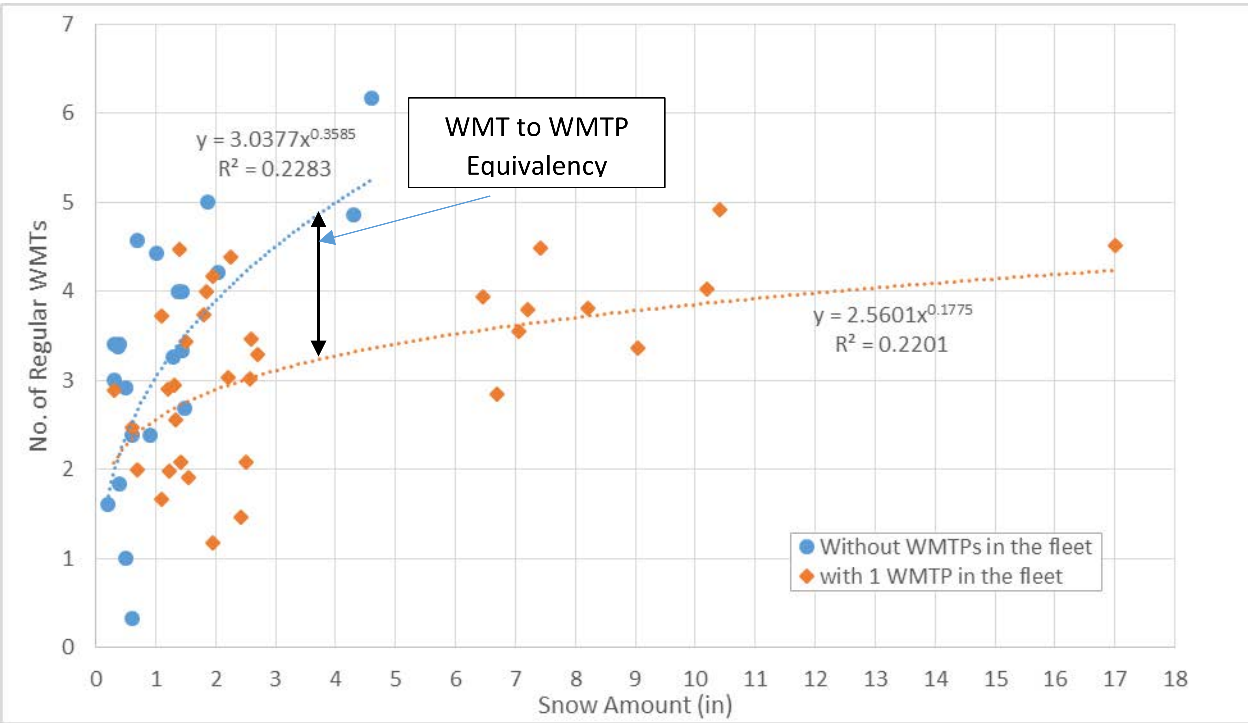


**Figure 5.9: Number of Regular WMTs with Snowstorm Severity for I-96 in Brighton**

As shown in Figure 5.9, the difference in the above relationships (trend lines) shows the regular WMT to WMTP equivalency as a function of the snowstorm severity. For example, when the snowstorm severity is 1 inch, the regular WMT to WMTP equivalency is 0.48. However, if the snowstorm severity is 2 inches, the WMT to WMTP equivalency is increased to 1.0. Although

Figure 5.9 shows the differences increase exponentially, the maximum equivalency should be 2.0, as shown in Figure 5.10.

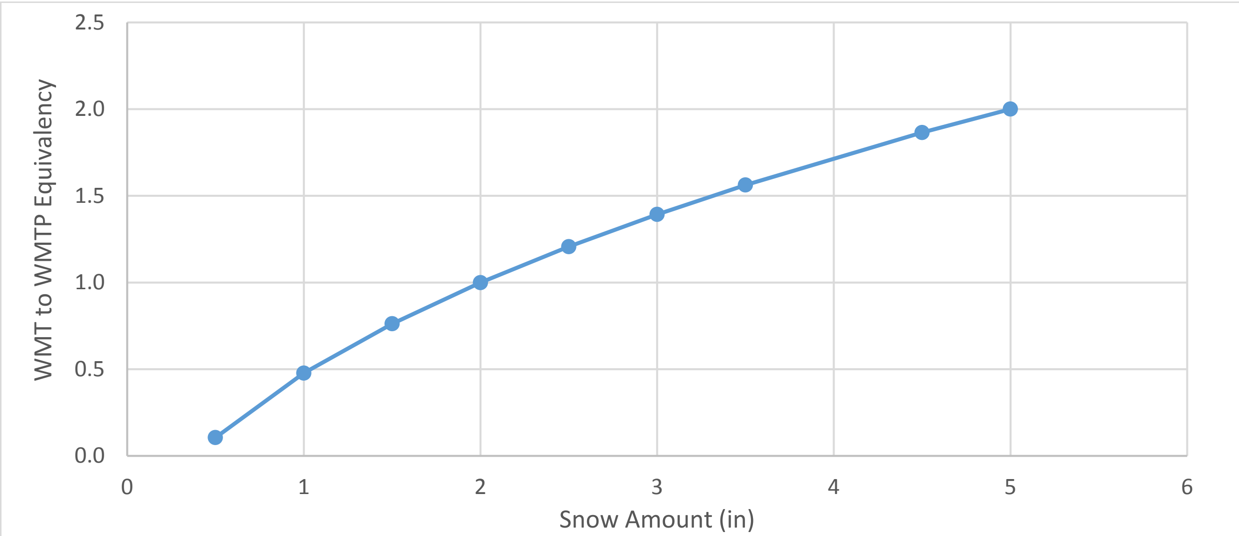


**Figure 5.10: Regular WMT to WMTP Equivalency for I-96 in Brighton (Six-Lane Expressway)**

The current equipment configuration can be modified for lower severity snowstorms by using fewer regular WMTs. Since the breakeven point for the total direct cost relationship (Figure 5.8) is 3.5 inches, the following recommended number of regular WMTs with one WMTP was developed using only total direct costs.

**Table 5.10: Recommended Equipment Configuration for Six-Lane Rural Expressway (Based on 121 Lane Miles only Considering Direct Costs)**

| Snowstorm Severity (inches) | Number of Regular WMTs* | Number of WMTPs* |
|---|---|---|
| 0.5 | 2 | 0 |
| 1.0 | 1 | 1 |
| 1.5 | 2 | 1 |
| 2.0 | 2 | 1 |
| 2.5 | 2 | 1 |
| 3.0 | 2 | 1 |
| 4.0 | 2 | 1 |
| 6.0 | 3 | 1 |
| 8.0 | 3 | 1 |
| 10.0 | 4 | 1 |
| 12.0 | 4 | 1 |

*These recommendations are purely based on direct cost calculations. MDOT should consider their equipment limitations when using these equipment configurations.

### 5.3.3 Modeling of Winter Maintenance Direct Costs for Four-Lane Expressway in a Rural Area (I-69 in Charlotte, 142 Lane Miles)

The analysis described in Section 5.3.2 was performed for data collected on a four-lane expressway (I-69) in Charlotte, Michigan. MDOT staff at the Charlotte garage focused on optimizing their winter maintenance fleet during the 2015-2016 snow season. When the WMTP was used in the snow fleet, the number of dispatched WMTs was modified based on the severity of the snowstorm. Total cost relationships for labor, salt, equipment and combined direct are shown in Figures 5.11 through 5.14.

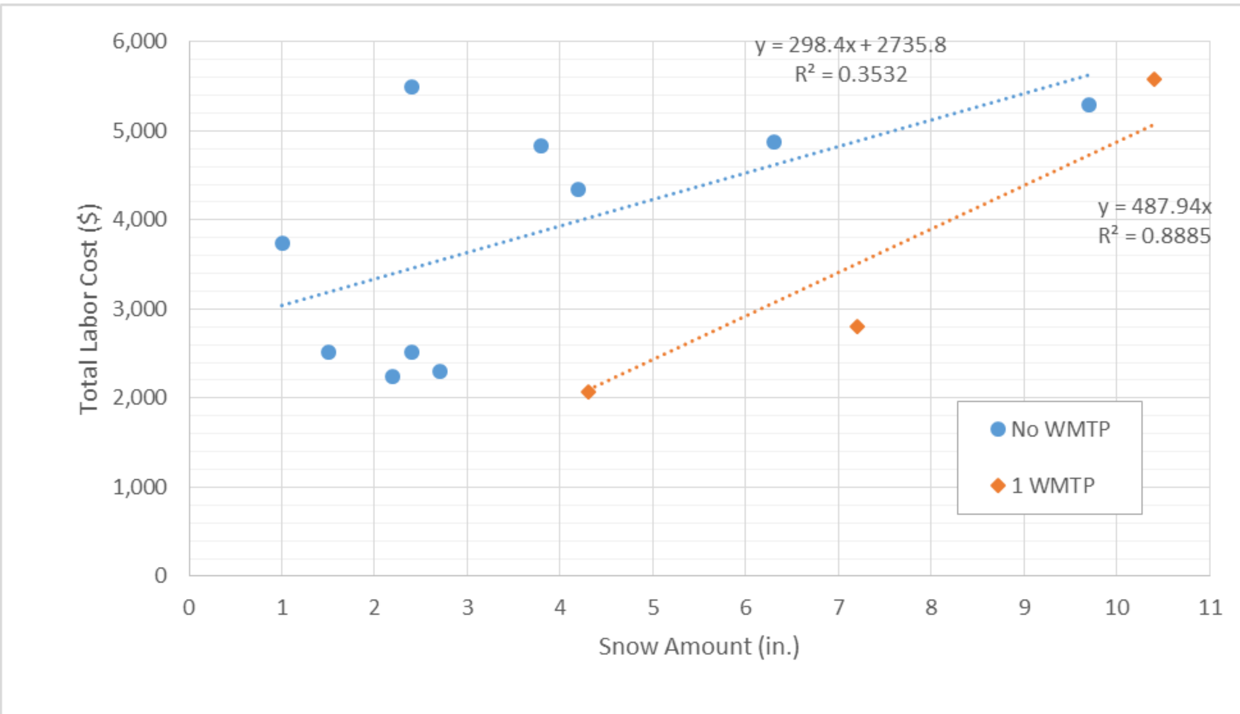


**Figure 5.11: Total Labor Cost with Snowstorm Severity for I-69 in Charlotte**

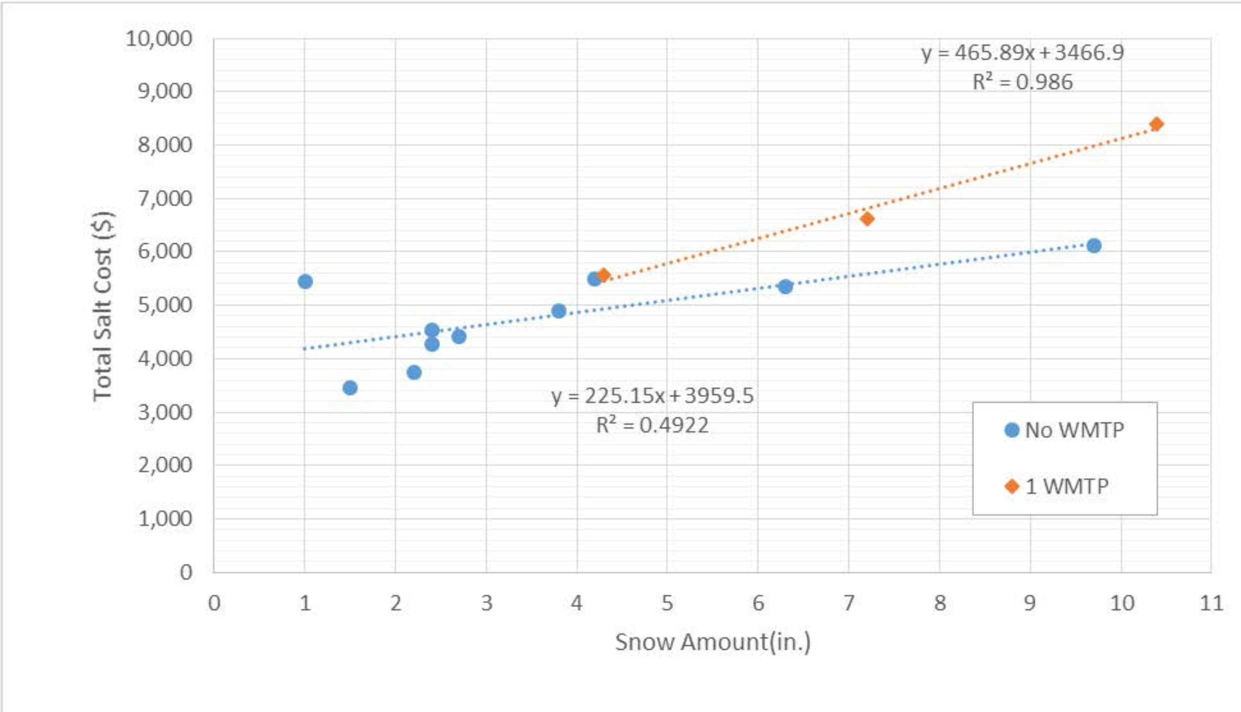


**Figure 5.12: Total Salt Cost with Snowstorm Severity for I-69 in Charlotte**

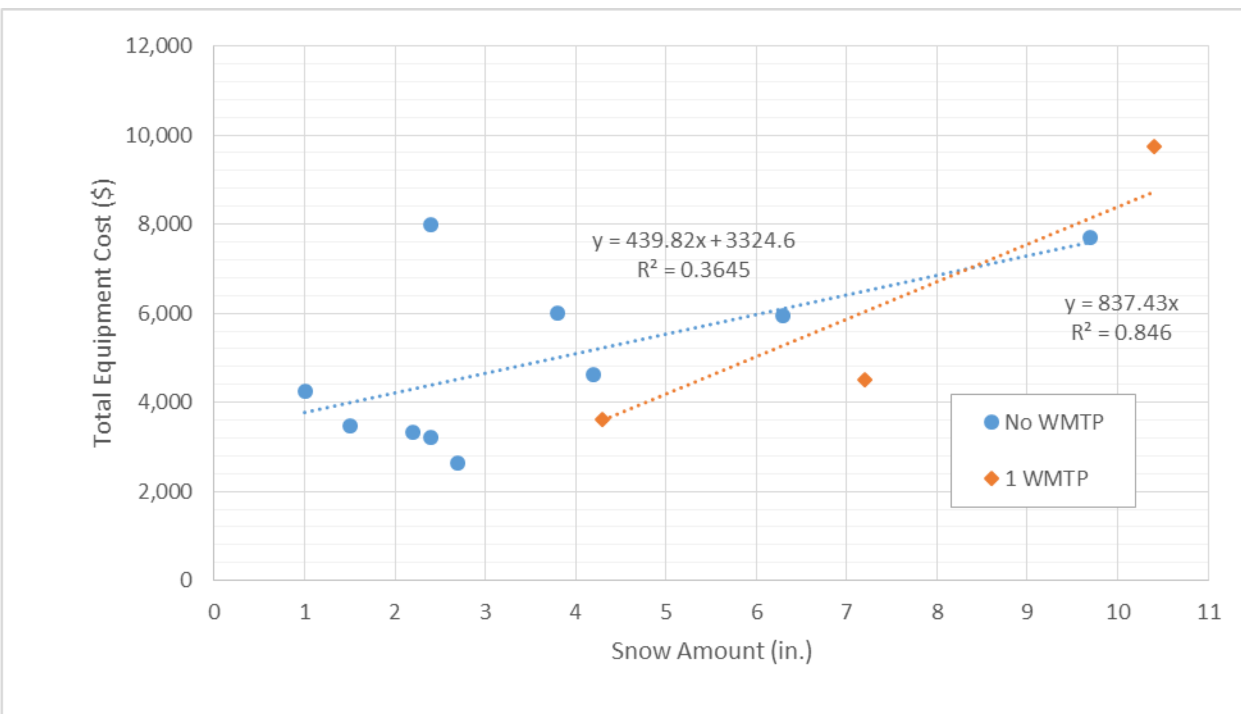


**Figure 5.13: Total Equipment Cost with Snowstorm Severity for I-69 in Charlotte**

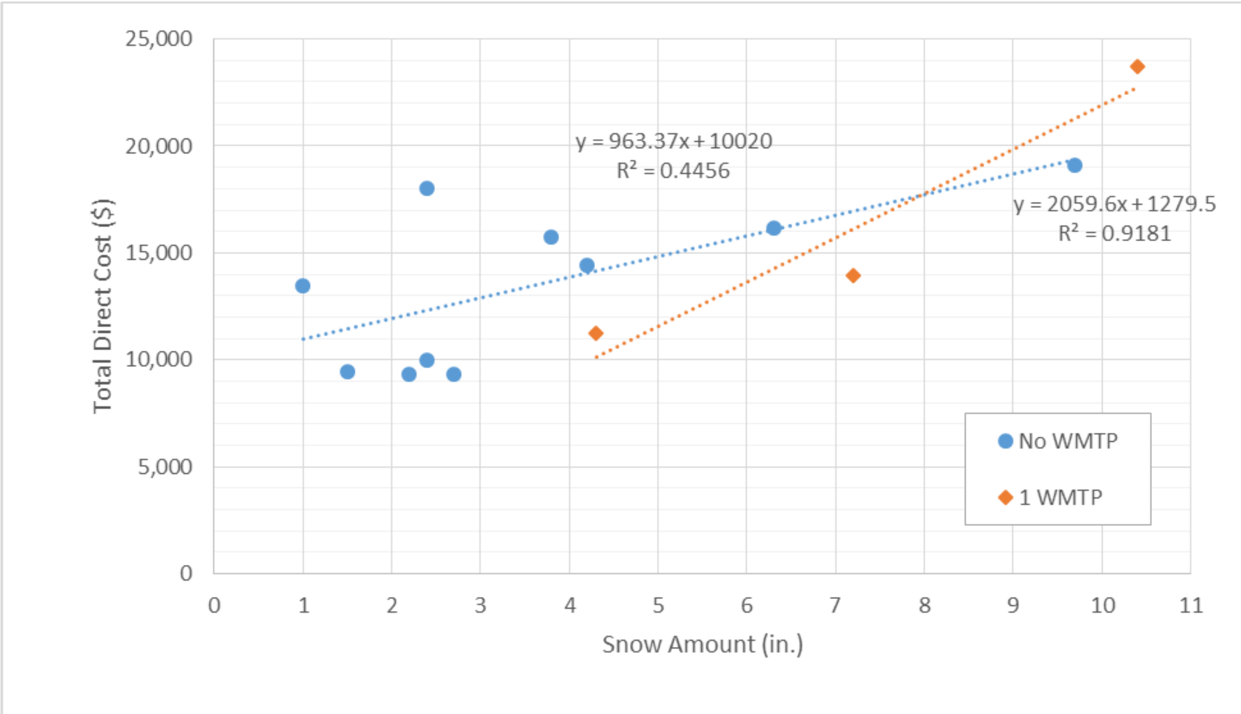


**Figure 5.14: Total Combined Direct Cost with Snowstorm Severity for I-69 in Charlotte**

The above-developed relationships are shown in Table 5.11 below.

**Table 5.11: Total Direct Cost Relationships for Four-Lane Expressway with 142 Lane Miles (I-69 in Charlotte)**

| Relationship | Type of Plow | Equation | Goodness of Fit ($R^2$) |
|---|---|---|---|
| Total Labor Cost | No WMTPs in the fleet | $\text{Total Labor Cost} = 2735.8 + 298.4 \times \text{Snow Amount}$ | 0.35 |
| | 1 WMTP in the fleet | $\text{Total Labor Cost} = 487.94 \times \text{Snow Amount}$ | 0.89 |
| Total Salt Cost | No WMTPs in the fleet | $\text{Total Salt Cost} = 3959.5 + 225.15 \times \text{Snow Amount}$ | 0.49 |
| | 1 WMTP in the fleet | $\text{Total Salt Cost} = 3466.9 + 465.89 \times \text{Snow Amount}$ | 0.99 |
| Total Equipment Cost | No WMTPs in the fleet | $\text{Total Equipment Cost} = 3324.6 + 439.82 \times \text{Snow Amount}$ | 0.36 |

| Relationship | Type of Plow | Equation | Goodness of Fit ($R^2$) |
|---|---|---|---|
| | 1 WMTP in the fleet | $Total\ Equipment\ Cost = 837.43 \times Snow\ Amount$ | 0.85 |
| Total Combined Direct Cost | No WMTPs in the fleet | $Total\ Combined\ Direct\ Cost = 10200 + 963.37 \times Snow\ Amount$ | 0.45 |
| | 1 WMTP in the fleet | $Total\ Combined\ Direct\ Cost = 1279.5 + 2059.6 \times Snow\ Amount$ | 0.92 |

Based on the winter maintenance cost data along I-69 in Charlotte, a total number of regular WMTs needed per each winter storm, with one WMTP in the fleet and without WMTPs in the fleet, were calculated.

**Table 5.12: Number of Regular WMTs for Four-Lane Expressway in a Rural Area with 142 Lane Miles (I-69 in Charlotte Area)**

| Condition | Equation |
|---|---|
| Without WMTPs in the fleet | $No.of\ WMTs = 0.0255 \times Snow\ Amount + 5$ |
| With one WMTP in the fleet | $No.of\ WMTs = 0.0304 \times Snow\ Amount + 3$ |

The following figure shows the relationships for a total number of regular WMTs required for winter storms with different severities in Charlotte.

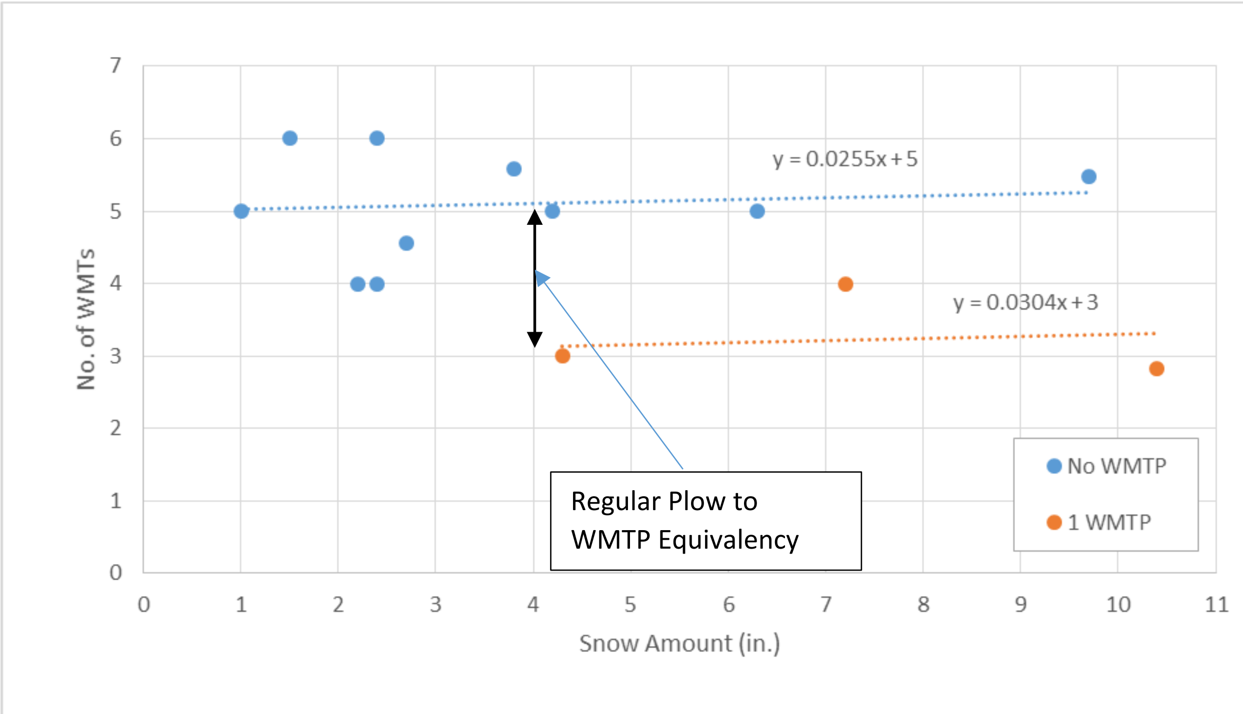


**Figure 5.15: Number of Regular WMTs with Snowstorm Severity for I-69 in Charlotte**

As shown in Figure 5.15, the difference in the above relationships (trend lines) shows the regular WMT to WMTP equivalency as a function of the snowstorm severity. The WMT to WMTP equivalency is close to 2.0 for all snowstorm severity levels.

Figure 5.16 shows regular WMT to WMTP equivalency for I-69 in Charlotte.

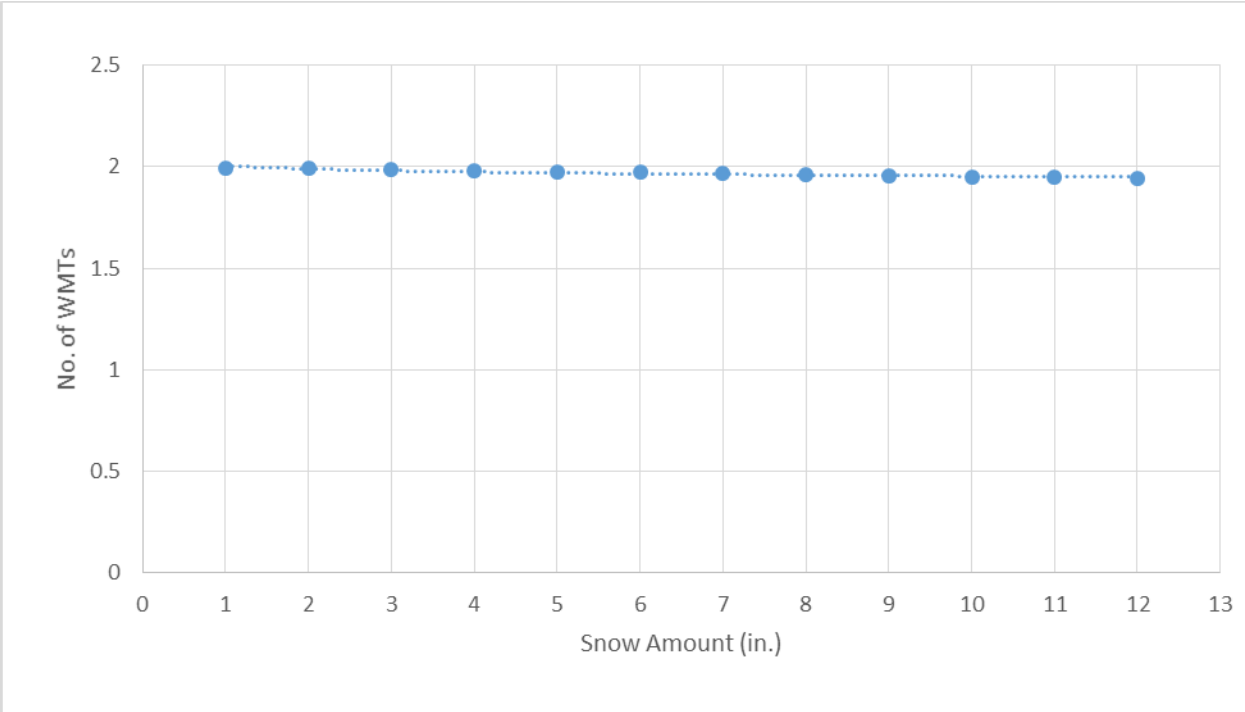


**Figure 5.16: Regular WMT to WMTP Equivalency for I-69 in Charlotte (Four-Lane Expressway with 142 Lane Miles)**

The following recommended equipment configuration was developed based on the snow severity and WMT to WMTP equivalency (only considering direct winter maintenance costs).

**Table 5.13: Recommended Number of Regular WMTs with one WMTP for Four-Lane Expressways with 142 Lane Miles**

| Snowstorm Severity (inches) | Number of WMTs | Number of WMTPs |
|---|---|---|
| 0.5 | 2 | 0 |
| 1.0 | 2 | 1 |
| 1.5 | 3 | 1 |
| 2.0 | 3 | 1 |
| 2.5 | 3 | 1 |
| 3.0 | 3 | 1 |
| 4.0 | 3 | 1 |
| 6.0 | 3 | 1 |
| 8.0 | 3 | 1 |
| 10.0 | 3 | 1 |
| 12.0 | 3 | 1 |

*These recommendations are purely based on direct cost calculations. MDOT should consider their equipment limitations when using these equipment configurations.

### 5.3.4 Modeling of Winter Maintenance Direct Costs for Four-Lane Expressway in a Rural Area (US-23 in Brighton, 98 Lane Miles)

The analysis described in Section 5.3.2 was performed for data collected on a four-lane expressway (US-23) located in Brighton, Michigan. Total cost relationships for labor, salt, equipment and combined direct are shown in Figures 5.17 through 5.20.

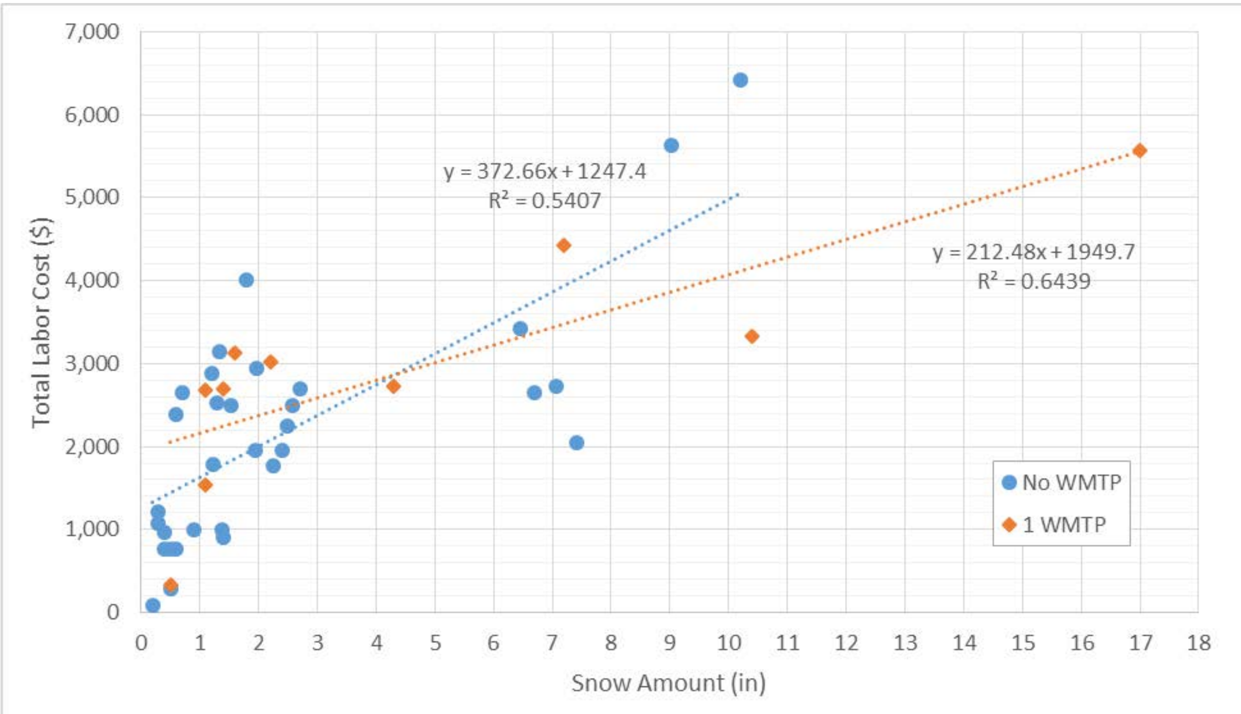


**Figure 5.17: Total Labor Cost with Snowstorm Severity for US-23 in Brighton**

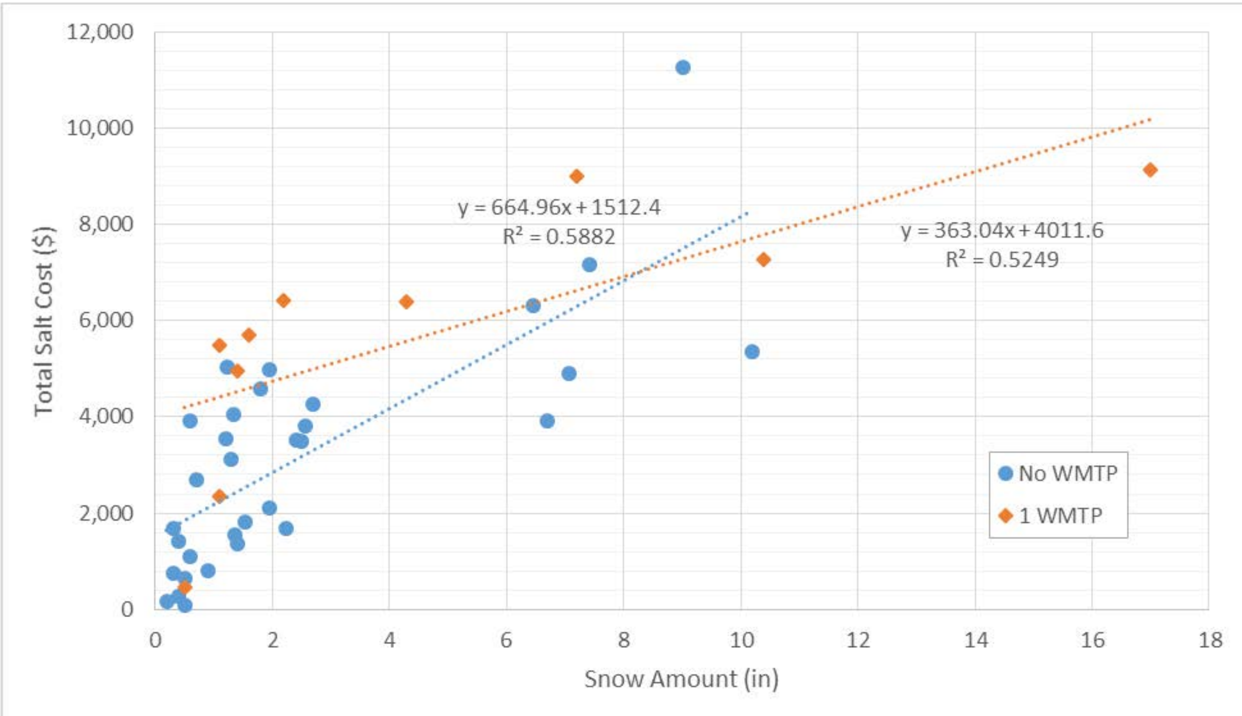


**Figure 5.18: Total Salt Cost with Snowstorm Severity for US-23 in Brighton**

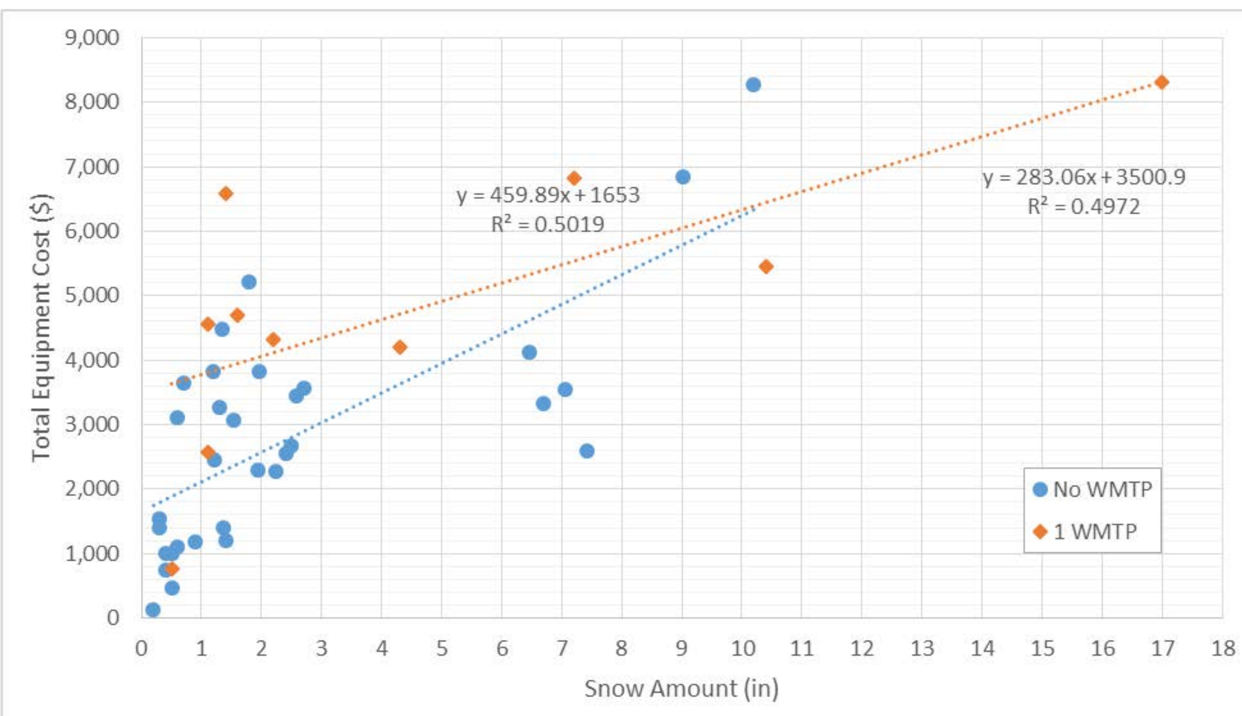


**Figure 5.19: Total Equipment Cost with Snowstorm Severity for US-23 in Brighton**

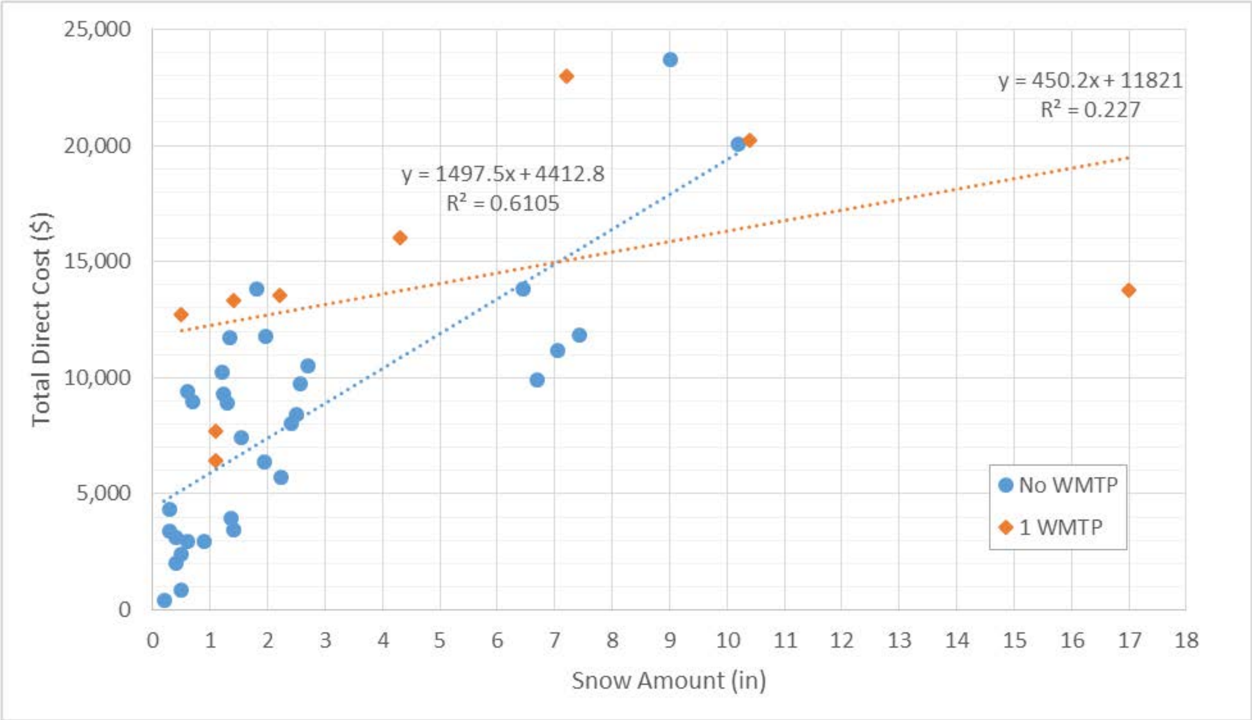


**Figure 5.20: Total Combined Direct Cost with Snowstorm Severity for US-23 in Brighton**

The above-developed relationships are shown in Table 5.14 below.

**Table 5.14: Total Direct Cost Relationships for Four-Lane Expressway with 98 Lane Miles (US-23 in Brighton)**

| **Relationship** | **Type of Plow** | **Equation** | **Goodness of Fit ($R^2$)** |
|---|---|---|---|
| Total Labor Cost | No WMTPs in the fleet | $Total\ Labor\ Cost = 1247.4 + 372.66 \times Snow\ Amount$ | 0.54 |
| | 1 WMTP in the fleet | $Total\ Labor\ Cost = 1949.7 + 212.48 \times Snow\ Amount$ | 0.64 |
| Total Salt Cost | No WMTPs in the fleet | $Total\ Salt\ Cost = 1512.4 + 664.96 \times Snow\ Amount$ | 0.59 |
| | 1 WMTP in the fleet | $Total\ Salt\ Cost = 4011.6 + 363.04 \times Snow\ Amount$ | 0.52 |
| Total Equipment Cost | No WMTPs in the fleet | $Total\ Equipment\ Cost = 1653 + 459.89 \times Snow\ Amount$ | 0.50 |

| Relationship | Type of Plow | Equation | Goodness of Fit ($R^2$) |
|---|---|---|---|
| | 1 WMTP in the fleet | $Total\ Equipment\ Cost = 3500.9 + 283.06 \times Snow\ Amount$ | 0.50 |
| Total Combined Direct Cost | No WMTPs in the fleet | $Total\ Combined\ Direct\ Cost = 4412.8 + 1497.5 \times Snow\ Amount$ | 0.61 |
| | 1 WMTP in the fleet | $Total\ Combined\ Direct\ Cost = 11821 + 450.2 \times Snow\ Amount$ | 0.23 |

Based on the winter maintenance cost data along US-23 in Brighton, a total number of regular WMTs needed per each winter storm, with one WMTP in the fleet and without WMTPs in the fleet, was calculated. Table 5.15 shows the developed relationships.

**Table 5.15: Number of Regular WMTs for Four-Lane Expressway in a Rural Area with 98 Lane Miles**

| Condition | Equation | Goodness of Fit ($R^2$) |
|---|---|---|
| Without WMTPs in the fleet | $No.of\ WMTs = 2.6641 \times Snow\ Amount^{0.2625}$ | 0.30 |
| With 1 WMTP in the fleet | $No.of\ WMTs = 1.6544 \times Snow\ Amount^{0.5727}$ | 0.57 |

The following figure shows the relationships for a total number of regular WMTs required for winter storms with different severities.

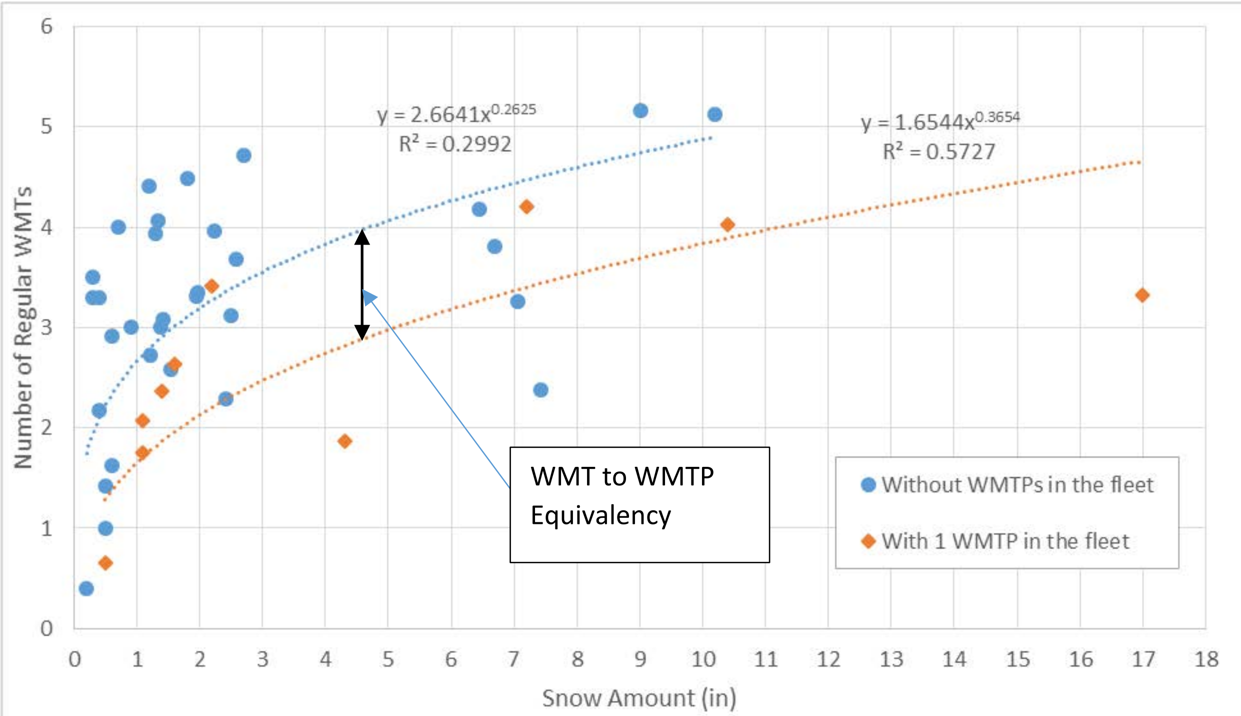


**Figure 5.21: Number of Regular WMTs with Snowstorm Severity for US-23 in Brighton**

As shown in Figure 5.21, the difference in the above relationships (trend lines) shows the regular WMT to WMTP equivalency as a function of the snowstorm severity. For example, when the snowstorm severity is 1 inch, the regular WMT to WMTP equivalency is 1.01. However, if the snowstorm severity is 3 inches, the regular WMT to WMTP equivalency is increased to 1.08. Although the expected equivalency should reach close to 2.0 as with I-96 (six-lane expressway), the maximum equivalency predicted from the relationship is approximately 1.088. During discussions with MDOT staff, they revealed that the number of regular WMTs was not reduced although a WMTP was introduced into the equipment fleet. The main goal of introducing the WMTP was to provide better Level of Service (LOS) for the motoring public by clearing the snow faster. Therefore, these WMT to WMTP equivalencies should not be used for further analysis. However, WMT to WMTP equivalencies for US-23 can be improved by optimizing the winter maintenance equipment fleet as demonstrated by the Charlotte garage (Section 5.3.3).

Figure 5.22 shows regular WMT to WMTP equivalency for US-23 in the Brighton area.

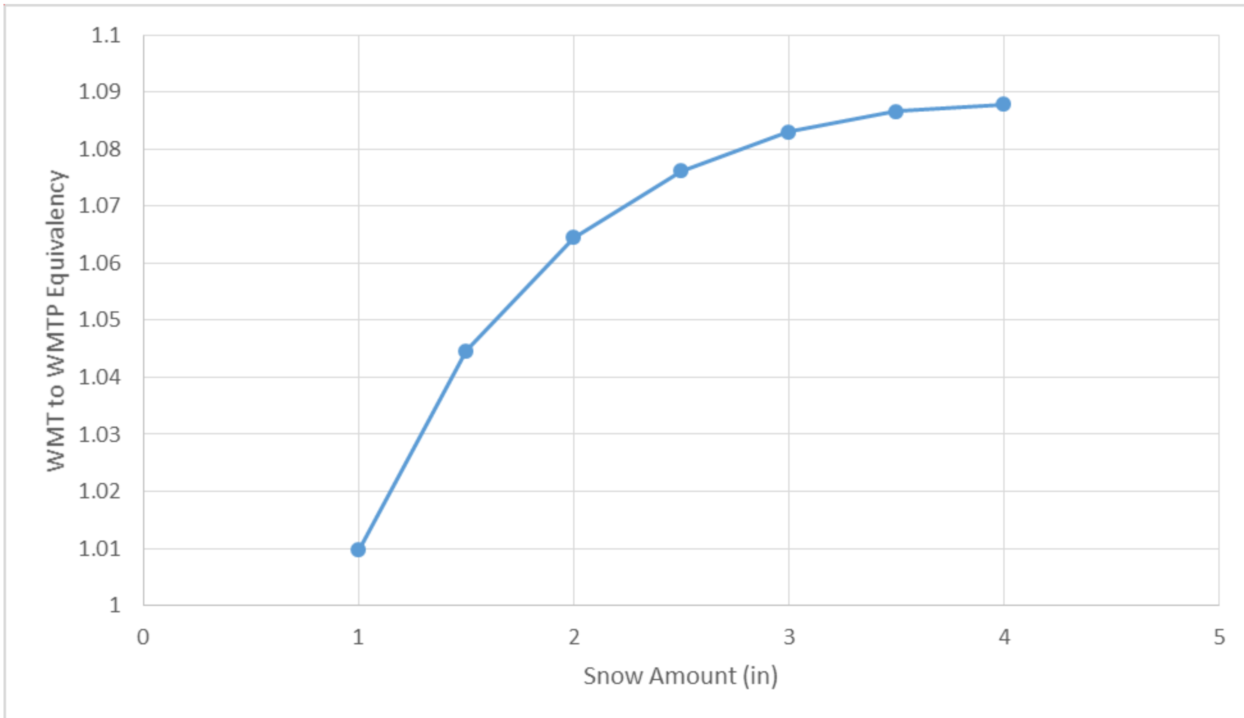


**Figure 5.22: Regular WMT to WMTP Equivalency for US-23 in Brighton (Four-Lane Expressway with 98 Lane Miles)**

### 5.3.5 Modeling of Winter Maintenance Direct Costs for Four-Lane Expressway in a Rural Area (I-96 in Williamston, 117 Lane Miles)

The WMTP was used on two snow routes (I-96 West and I-96 East in Williamston, Michigan) during some snowstorms in 2015 and 2016. For the total direct cost analysis, the usage data for these two routes were combined. The total cost relationships for labor, salt and equipment are shown in Figures 5.23 through 5.26 below.

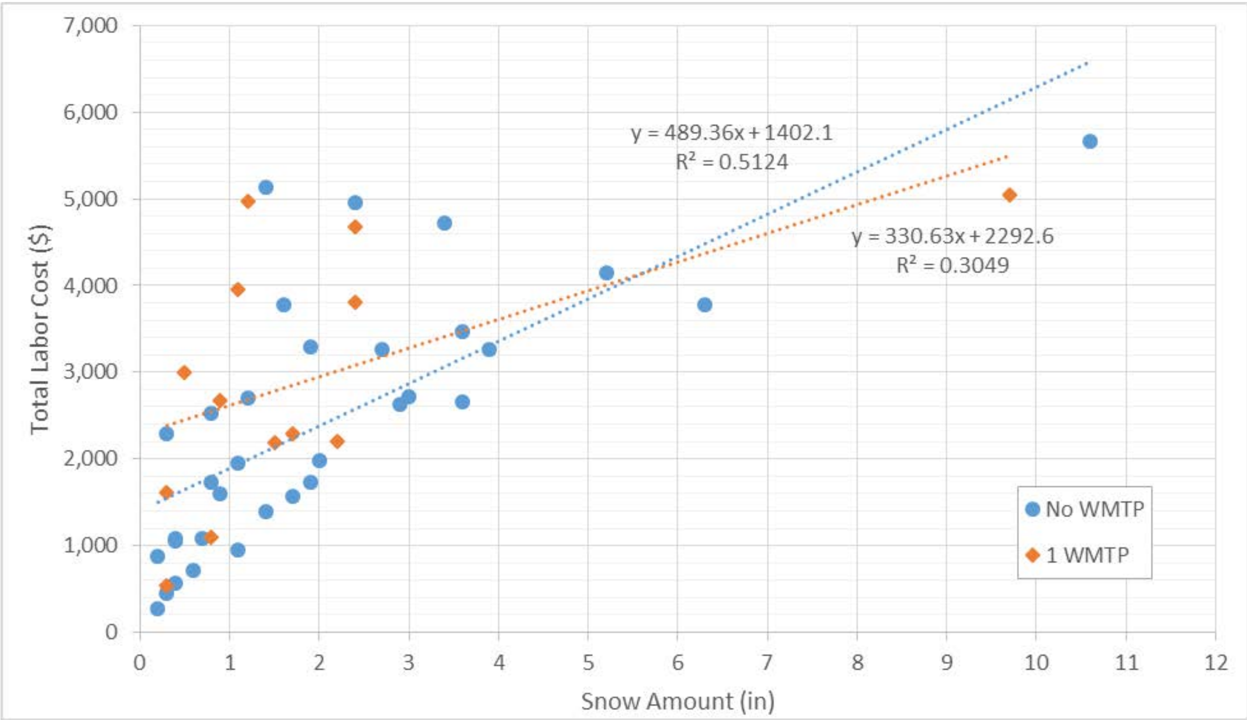


**Figure 5.23: Total Labor Cost with Snowstorm Severity for I-96 in Williamston**

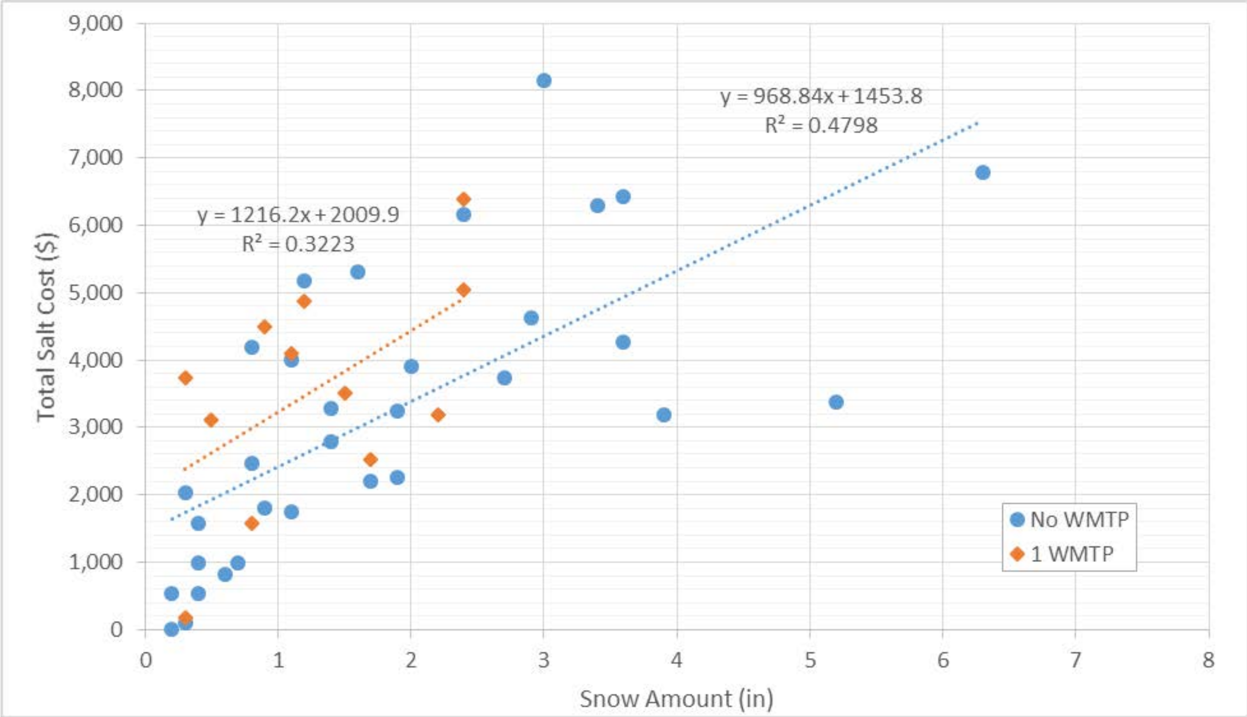


**Figure 5.24: Total Salt Cost with Snowstorm Severity for I-96 in Williamston**

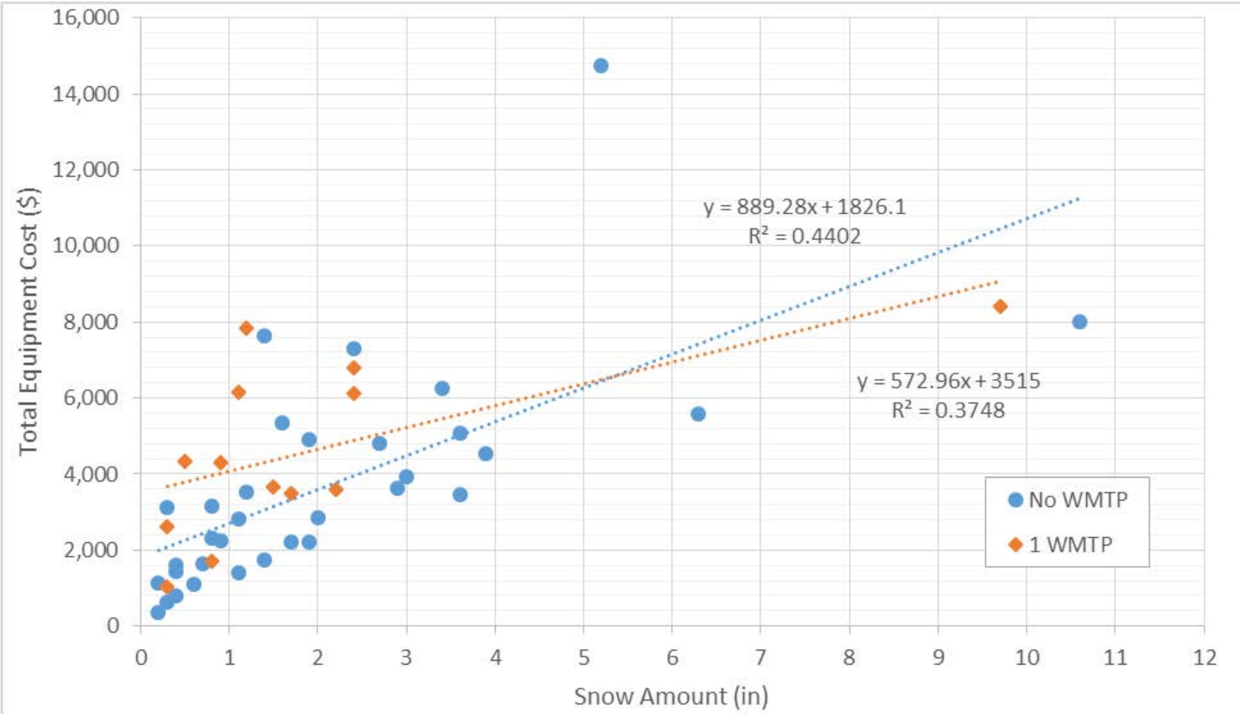


**Figure 5.25: Total Equipment Cost with Snowstorm Severity for I-96 in Williamston**

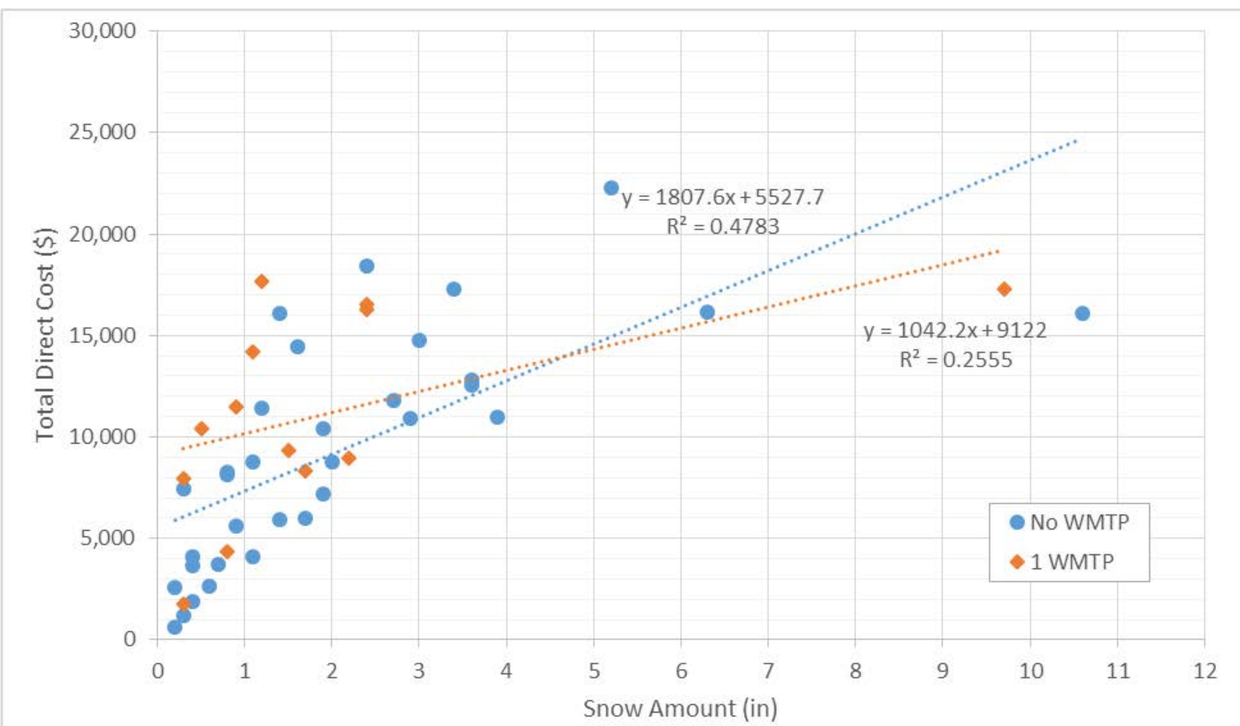


**Figure 5.26: Total Combined Direct Cost with Snowstorm Severity for I-96 in Williamston**

The relationships developed from the preceding data are shown in the Table 5.16.

**Table 5.16: Total Direct Cost Relationships for Four-Lane Expressway with 117 Lane Miles (I-96, Williamston)**

| Relationship | Type of Plow | Equation | Goodness of Fit ($R^2$) |
|---|---|---|---|
| Total Labor Cost | No WMTPs in the fleet | $Total\ Labor\ Cost = 1402.1 + 489.36 \times Snow\ Amount$ | 0.51 |
| | 1 WMTP in the fleet | $Total\ Labor\ Cost = 2292.6 + 330.63 \times Snow\ Amount$ | 0.30 |
| Total Salt Cost | No WMTPs in the fleet | $Total\ Salt\ Cost = 1453.8 + 968.84 \times Snow\ Amount$ | 0.48 |
| | 1 WMTP in the fleet | $Total\ Salt\ Cost = 2009.9 + 1216.2 \times Snow\ Amount$ | 0.32 |
| Total Equipment Cost | No WMTPs in the fleet | $Total\ Equipment\ Cost = 1826.1 + 889.28 \times Snow\ Amount$ | 0.44 |
| | 1 WMTP in the fleet | $Total\ Equipment\ Cost = 3515 + 572.96 \times Snow\ Amount$ | 0.37 |
| Total Combined Direct Cost | No WMTPs in the fleet | $Total\ Combined\ Direct\ Cost = 5527.7 + 1807.6 \times Snow\ Amount$ | 0.48 |
| | 1 WMTP in the fleet | $Total\ Combined\ Direct\ Cost = 9122 + 1042.2 \times Snow\ Amount$ | 0.26 |

Based on the winter maintenance cost data along I-96 in Williamston, a total number of regular WMTs required per each winter storm, with 1 WMTP in the fleet and without WMTPs in the fleet, were calculated. The table below shows the developed relationships.

**Table 5.17: Number of Regular WMTs for Four-Lane Expressway in a Rural Area with 117 Lane Miles (I-96, Williamston)**

| Condition | Equation | Goodness of Fit ($R^2$) |
|---|---|---|
| Without WMTPs in the fleet | $No.of\ WMTs = 2.6423 \times Snow\ Amount^{0.1812}$ | 0.36 |
| With 1 WMTP in the fleet | $No.of\ WMTs = 2.4686 \times Snow\ Amount^{0.1729}$ | 0.09 |

The following figure shows the relationships for a total number of regular WMTs required for winter storms with different severities relative to I-96 in Williamston.

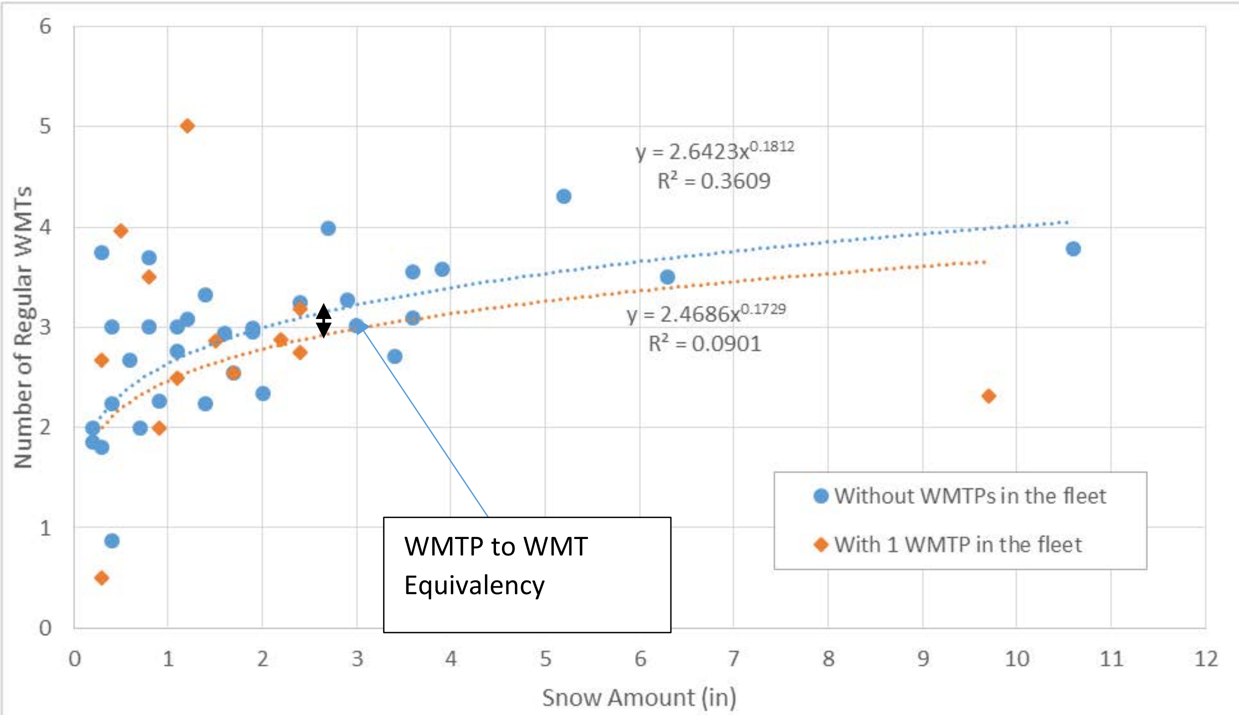


**Figure 5.27: Number of Regular WMTs with Snowstorm Severity for I-96 in Williamston**

As shown in Figure 5.27, the difference in the above relationships (trend lines) shows the WMTP to WMT equivalency as a function of the snowstorm severity. Although the expected equivalency should reach close to 2.0, the maximum equivalency predicted from the relationship is approximately 0.33. During the discussions with MDOT staff, they revealed that the number of regular WMTs was not reduced although a WMTP was introduced into the equipment fleet. The main goal of introducing the WMTP was to provide better Level of Service (LOS) for the motoring public by clearing the snow faster. Therefore, these WMT to WMTP equivalencies should not be used for further analysis. ***The use of I-69 in Charlotte area data for all four-lane expressway analyses is recommended.***

The WMT to WMTP equivalencies for I-96 in Williamston area can be improved by optimizing the winter maintenance equipment fleet as demonstrated by the Charlotte garage (Section 5.3.3).

Figure 5.28 shows regular WMT to WMTP equivalency for I-96 in the Williamston area.

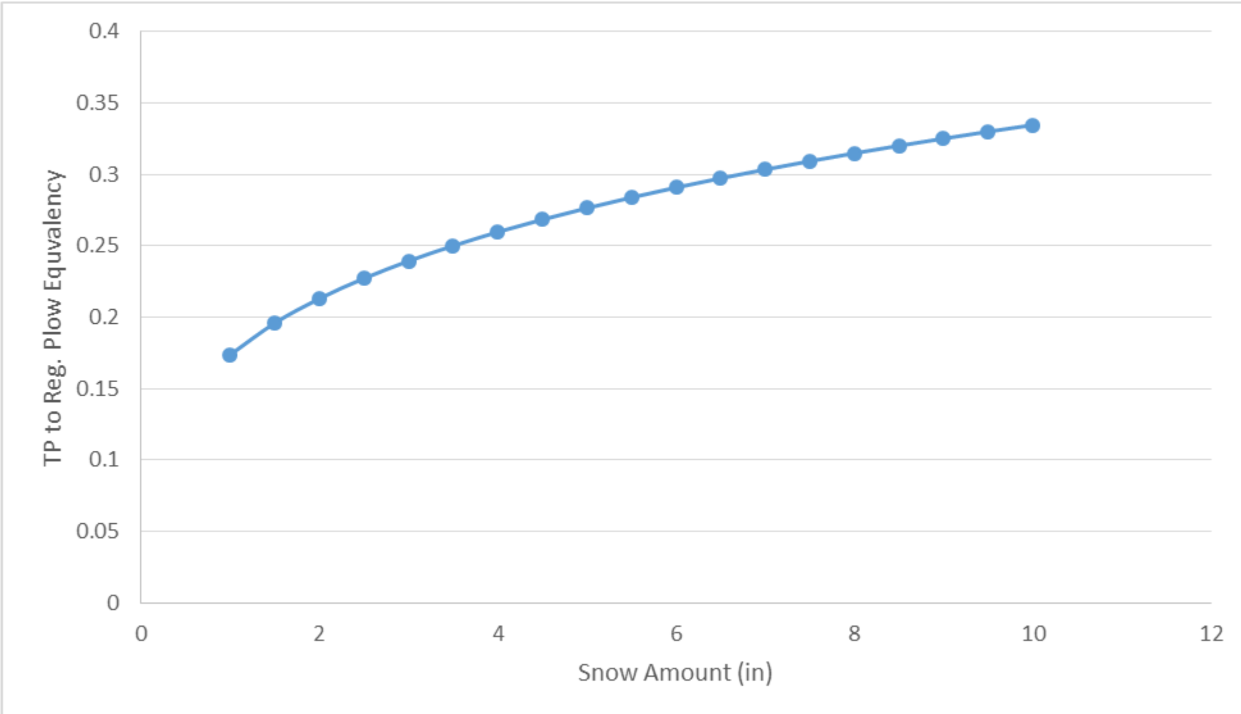


**Figure 5.28: Regular WMT to WMTP Equivalency for I-96 in Williamston (Four-Lane Expressway with 117 Lane Miles)**

### 5.3.6 Modeling of Winter Maintenance Direct Costs for Grand Ledge and Reed City Routes

The winter maintenance cost data analysis for Grand Ledge and Reed City garage snow routes did not yield satisfactory results.

## 5.4 Winter Maintenance Indirect Cost Modeling

Indirect cost-benefits of winter maintenance include safety benefits, travel delay cost, and fuel usage costs. Winter maintenance fuel usage costs relative to different equipment configurations are hard to quantify and were neglected during this study. However, performing further analyses in order to include fuel cost savings in the total winter maintenance costs-benefits is recommended.

### 5.4.1 Safety Benefits Analysis

As described in Section 5.1.2, traffic accident reductions due to winter maintenance improvements should be quantified in order to analyze the safety benefits of using these improvements. The first step of such analyses includes obtaining winter-related accident data before and after the implementation of winter maintenance improvements. Accident data for this study was obtained from the Michigan Traffic Crash Facts (MTCF) website maintained by the Office of Highway Safety Planning of Michigan State Police (michigantrafficcrashfacts.org). Winter weather-related accidents were defined as when the road condition is categorized as “Snowy”, “Icy” or “Slushy”.

The MTCF online database was queried to obtain the past 10 years of crash data related to winter weather conditions. Figure 5.29 shows I-96 and US-23 (in Livingston County) accident summary data for the past 10 years.

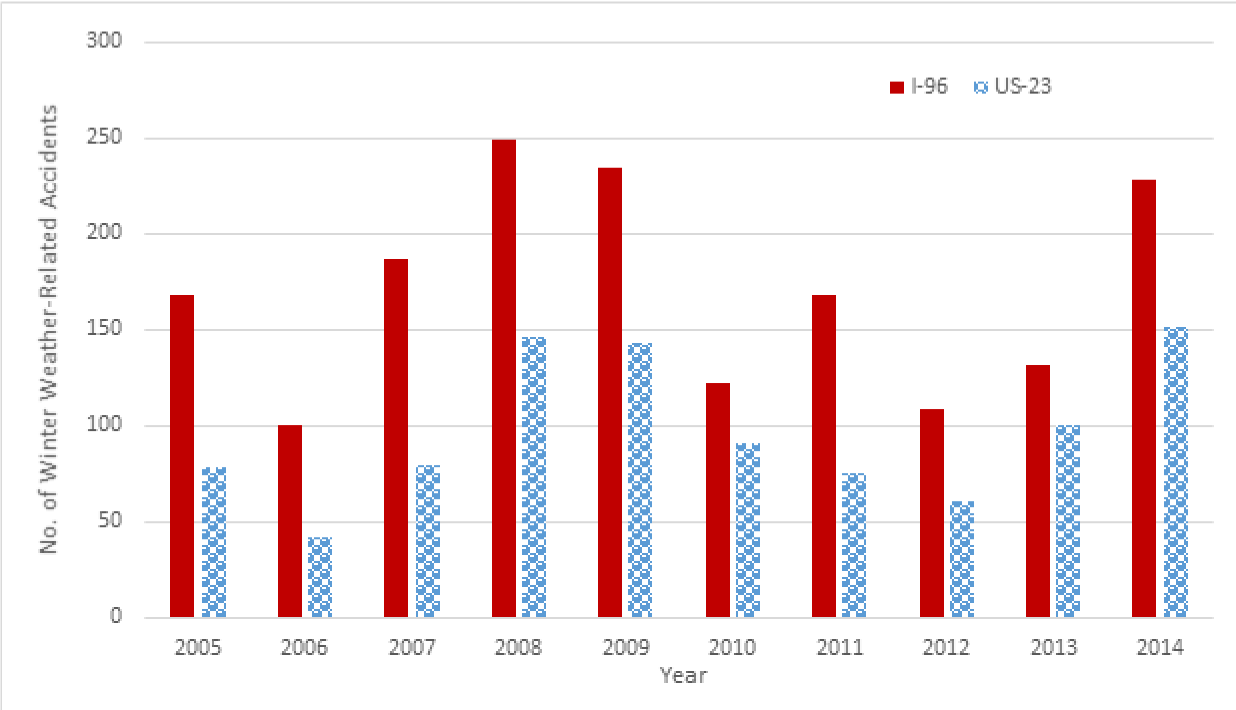


**Figure 5.29: Winter Weather-Related Accident Data for I-96 and US-23 in Livingston County**

The generally accepted method of normalizing accident data involves calculating accident rates based on the traffic exposure of the roadways under consideration. The following equation was used for calculating Accident Rate per 100-Million Vehicle Miles (RMVM):

$$RMVM = \frac{A \times 100{,}000{,}000}{VMT}$$

Where,

*RMVM* = Rate per 100-million vehicle miles
*A* = Number of accidents (in this case, number of winter weather-related accidents)
*VMT* = Vehicle miles of travel during the study period =
$Winter\ Time\ ADT \times length\ of\ road \times$
$number\ of\ days\ in\ study\ period\ (winter\ time)$

In the above analysis, wintertime was designated as December to March. The wintertime ADT (Average Daily Traffic) of those months per each year was obtained from Michigan Department of Transportation online data sources (http://mdotnetpublic.state.mi.us/tmispublic/).

The following figure shows the accident rates for I-96 and US-23 (in Livingston County) for the past 10 years.

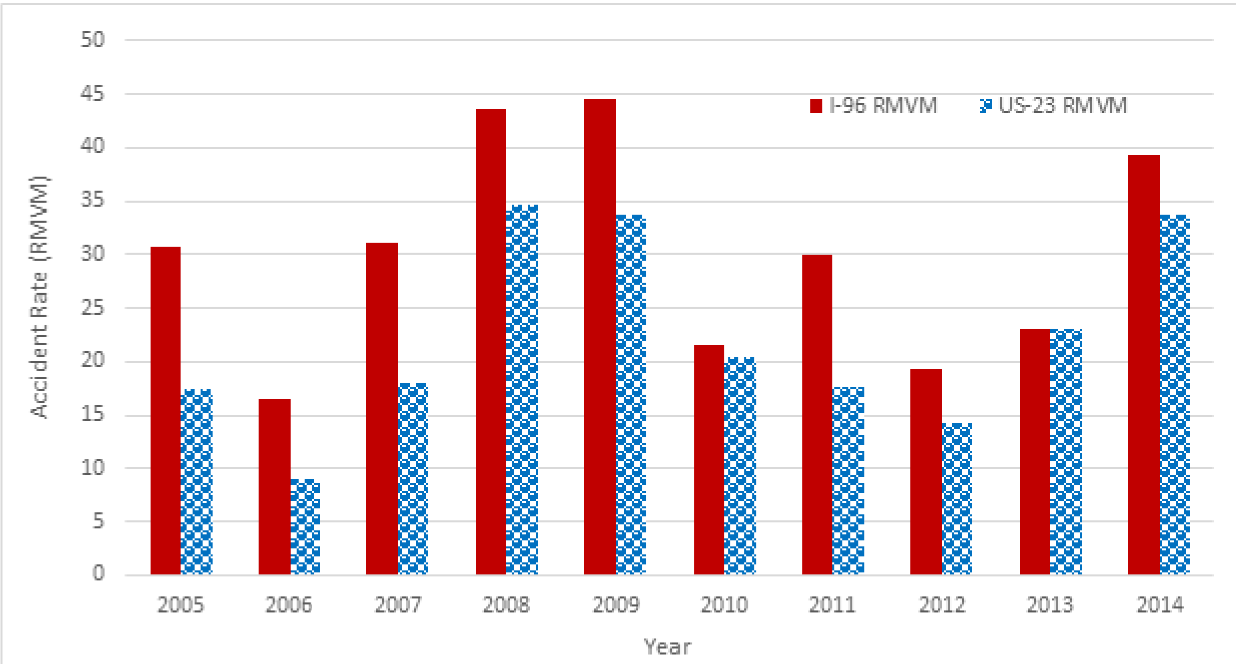


**Figure 5.30: Winter Weather-Related Accident Rates for I-96 and US-23 in Livingston County**

Since winter weather-related accidents depend on the severity of each storm event and how quickly roads are cleared during each event, the above-observed accidents were compared with total annual snowfall amounts recorded during those years. The recorded total annual snowfall amounts varied from 14.9 inches in 2006 to 82.6 inches in 2008. The total snowfall amount in 2014 was 82.3 inches. Table 5.18 shows the recorded total snowfall amounts for the last 10 years in Livingston County.

**Table 5.18: Recorded Total Snowfall Amounts for Livingston County**

| Year | Total Recorded Snow Amounts (inches) |
|---|---|
| 2005 | 75.3 |
| 2006 | 14.9 |
| 2007 | 40.3 |
| 2008 | 82.6 |
| 2009 | 49.9 |
| 2010 | 45.2 |
| 2011 | 66.1 |
| 2012 | 30.7 |
| 2013 | 53.4 |
| 2014 | 82.3 |

The following figure shows the correlation of accident rates relative to annual snowfall amount.

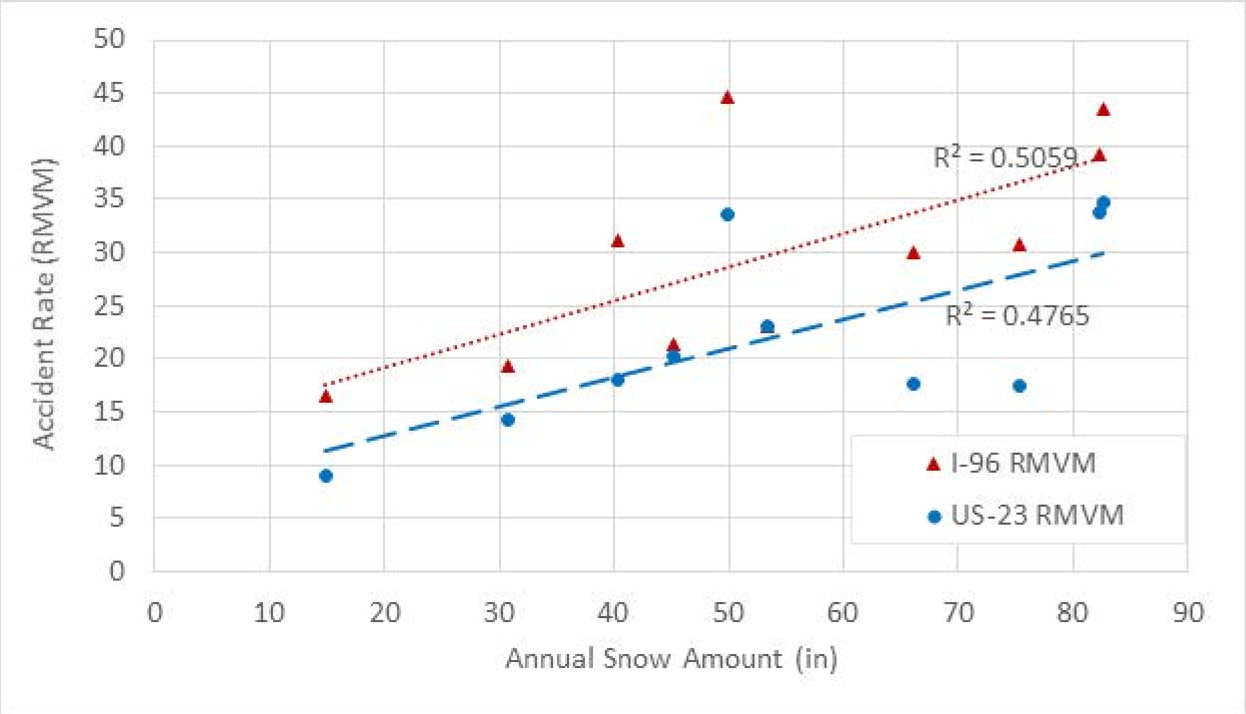


**Figure 5.31: Accident Rates vs. Annual Snow Amount**

As shown above, I-96 accident rates trend higher than the US-23 rates. The wider lanes and shoulders along this section of I-96 in Livingston County may give drivers a false sense of security. As a result, drivers may be driving at higher speeds along I-96 during winter storm events. Implementing variable winter weather speed limits as given in Appendix C of this report will be valuable to reduce some of these winter weather-related accidents.

Since the accident rates are highly correlated to the annual snow amount, yearly winter weather-related accidents were normalized to a yearly snow fall amount of 50 inches (average snow amount for the last 10 years). The normalized winter weather-related accidents for the last 10 years are shown in Figure 5.32.

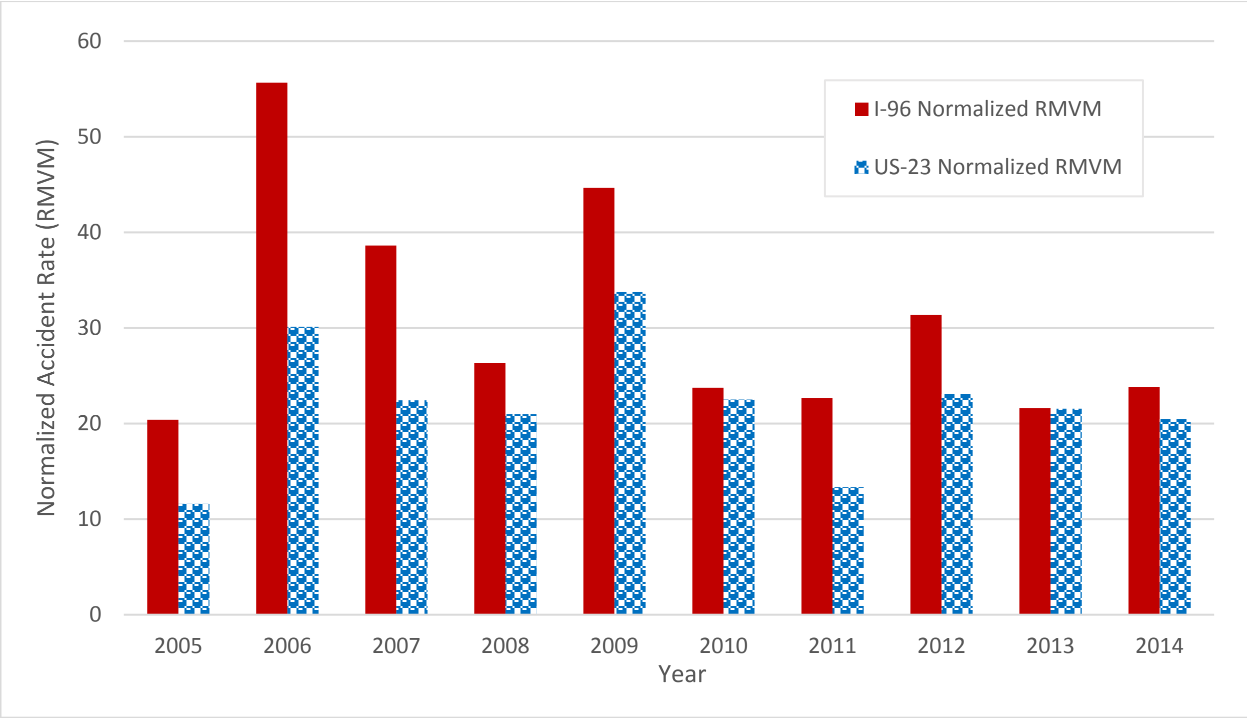


**Figure 5.32: Normalized Winter Weather-Related Accident Data for I-96 and US-23 in Livingston County**

The WMTP was first used on I-96 in January 2013 and on US-23 in November 2014. Therefore, only I-96 data with 2 years of WMTP usage can be used for any analysis. As shown in Figure 5.32, the normalized accident rate chart indicates no significant change in accident rates were observed in 2013 and 2014.[8]

### 5.4.2 Travel Time and Delay Analysis

Both of these performance measures (travel time and delay) were obtained from vehicle probe data recorded and archived by the Regional Integrated Transportation Information System (RITIS) database. RITIS was developed and is maintained by the University of Maryland Center for Advanced Transportation Technology. The center automatically fuses, translates, and standardizes data obtained from multiple agencies. The following figure shows an example of the output

[8]Since only 2 years of WMTP usage are included in the analysis, safety benefits of using WMTP to traditional WMTs in terms of accident costs were not included in the analysis. More data is needed to determine statistically significant accident cost reductions due to the use of WMTP.

produced when evaluating vehicle speed recovery during a storm event. The "average of average speed" represents the 3-year average speed for 10-minute intervals. A 5-mile/hour buffer was applied to the 3-year average speed to account for any local/daily variation of speed data. Storm start times and end times were obtained from the National Weather Service (NWS) daily observation data from the Howell weather station. The regain time is defined as the average speed within 5 mph of the historical average speed for at least 1 hour after the end of the event.

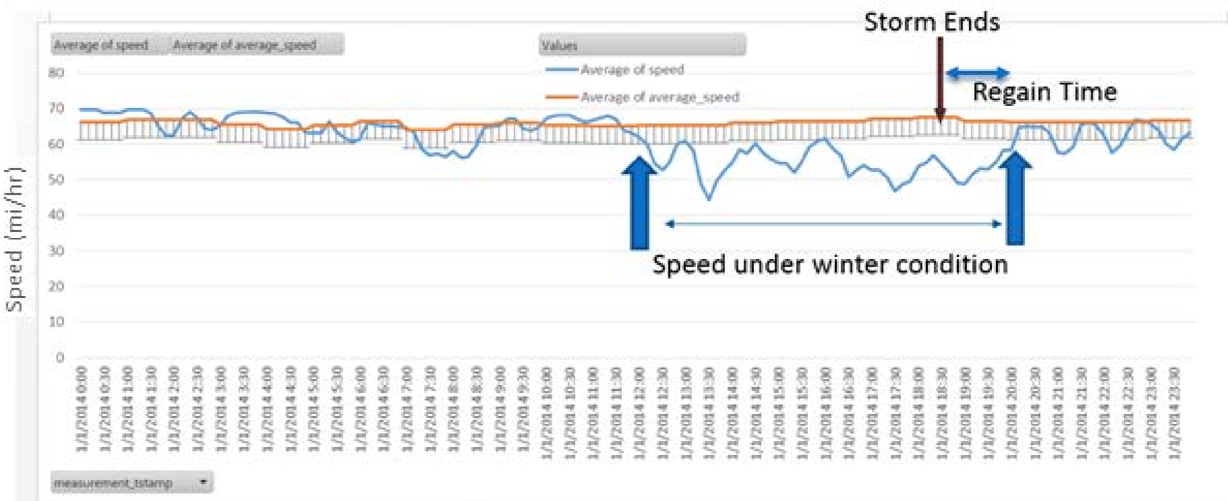


**Figure 5.33: Analysis Process of Vehicle Speed Data**

Based on the speed data analyzed during snow events, several "byproduct-type" relationships were obtained. The details of these relationships are included in Appendix E of this report. These winter travel speed-based relationships can be used as performance measures for winter operations.

### 5.4.3 Travel Delay Cost Analysis

A travel delay analysis was performed by MDOT personnel using the RITIS Michigan Analytic Tools. Delay costs were calculated during each storm event for all the respective snow routes. Travel delay represents the extra time spent traveling due to winter storm events. These costs are calculated at the hourly level using MDOT-provided Annual Average Daily Traffic (AADT) volumes that were adjusted using daily adjustment factor hourly profiles. A brief description of the delay cost analysis process is given below. A complete description of this process can be obtained from the "Help" section of RITIS Michigan Analytic Tools.

#### 5.4.3.1 RITIS Michigan Analytic Delay Analysis Procedure

The travel delay cost of a road segment due to winter weather is based on several variables. These include storm start time, storm end time, passenger value of time, commercial vehicle operating cost, hourly traffic volume, vehicle speed, the length of the road section, and historical average speed.

Storm start and end times were obtained from National Oceanic and Atmospheric Administration (NOAA) databases. MDOT provided the AADT values for each route and RITIS used the following adjustments to calculate hourly traffic volumes. To calculate average daily traffic (ADT) from AADT, the following daily adjustment factors were used.

**Table 5.19: RITIS Daily AADT Adjustment Factors for Calculating Traffic Delay Costs**

| Day of Week | Adjustment Factor |
|---|---|
| Monday to Thursday | +5% |
| Friday | +10% |
| Saturday | -10% |
| Sunday | -20% |

In order to calculate hourly traffic volumes, standard hourly traffic profiles were based on the functional class of the roadway (freeway or non-freeway), day type (weekday or weekend) and congestion level (low, moderate or severe). An example hourly profile for a weekday/low congestion condition is shown in Figure 5.34.

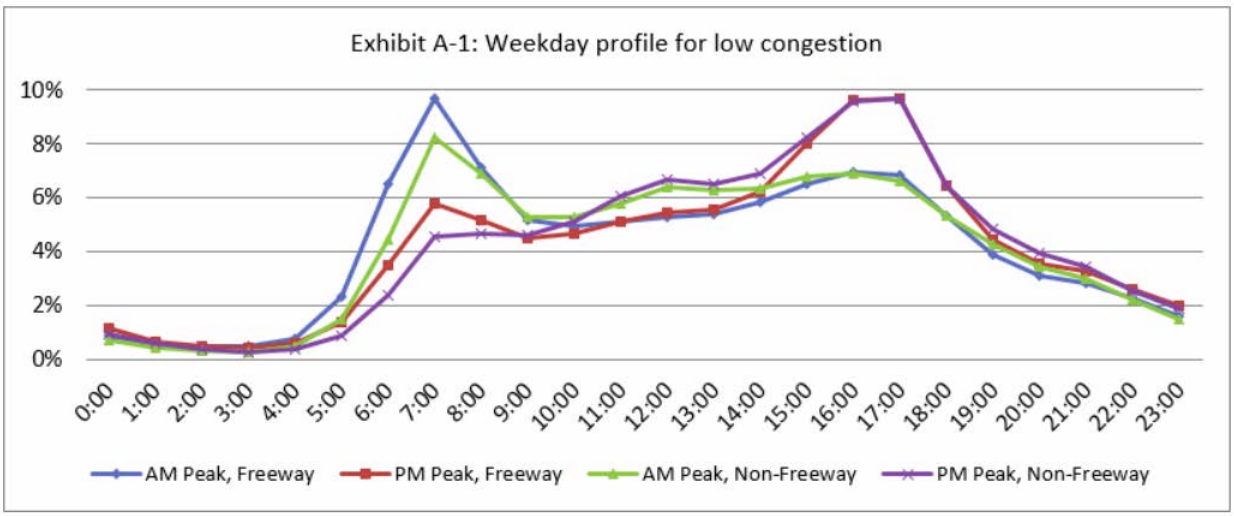


**Figure 5.34: Example Hourly Profile from RITIS Michigan Analytics Tools**

Once the hourly traffic volumes are determined, vehicle miles of travel (VMT) were determined from the following equation.

$$VMT = passenger\ or\ commercial\ volume\ during\ time\ period \times roadway\ length$$

The travel delay can then be calculated as shown below.

$$vehicle\ hours\ of\ delay = \left(\frac{VMT}{speed}\right) - \left(\frac{VMT}{freeflow\ speed}\right)$$

$$person\ hours\ of\ delay = \left[\left(\frac{VMT}{speed}\right) - \left(\frac{VMT}{freeflow\ speed}\right)\right] \times vehicle\ occupancy$$

Finally, the delay costs are calculated as shown below.

$$passenger\ delay\ cost = passenger\ vehicle\ hours\ of\ delay \times value\ of\ person\ time \times vehicle\ occupancy$$

$$commercial\ delay\ cost = commercial\ vehicle\ hours\ of\ delay \times commercial\ vehicle\ operating\ cost$$

Vehicle occupancy for passenger vehicles and commercial vehicles was assigned as 1.25 and 1.0, respectively. The value of person time in 2012 was $17.09 while the commercial vehicle operating cost was $30.14. These values were updated to other years by using a consumer price index.

Calculated travel delay costs of each snow route for each storm are shown in the following tables.

**Table 5.20: Travel Delay Cost for I-96 Route in Brighton Garage**

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 12/21/2012 | 1.02 | 75,809.65 |
| 12/24/2012 | 0.70 | 81,028.89 |
| 12/26-12/27/2012 | 4.59 | 158,437.52 |
| 12/29/2012 | 1.44 | 11,238.62 |
| 1/21/2013 | 1.50 | 45,189.08 |
| 1/22/2013 | 0.30 | 7,733.17 |
| 1/25/2013 | 1.85 | 64,925.19 |
| 1/27/2013 | 1.87 | 34,477.93 |
| 2/2/2013 | 1.28 | 5,417.65 |
| 2/3/2013 | 0.38 | 5,750.02 |
| 2/4/2013 | 2.03 | 13,262.21 |
| 2/7-2/8/2013 | 1.85 | 66,656.47 |
| 2/16/2013 | 1.44 | 16,182.95 |
| 3/15-3/16/2013 | 1.48 | 5,997.76 |
| 11/11/2013 | 0.50 | 8,172.56 |
| 12/14/2013 | 6.70 | 148,517.60 |
| 12/15/2013 | 0.70 | 29,171.99 |
| 12/16-12/17/2013 | 1.34 | 7,388.16 |
| 12/25-12/26/2013 | 1.96 | 37,364.34 |
| 12/31/2013 | 1.22 | 17,739.11 |
| 1/1/14-1/2/2014 | 9.04 | 204,050.60 |
| 1/5-1/6/2014 | 10.20 | 292,309.70 |

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 1/24-1/25/2014 | 1.54 | 48,487.46 |
| 1/26/2014 | 1.94 | 29,989.74 |
| 2/1/2014 | 7.42 | 125,657.20 |
| 2/4-2/5/2014 | 6.45 | 144,267.90 |
| 2/8-2/9/2014 | 2.41 | 14,667.65 |
| 2/17-2/18/2014 | 2.57 | 86,270.38 |
| 2/20/2014 | 1.37 | 50,511.75 |
| 3/12/2014 | 7.06 | 180,506.00 |
| 4/14-4/15/2014 | 1.41 | 6,465.11 |
| 11/16/2014 | 0.60 | 35.81 |
| 11/19/2014 | 1.10 | 77,822.70 |
| 1/4/2015 | 0.60 | 17,397.76 |
| 1/6-1/7/2015 | 1.20 | 120,242.00 |
| 1/8-1/9/2015 | 1.80 | 21,561.65 |
| 1/11-1/12/2015 | 2.70 | 78,003.03 |
| 1/21/2015 | 2.50 | 31,409.47 |
| 1/29/2015 | 1.30 | 9,585.94 |
| 2/1-2/2/2015 | 17.00 | 92,923.97 |
| 2/3-2/4/2015 | 2.60 | 7,617.33 |
| 2/13-2/14/2015 | 2.20 | 23,987.85 |
| 2/21/2015 | 0.50 | 229.34 |
| 2/26/2015 | 0.30 | 9,372.91 |
| 3/1/2015 | 0.40 | 253.48 |
| 3/3/2015 | 1.10 | 67,797.49 |

**Table 5.21: Travel Delay Cost for I-69 Route in Charlotte Garage**

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 12/25-12/26/2013 | 2.4 | 23,000.02 |
| 12/31-1/2/2014 | 3.8 | 109,261.30 |
| 1/16 - 1/17/2014 | 1.0 | 31,495.15 |
| 2/17 - 2/18/2014 | 2.7 | 56,630.08 |
| 3/12/2014 | 6.3 | 102,930.30 |
| 11/19 - 11/21/2014 | 4.2 | 21,492.32 |
| 1/8 - 1/9/2015 | 2.4 | 48,062.52 |
| 1/21/2015 | 2.2 | 21,795.50 |
| 2/1 - 2/2/2015 | 9.7 | 47,304.77 |
| 3/3/2015 | 1.5 | 21,776.34 |
| 11/21/2015 | 8.2 | 22,775.79 |
| 12/28/2015 | 1.4 | 50,922.68 |
| 1/10 -1/12/2016 | 4.3 | 44,476.18 |
| 2/24 - 2/25/2016 | 10.4 | 63,216.94 |
| 3/1 - 3/2/2016 | 7.2 | 81,084.66 |

**Table 5.22: Travel Delay Cost for US-23 Route in Brighton Garage**

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 12/21/2012 | 1.02 | 61,777.80 |
| 12/24/2012 | 0.70 | 88,969.09 |
| 12/26-12/27/2012 | 4.59 | 130,614.60 |
| 12/29/2012 | 1.44 | 7,840.68 |
| 1/21/2013 | 1.50 | 15,579.85 |
| 1/22/2013 | 0.30 | 2,326.37 |
| 1/25/2013 | 1.85 | 48,037.63 |
| 1/27/2013 | 1.87 | 15,329.76 |
| 2/2/2013 | 1.28 | 1,627.54 |
| 2/3/2013 | 0.38 | 1,850.18 |
| 2/4/2013 | 2.03 | 6,191.61 |
| 2/7-2/8/2013 | 1.85 | 38,651.25 |
| 2/16/2013 | 1.44 | 5,092.45 |
| 3/15-3/16/2013 | 1.48 | 3,384.27 |
| 11/11/2013 | 0.50 | 10,171.00 |
| 12/14/2013 | 6.70 | 80,237.63 |
| 12/15/2013 | 0.70 | 20,815.89 |
| 12/16-12/17/2013 | 1.34 | 5,285.48 |
| 12/25-12/26/2013 | 1.96 | 38,681.53 |
| 12/31/2013 | 1.22 | 9,623.69 |
| 1/1/14-1/2/2014 | 9.04 | 231,321.90 |
| 1/5-1/6/2014 | 10.20 | 207,697.30 |
| 1/24-1/25/2014 | 1.54 | 37,116.77 |
| 1/26/2014 | 1.94 | 8,799.34 |
| 2/1/2014 | 7.42 | 73,308.97 |
| 2/4-2/5/2014 | 6.45 | 132,507.40 |
| 2/8-2/9/2014 | 2.41 | 9,502.39 |
| 2/17-2/18/2014 | 2.57 | 73,789.15 |
| 2/20/2014 | 1.37 | 48,825.11 |
| 3/12/2014 | 7.06 | 156,445.30 |
| 4/14-4/15/2014 | 1.41 | 5,267.15 |
| 11/16/2014 | 0.60 | 0.00 |
| 11/19/2014 | 1.10 | 45,658.27 |
| 1/4/2015 | 0.60 | 14,752.74 |
| 1/6-1/7/2015 | 1.20 | 46,129.42 |
| 1/8-1/9/2015 | 1.80 | 13,494.73 |
| 1/11-1/12/2015 | 2.70 | 50,302.73 |

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 1/21/2015 | 2.50 | 26,272.80 |
| 1/29/2015 | 1.30 | 10,844.68 |
| 2/1-2/2/2015 | 17.00 | 51,786.52 |
| 2/3-2/4/2015 | 2.60 | 11,318.36 |
| 2/13-2/14/2015 | 2.20 | 16,493.58 |
| 2/21/2015 | 0.50 | 67.79 |
| 2/26/2015 | 0.30 | 10,679.30 |
| 3/1/2015 | 0.40 | 123.74 |
| 3/3/2015 | 1.10 | 45,936.50 |

**Table 5.23: Travel Delay Cost for I-96 Route in Williamston Garage**

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 12/21/2012 | 1.02 | 22,991.80 |
| 12/24/2012 | 0.70 | 40,503.14 |
| 12/26-12/27/12 | 4.59 | 54,290.07 |
| 12/29/2012 | 1.44 | 3,203.46 |
| 1/21/2013 | 1.50 | 8,910.35 |
| 1/22/2013 | 0.30 | 1,059.62 |
| 1/25/2013 | 1.85 | 15,336.91 |
| 1/27/2013 | 1.87 | 10,829.39 |
| 2/2/2013 | 1.28 | 836.86 |
| 2/3/2013 | 0.38 | 575.66 |
| 2/4/2013 | 2.03 | 1,286.07 |
| 2/7-2/8/2013 | 1.85 | 26,466.93 |
| 2/16/2013 | 1.44 | 1,266.59 |
| 3/15-3/16/2013 | 1.48 | 880.80 |
| 11/11/2013 | 0.50 | 1,148.28 |
| 12/14/2013 | 6.70 | 52,361.23 |
| 12/15/2013 | 0.70 | 6,462.07 |
| 12/16-12/17/2013 | 1.34 | 3,060.77 |
| 12/25-12/26/2013 | 1.96 | 15,715.10 |
| 12/31/2013 | 1.22 | 3,048.77 |
| 1/1/14-1/2/2014 | 9.04 | 54,635.20 |
| 1/5-1/6/2014 | 10.20 | 99,053.20 |
| 1/24-1/25/2014 | 1.54 | 15,716.20 |
| 1/26/2014 | 1.94 | 9,952.70 |
| 2/1/2014 | 7.42 | 39,779.29 |
| 2/4-2/5/2014 | 6.45 | 80,119.77 |
| 2/8-2/9/2014 | 2.41 | 4,533.66 |
| 2/17-2/18/2014 | 2.57 | 53,047.24 |
| 2/20/2014 | 1.37 | 18,656.42 |
| 3/12/2014 | 7.06 | 80,393.90 |

| Date | Snow Amount (inches) | Total Delay Cost ($) |
|---|---|---|
| 4/14-4/15/2014 | 1.41 | 1,604.32 |
| 11/16/2014 | 0.60 | 0.00 |
| 11/19/2014 | 1.10 | 12,958.74 |
| 1/4/2015 | 0.60 | 8,846.56 |
| 1/6-1/7/2015 | 1.20 | 10,550.61 |
| 1/8-1/9/2015 | 1.80 | 6,992.44 |
| 1/11-1/12/2015 | 2.70 | 11,044.32 |
| 1/21/2015 | 2.50 | 6,595.49 |
| 1/29/2015 | 1.30 | 368.28 |
| 2/1-2/2/2015 | 17.00 | 21,421.17 |
| 2/3-2/4/2015 | 2.60 | 2,356.27 |
| 2/13-2/14/2015 | 2.20 | 6,616.72 |
| 2/21/2015 | 0.50 | 0.00 |
| 2/26/2015 | 0.30 | 5,329.64 |
| 3/1/2015 | 0.40 | 39.25 |
| 3/3/2015 | 1.10 | 18,929.59 |

Based on the above data, the following relationships were developed between total delay cost and snowstorm severity (amount of snow) for the following cases: with a one WMTP in the fleet (1 WMTP) and without a WMTP in the fleet (No WMTP). The developed relationships for each winter maintenance route are shown in the following figures.

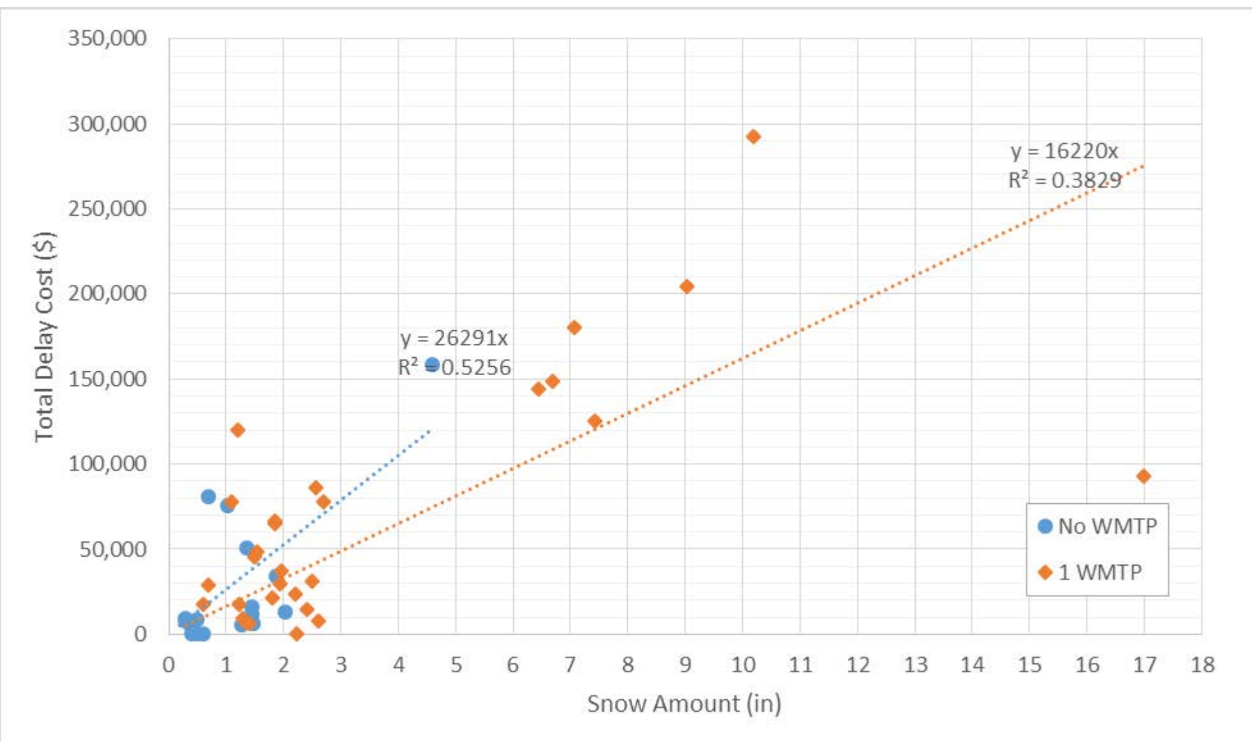


**Figure 5.35: Total Delay Costs for I-96 in Brighton Garage Area**

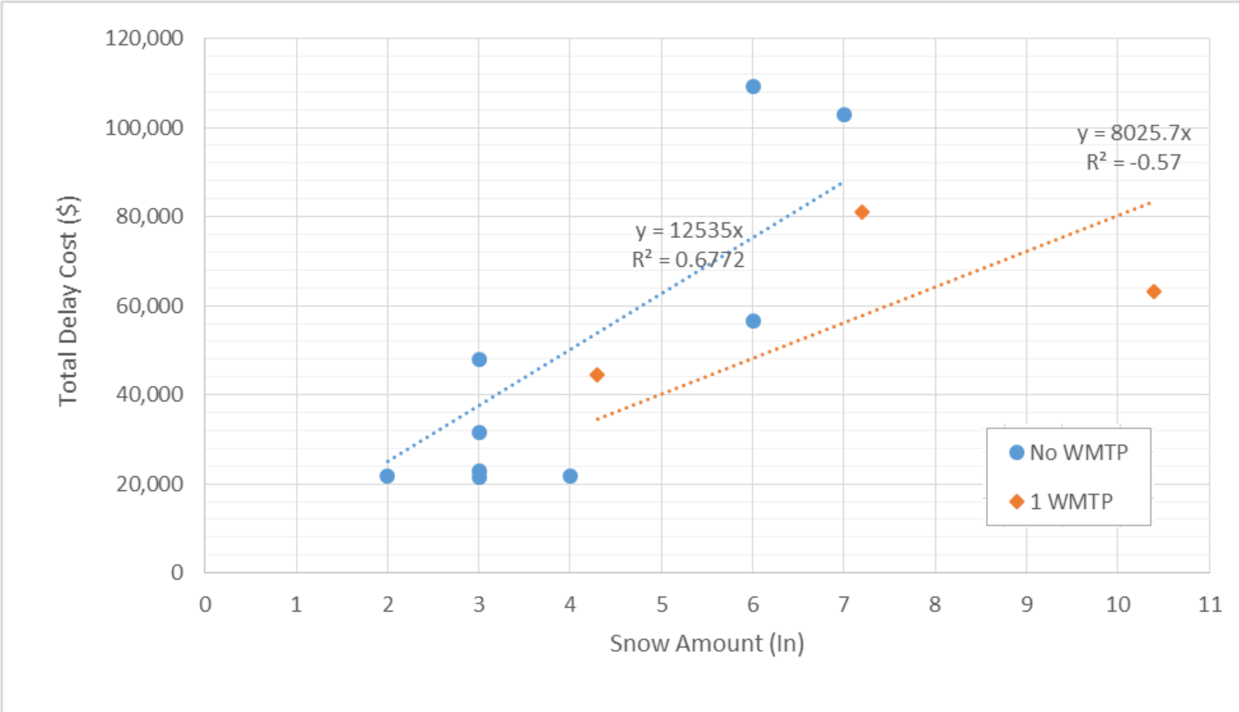


**Figure 5.36: Total Delay Costs for I-69 in Charlotte Garage Area**

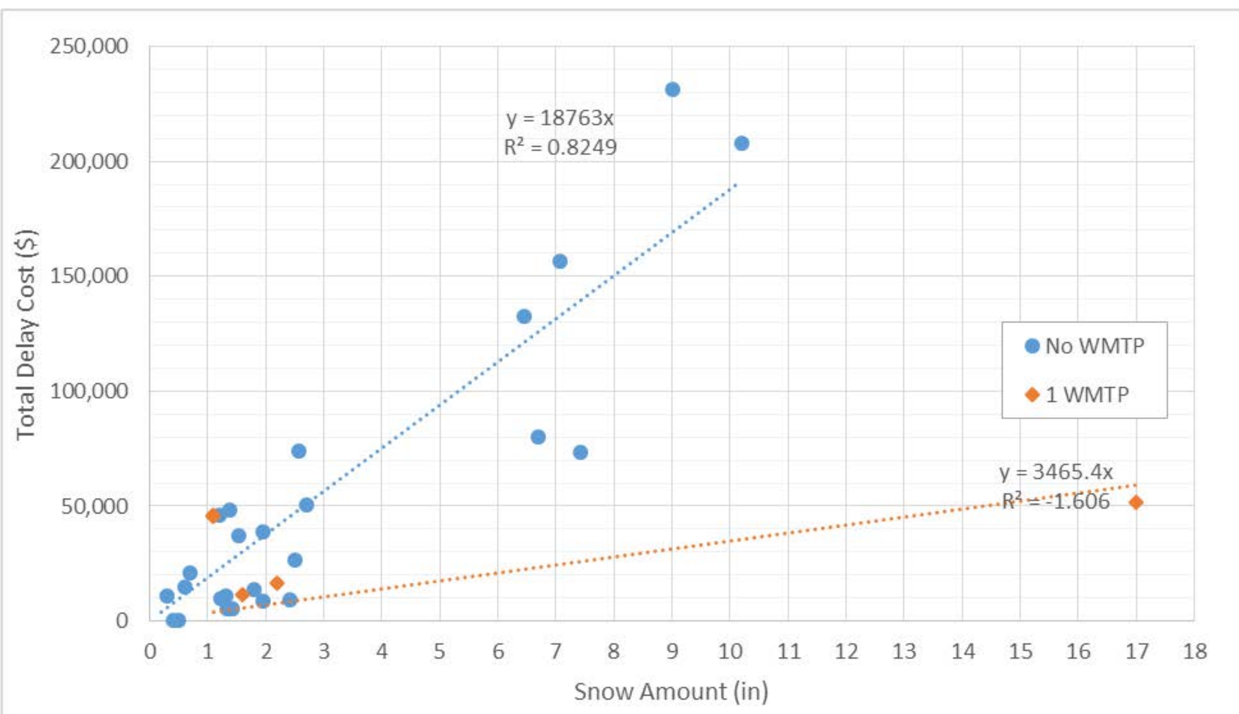


**Figure 5.37: Total Delay Costs for US-23 in Brighton Garage Area**

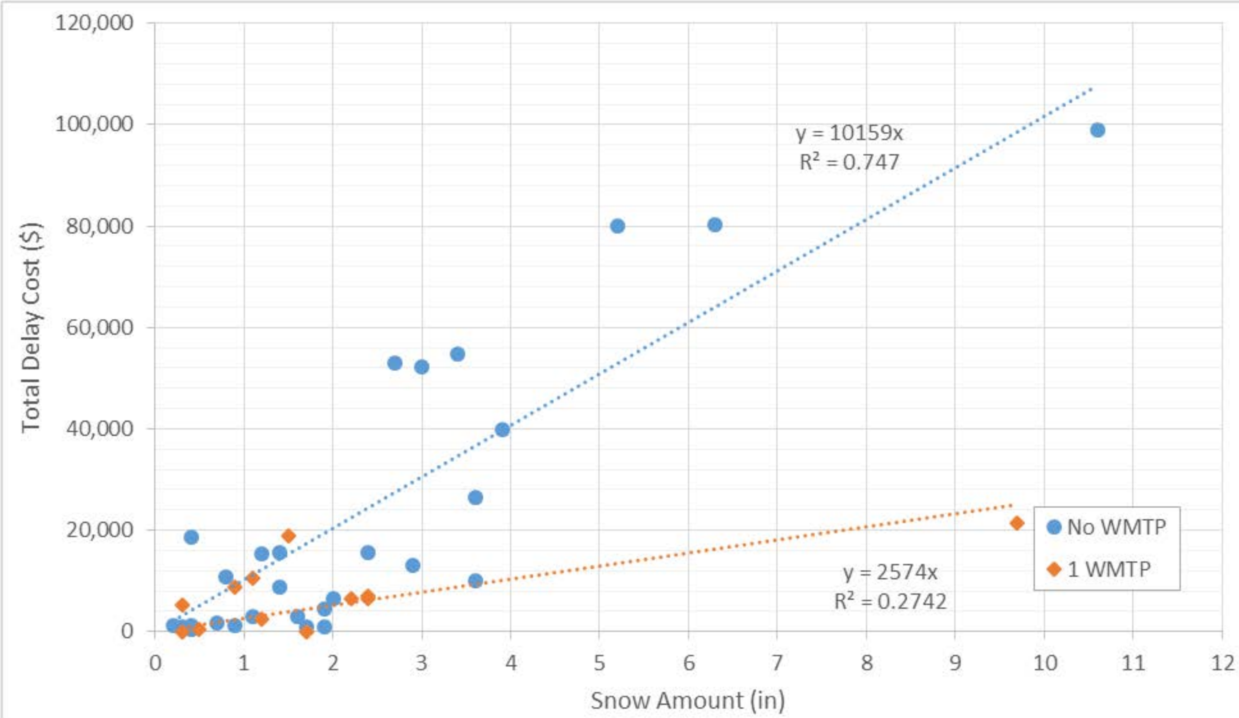


**Figure 5.38: Total Delay Costs for I-96 in Williamston Area**

The relationships for I-96 in the Brighton area, I-69 in the Charlotte area, US-23 in the Brighton garage area, and I-96 in the Williamston garage area, show lower total delay costs when the WMTP is included in the fleet.

## 5.5 Calculation of Cost-Benefit of Using a Tow Plow Combo Unit (WMTP)

### 5.5.1 Modeling of Cost-Benefit of Using a Tow Plow Combo Unit (WMTP) in the Equipment Fleet

The above-described costs of winter maintenance for different types of snow routes were analyzed to obtain a cost-benefit model for WMTP implementation. This analysis was performed for total direct costs and total costs (including indirect cost) separately. The total direct cost analysis included labor, salt, and equipment costs. However, for the indirect costs, only the delay costs due to winter storms/winter maintenance were included in the analysis as a separate cost item. Societal costs, such as accident costs, were not used for this analysis at this time. Once WMTPs are included in the equipment fleet for some time, the inclusion of accident cost calculations is recommended.

Based on the total costs for winter maintenance (labor, salt, and equipment), the following relationships were developed for different snow severity levels (snow amount) for different types of snow routes.

Total costs relationships for I-96 in the Brighton garage area (six-lane expressway route in a rural area) are shown in Figure 5.39.

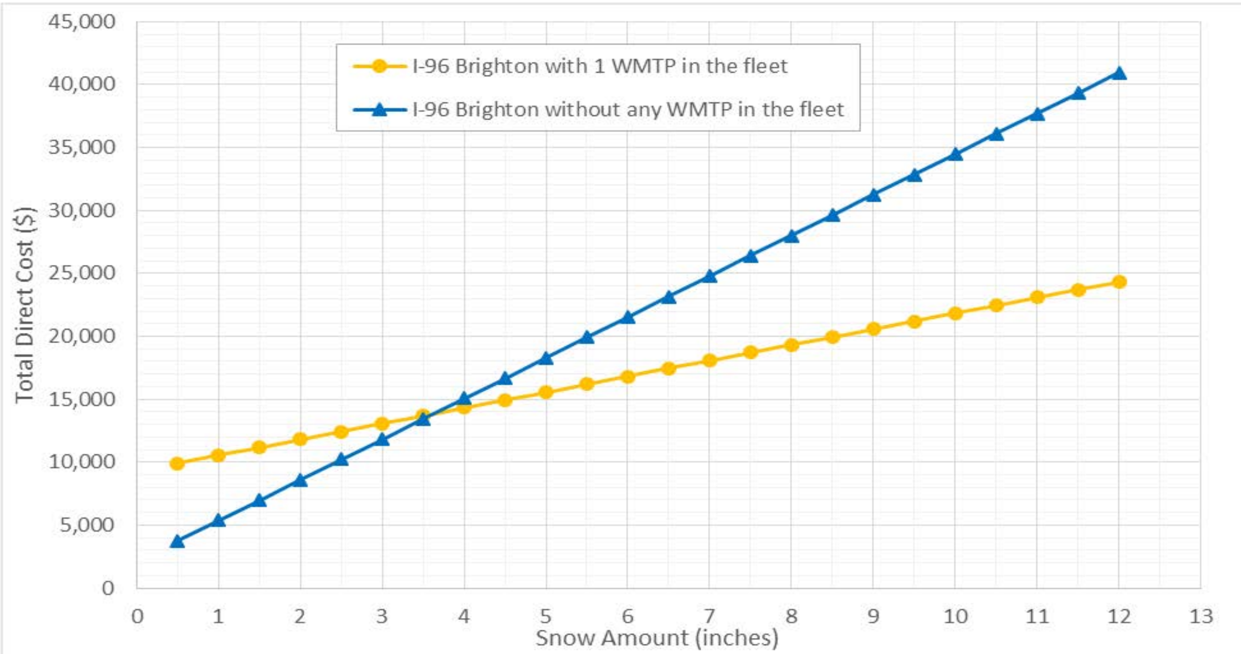


**Figure 5.39: Total Direct Cost versus Snow Amount for I-96 in Brighton Area**

In Figure 5.39, only direct costs (labor, salt, and equipment) were considered. For winter storms with at least 3 inches of snow, the use of one WMTP in the current equipment configuration is cost effective for six-lane expressways.

Similar relationships were developed for the four-lane expressways in rural areas: I-69 in Charlotte, US-23 in Brighton, and I-96 in Williamston. When evaluating the Charlotte results in Figure 5.40, use of one WMTP is cost effective, in terms of direct costs, until the snowstorm severity reaches 8 inches.[9] As for the Williamston (Figure 5.42) and Brighton (Figure 5.41) results, the use of one WMTP is cost effective after the snowstorm severity exceeds 5 and 7 inches, respectively. Therefore, the direct cost relationships developed for I-96 in the Charlotte area are preferred in terms of WMT and WMTP equipment configurations.

[9] As snowstorm severity increases, total direct costs typically decrease when one WMTP is included in the equipment fleet. In the case of I-69 in Charlotte, the number of high severity snowstorms may be lacking. Therefore, analyzing a few more years of WMTP usage is recommended.

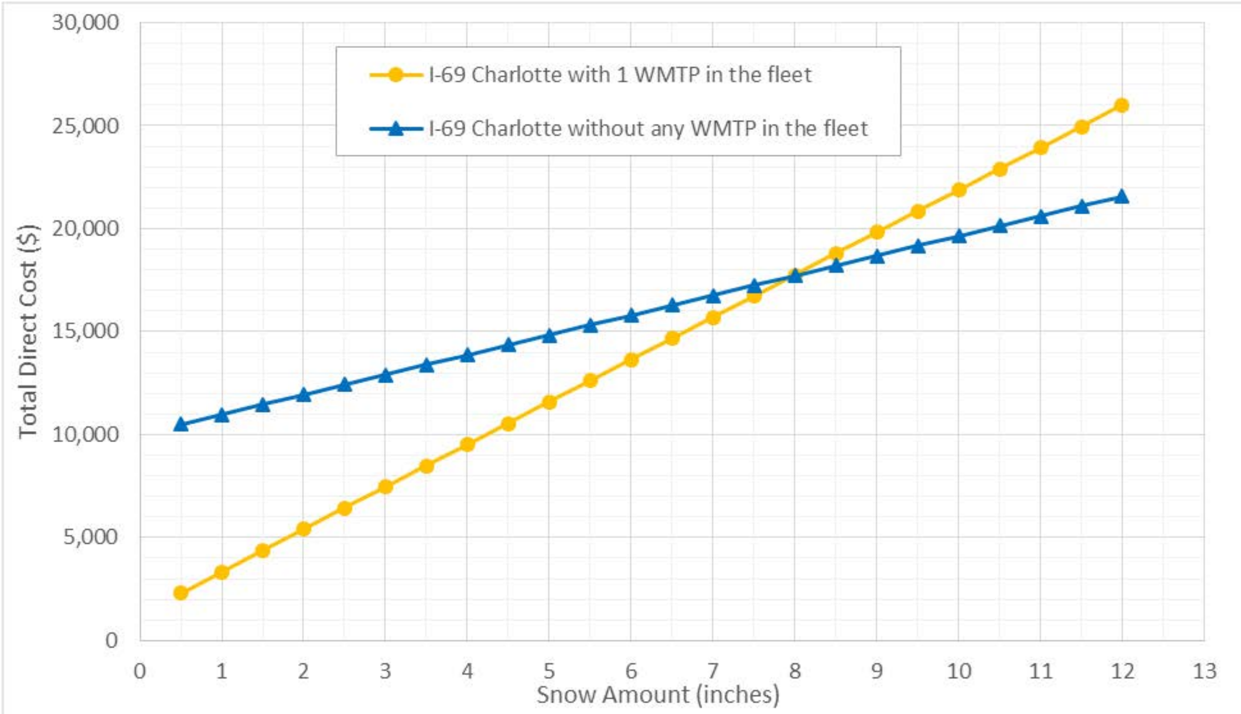


**Figure 5.40: Total Direct Cost versus Snow Amount for I-69 in Charlotte Area**

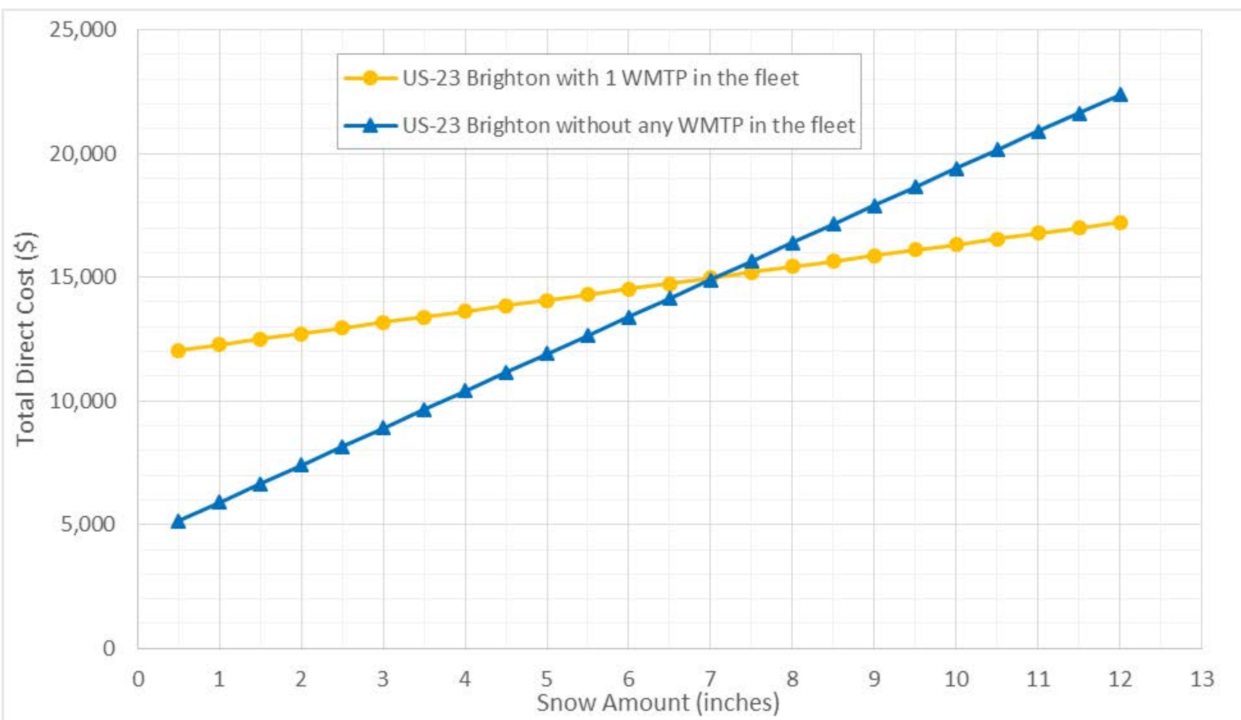


**Figure 5.41: Total Direct Cost versus Snow Amount for US-23 in Brighton Area**

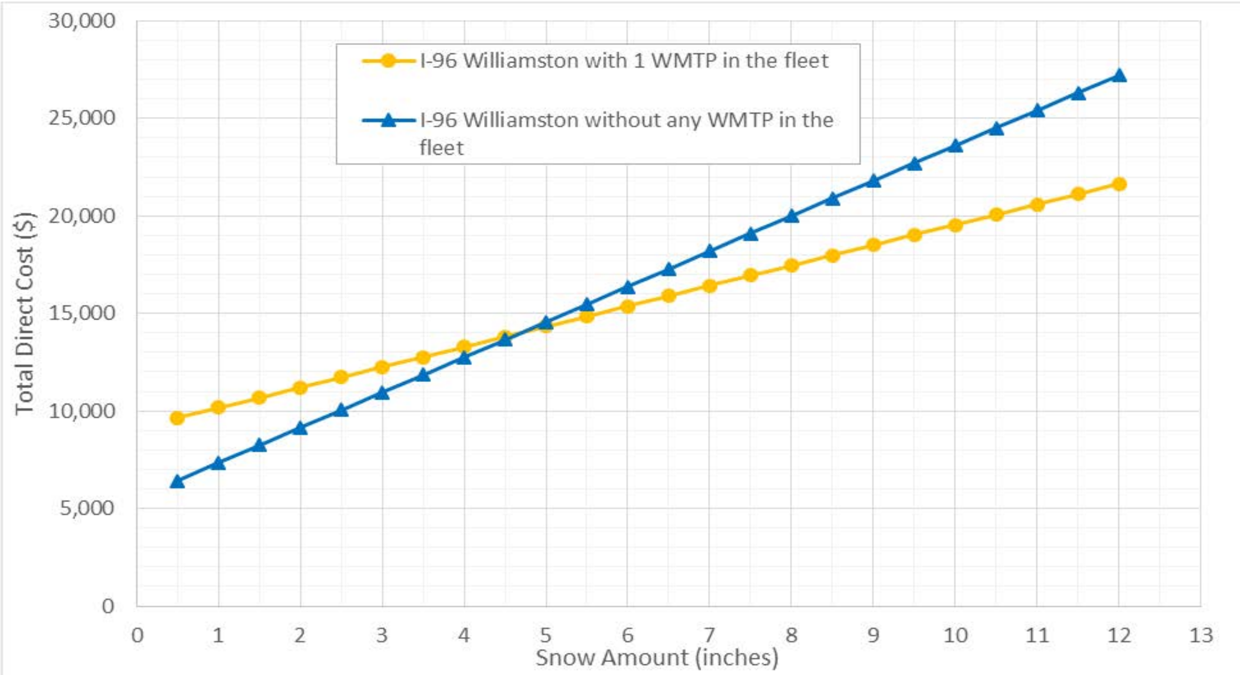


**Figure 5.42: Total Direct Cost versus Snow Amount for I-96 in Williamston Area**

A similar analysis was performed to include delay costs in the total cost of winter maintenance. As seen in Figures 5.43 to 5.46, use of a one WMTP is always beneficial when the delay cost is included in the analysis.

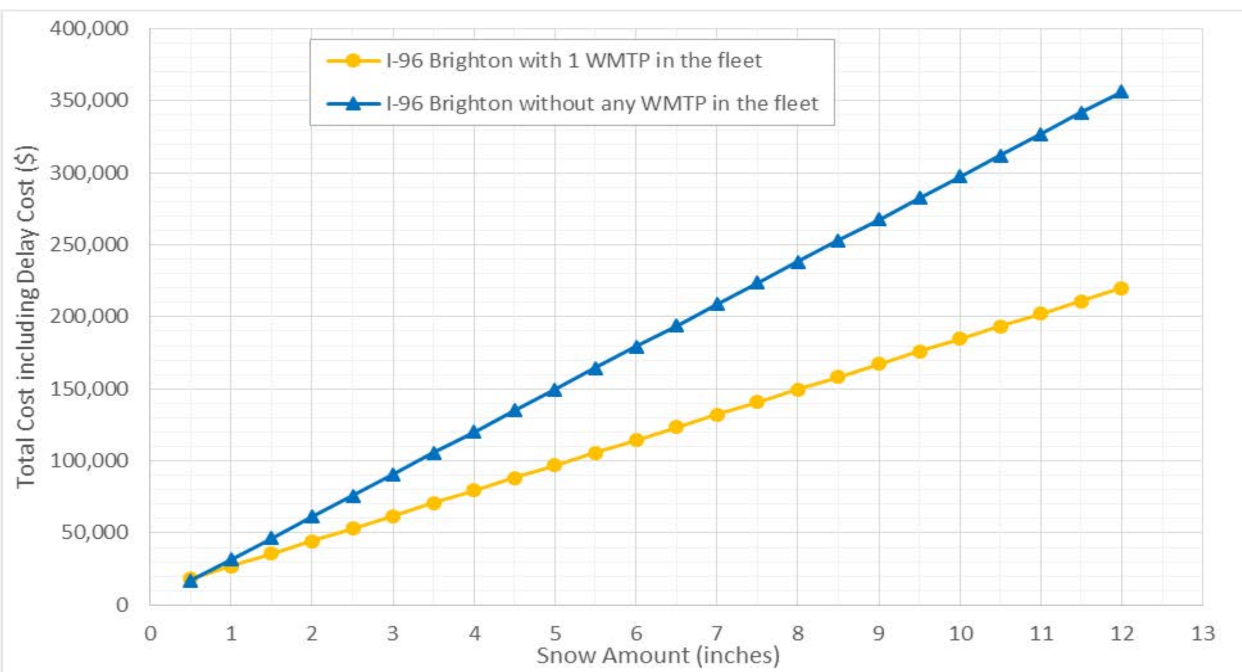


**Figure 5.43: Total Cost including Delay Cost versus Snow Amount for I-96 in Brighton Area**

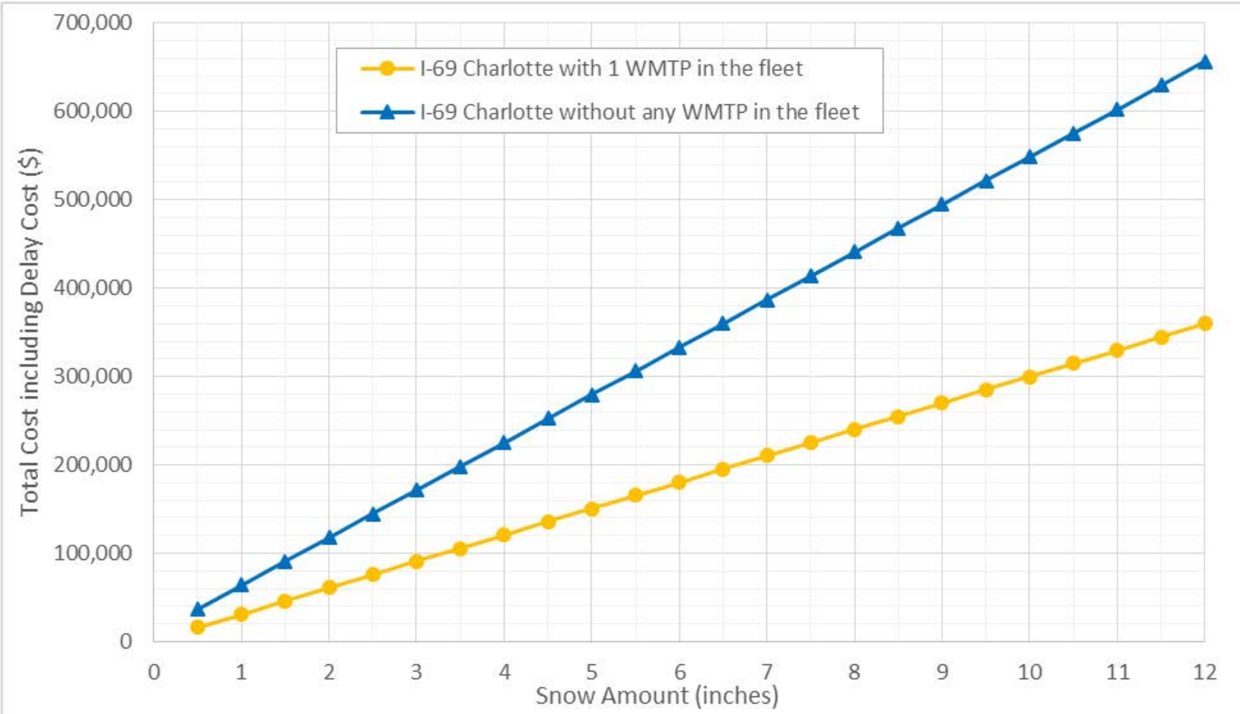


**Figure 5.44: Total Cost including Delay Cost versus Snow Amount for I-69 in Charlotte Area**

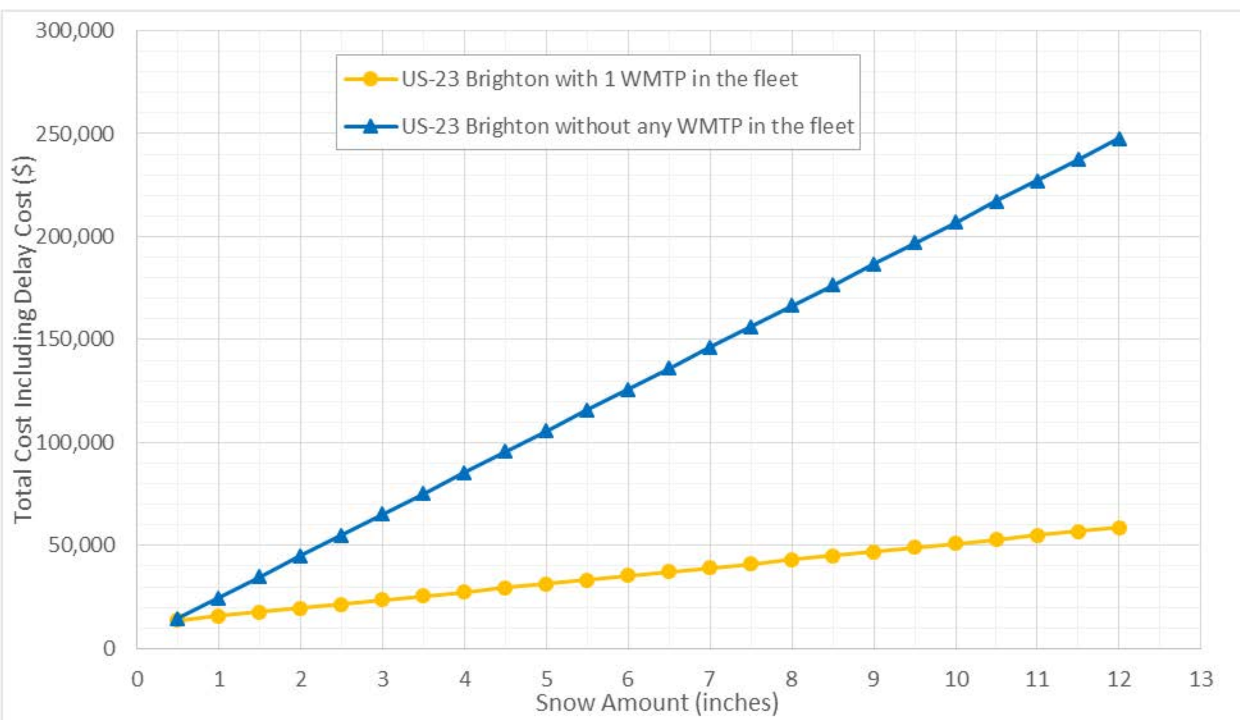


**Figure 5.45: Total Cost including Delay Cost versus Snow Amount for US-23 in Brighton Area**

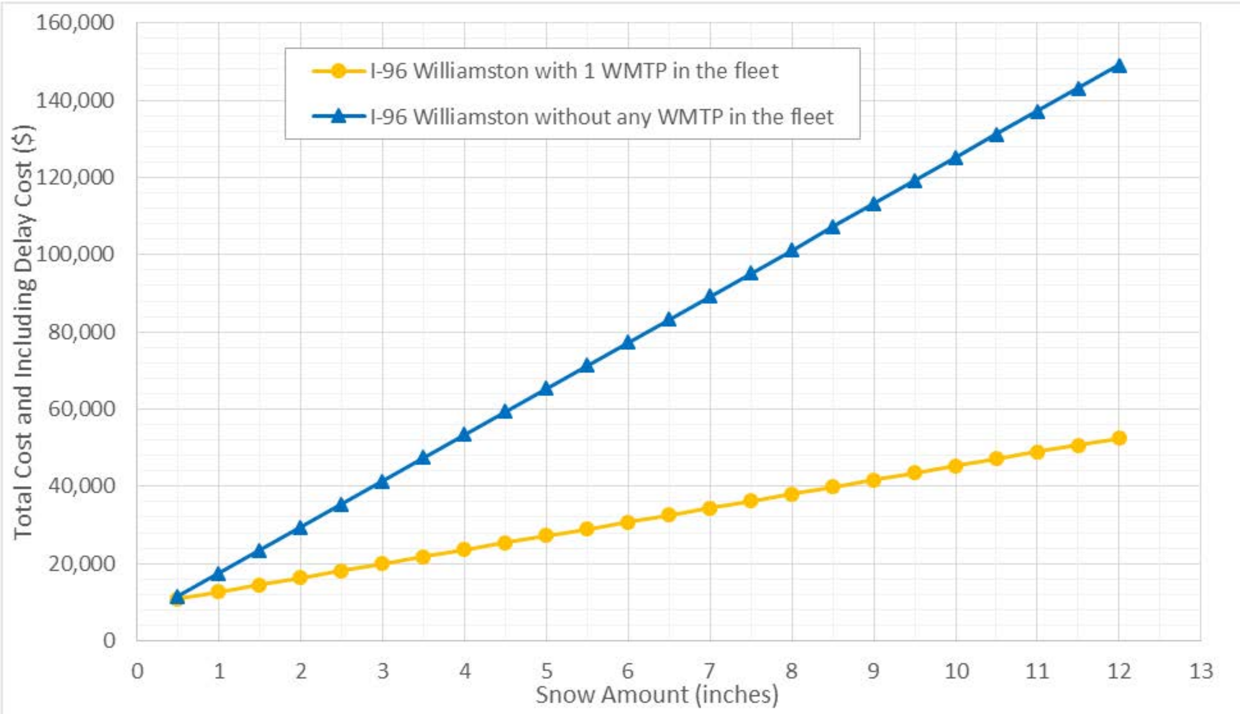


**Figure 5.46: Total Cost including Delay Cost versus Snow Amount for I-96 in Williamston Area**

These results and related discussion show the cost-benefit of including one WMTP in the equipment fleet for winter maintenance for expressways having four and six lanes. The cost effectiveness of using a WMTP in the equipment fleet was varied at different snow severity levels (measured in snow amount) for different types of snow routes. However, when the delay costs were included in the analysis, use of a WMTP was always beneficial irrelevant of route type.

### 5.5.2 Calculation of Cost-Benefit of Using One Tow Plow Combo Unit (WMTP) in the Equipment Fleet

The above-developed relationships were used to calculate the cost-benefit of using one WMTP in the equipment fleet for different snow routes having different snow severities. Different parts of the state receive varied amounts of snow as shown in the Figure 5.47. The majority of the cities included in Figure 5.47 are located in Michigan's Lower Peninsula. Michigan's Upper Peninsula receives much higher snow totals as seen from the Sault Ste. Marie data. Snowstorm data for the city of Sault Ste. Marie, Michigan, were included in the following analysis even though MDOT is not considering deploying WMTPs to the Upper Peninsula at this time.

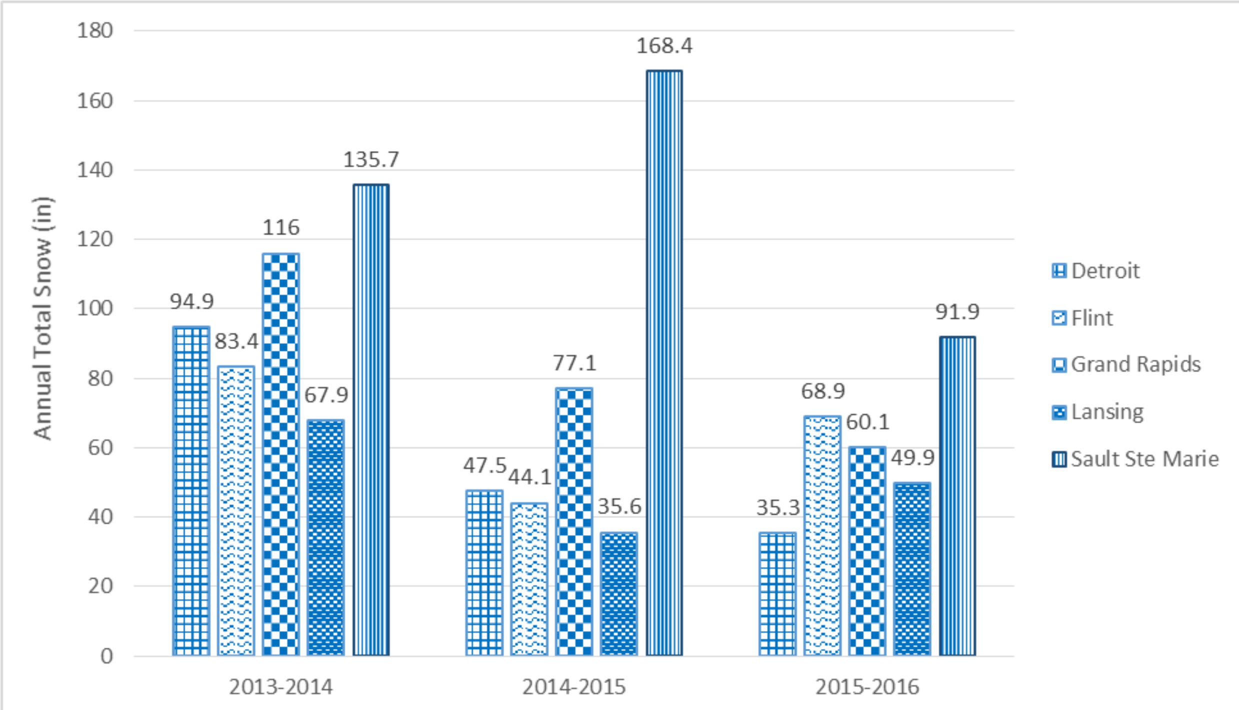


**Figure 5.47: Yearly Snowstorm Totals for Select Cities in Michigan**

As seen from the above figure, snow totals vary from 35 inches to 168 inches. These snow totals are comprised of individual storms with varied severity. Therefore, the frequency distribution of each individual snowstorms was analyzed for the above-selected cities in Michigan.

The following analysis includes snowstorm information for the last 10 years for the selected cities: Detroit, Flint, Grand Rapids, Lansing and Sault Ste. Marie. Figures 5.48 to 5.52 show the average frequency histograms of individual snowstorm severity.

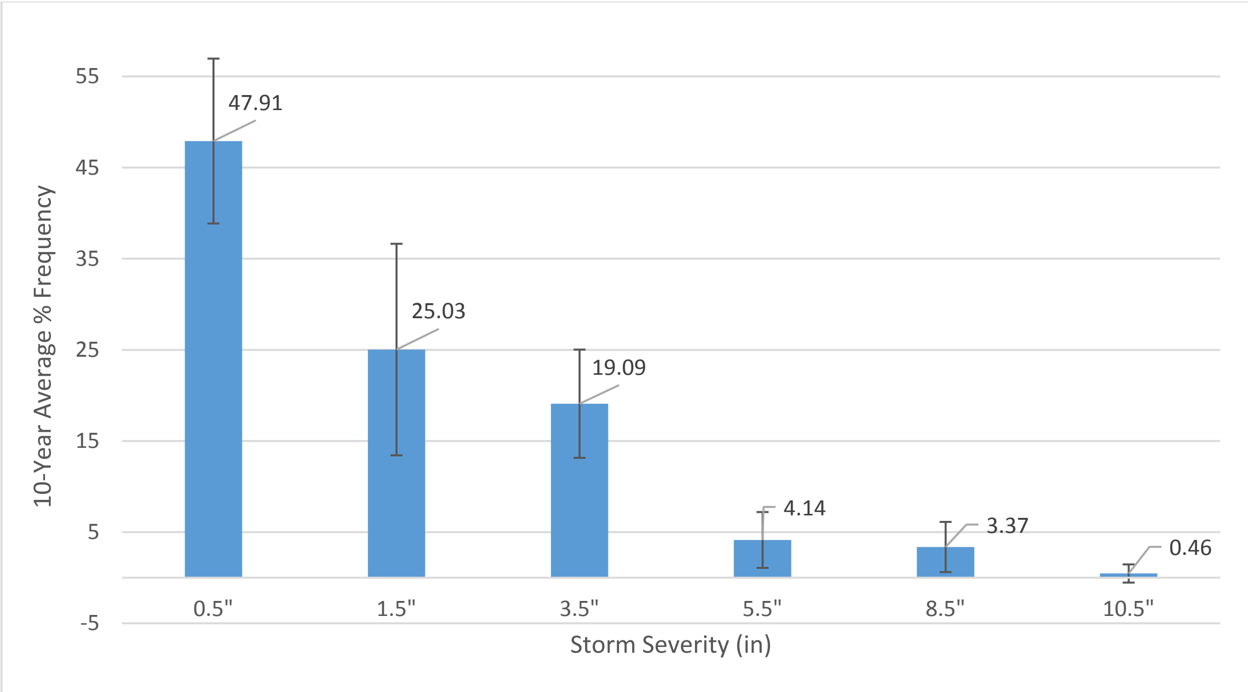


**Figure 5.48: Storm Severity Average Frequency in the Detroit Area**

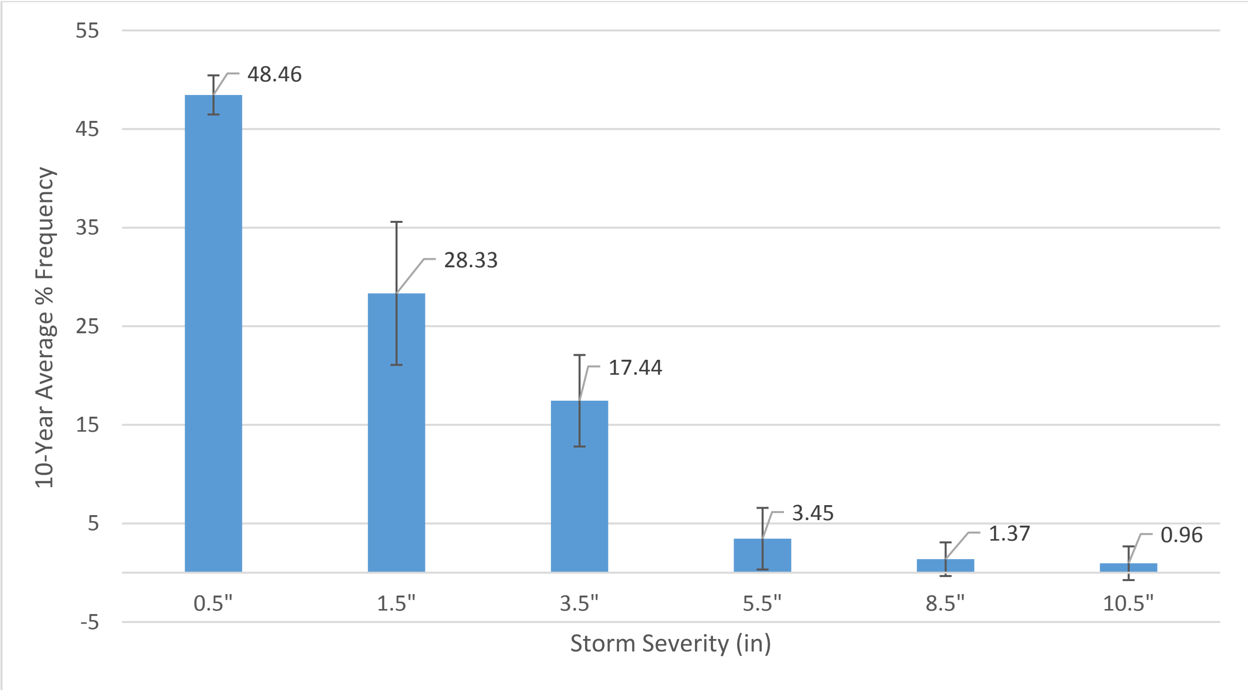


**Figure 5.49: Storm Severity Average Frequency in the Flint Area**

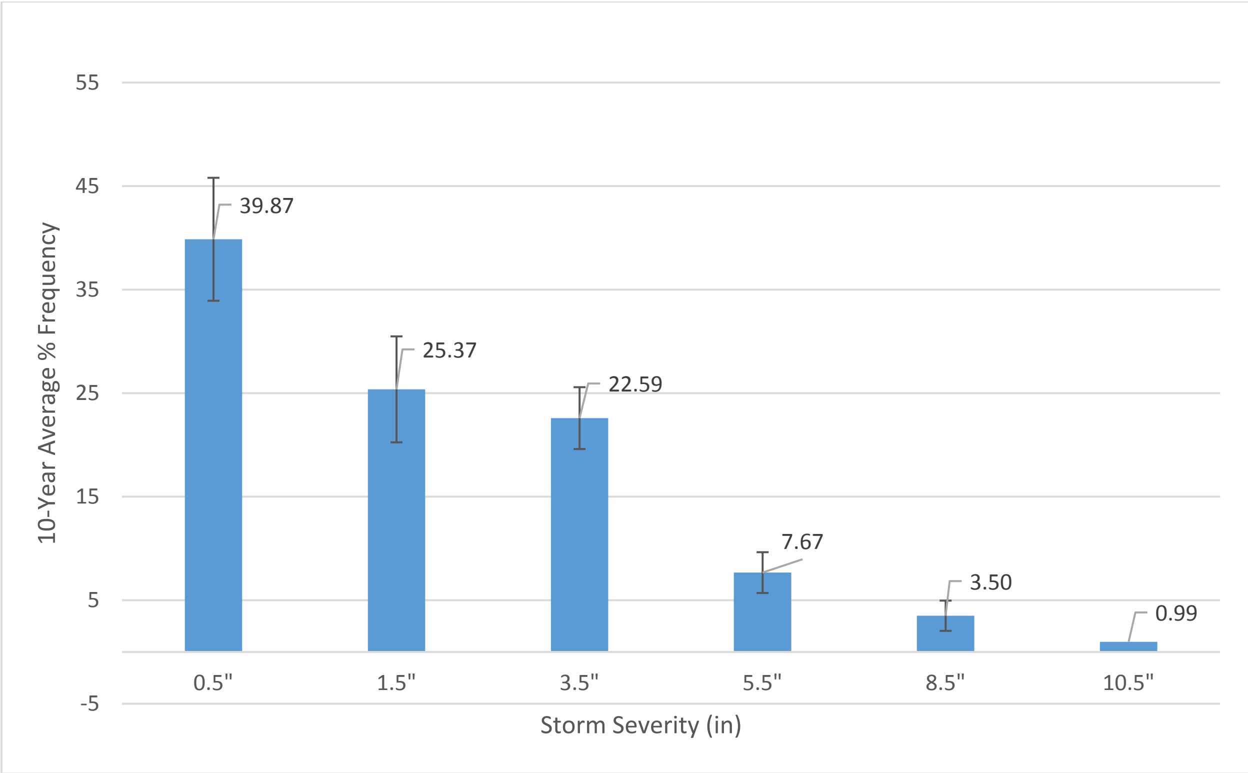


**Figure 5.50: Storm Severity Average Frequency in the Grand Rapids Area**

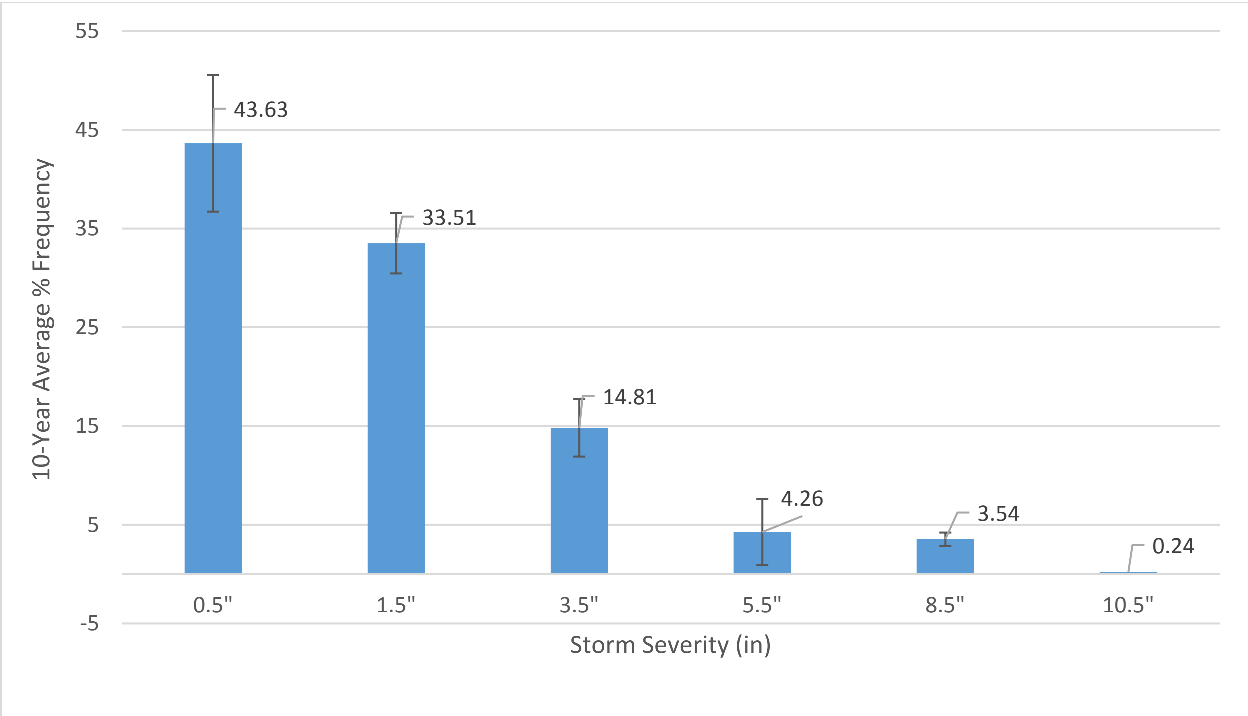


**Figure 5.51: Storm Severity Average Frequency in the Lansing Area**

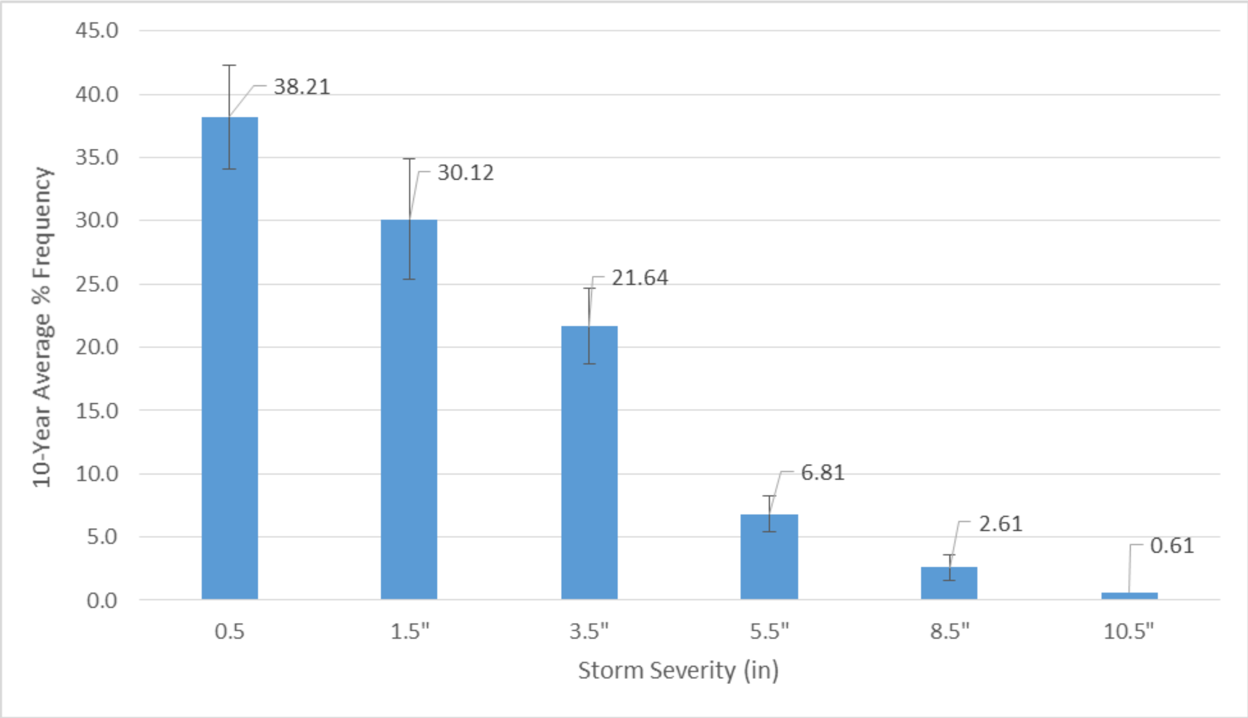


**Figure 5.52: Storm Severity Average Frequency in the Sault Ste. Marie Area**

Based on the frequency histograms, the percentage of different snowstorm severity in a given season was developed for the different parts of the state as shown in Tables 5.24 to 5.28. Average and standard deviation of individual storms per season are also given in the following tables.

**Table 5.24: Percentage of Different Snowstorms in the Detroit Area (SE Michigan)**

| Snowstorm Severity | Average Percentage of Storms in a Season | Standard Deviation of Storms in a Season |
|---|---|---|
| 0.5 inches or below | 47.91 | 9.04 |
| 1.5 inches | 25.03 | 11.61 |
| 3.5 inches | 19.09 | 5.94 |
| 5.5 inches | 4.14 | 3.06 |
| 8.5 inches | 3.37 | 2.75 |
| 10 inches or more | 0.46 | 1.00 |
| Average Number of Storms per Season | 40.50 | 8.67 |

**Table 5.25: Percentage of Different Snowstorms in the Flint Area (Flint/Tri-City Area)**

| Snowstorm Severity | Average Percentage of Storms in a Season | Standard Deviation of Storms in a Season |
|---|---|---|
| 0.5 inches or below | 48.46 | 1.98 |
| 1.5 inches | 28.33 | 7.25 |
| 3.5 inches | 17.44 | 4.64 |
| 5.5 inches | 3.45 | 3.12 |
| 8.5 inches | 1.37 | 1.71 |
| 10 inches or more | 0.96 | 1.71 |
| Average Number of Storms per Season | 51.40 | 9.88 |

**Table 5.26: Percentage of Different Snowstorms in the Grand Rapids Area (West Michigan)**

| Snowstorm Severity | Average Percentage of Storms in a Season | Standard Deviation of Storms in a Season |
|---|---|---|
| 0.5 inches or below | 39.87 | 6.99 |
| 1.5 inches | 25.37 | 5.94 |
| 3.5 inches | 22.59 | 5.12 |
| 5.5 inches | 7.67 | 2.99 |
| 8.5 inches | 3.50 | 1.97 |
| 10 inches or more | 0.99 | 1.46 |
| Average Number of Storms per Season | 51.10 | 13.21 |

**Table 5.27: Percentage of Different Snowstorms in the Lansing Area (Mid-Michigan)**

| Snowstorm Severity | Average Percentage of Storms in a Season | Standard Deviation of Storms in a Season |
|---|---|---|
| 0.5 inches or below | 43.63 | 5.86 |
| 1.5 inches | 33.51 | 6.92 |
| 3.5 inches | 14.81 | 3.06 |
| 5.5 inches | 4.26 | 2.91 |
| 8.5 inches | 3.54 | 3.37 |
| 10 inches or more | 0.24 | 0.67 |
| Average Number of Storms per Season | 39.38 | 10.25 |

**Table 5.28: Percentage of Different Snowstorms in the Sault Ste. Marie Area (North/Upper Peninsula)**

| Snowstorm Severity | Average Percentage of Storms in a Season | Standard Deviation of Storms in a Season |
|---|---|---|
| 0.5 inches or below | 38.21 | 5.85 |
| 1.5 inches | 30.12 | 4.12 |
| 3.5 inches | 21.64 | 4.77 |
| 5.5 inches | 6.81 | 2.99 |
| 8.5 inches | 2.61 | 1.42 |
| 10 inches or more | 0.61 | 0.99 |
| Average Number of Storms per Season | 80.20 | 16.68 |

The above snowstorm severities and the number of storms per season were used to estimate the cost-benefit of using one WMTP in the equipment fleet on different types of roadways in different areas of the state.

#### 5.5.2.1 Cost-Benefit of Using One Tow Plow Combo Unit (WMTP) on Rural Six-Lane Expressways

The cost-benefit of using one WMTP on rural six-lane expressways was analyzed using the relationships developed for the I-96 in Brighton data. The developed relationships for labor cost, salt cost, and equipment cost were used to calculate the total cost of winter maintenance of two different winter maintenance configurations: the current equipment fleet and modified equipment fleet. The current configuration includes one WMTP in the fleet or no WMTP in the fleet. The modified, or optimized, configuration uses one WMTP with a modified number of WMTs based on storm severity. The different winter storm severities and frequencies were based on the selected cities in Michigan as shown in Tables 5.24 to 5.28.

1. Current Equipment Configuration:
   a. One WMTP in the Equipment Fleet - One WMTP and a different number of regular WMTs will be used for all snowstorms events. In this configuration, the WMTP will be used for every snowstorm event having more than 0.5 inches of snow.
   b. No WMTPs in the Equipment Fleet
2. Modified Equipment Configuration - The WMTP will only be used with a modified number of regular WMTs based on snowstorm severity as shown in Table 5.10.

A Monte Carlo simulation was used to predict the distribution of winter storms per season. Predicted costs were calculated for each simulated number of storms. Two thousand simulations were run to simulate approximately 25 years of snowstorms. The following figure shows the resulting distribution of the number of storms per region in Michigan.

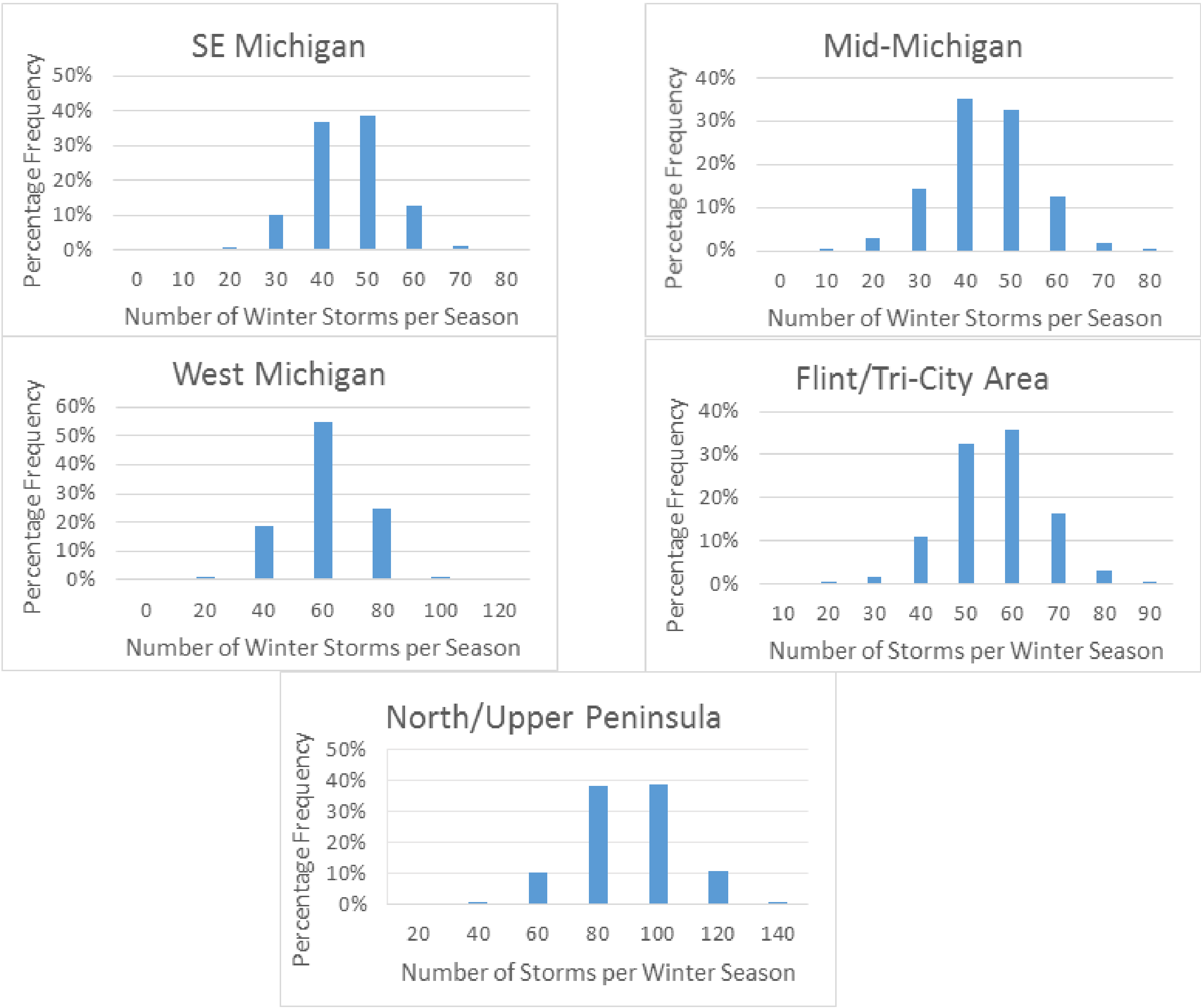


**Figure 5.53: Distribution of Winter Storm Events in Different Areas of the State**

Since the delay costs for a six-lane expressway were calculated for the I-96 expressway in Livingston County, adjustment factors were calculated to determine delay costs in other areas. Annual Average Daily Traffic (AADT) results were applied to selected roadways as shown in the following table.

**Table 5.29: AADT Adjustment Factors for Different Areas of the State**

| Analysis Area | Selected Route and County | AADT (in 2014) | AADT Adjustment Factor for Delay Calculations |
|---|---|---|---|
| Livingston County | I-96 in Livingston | 72,485 | 1.00 |
| SE Michigan | I-94 in Wayne | 116,857 | 1.61 |
| Mid-Michigan | I-96 in Ingham | 45,963 | 0.63 |
| West Michigan | I-196 in Kent | 55,918 | 0.77 |
| Flint/Tri-City Area | I-75 in Genesee | 63,832 | 0.88 |
| North/Upper Peninsula | I-75 in Cheboygan* | 8,754 | 0.12 |

*Four-lane expressway

The respective delay costs are recorded with the total direct costs in Table 5.29. Values in parentheses indicate negative savings meaning that the inclusion of one WMTP will increase the cost of winter maintenance.

The total direct costs are higher when one WMTP is used in the current equipment fleet configuration. However, substantial cost savings are realized when delay costs are factored into the total costs. This is due to the fact that snow is cleared faster and travel speed is regained more quickly when the WMTP is used in the equipment fleet. MDOT and the traveling public will greatly benefit from the use of WMTP for snow-clearing operations.

Furthermore, positive direct cost savings can be obtained by optimizing the equipment fleets as recommended in Table 5.10. Table 5.30 shows total direct cost savings by using the modified equipment configuration. The modified equipment configuration includes using a reduced number of regular WMTs for all storms events greater than 0.5 inches. Only regular WMTs will be used for any storm equal to or less than 0.5 inches.

**Table 5.30: Cost-Benefit of Using WMTPs on Rural Six-Lane Expressway (121 Lane Miles) – Current Equipment Configuration (One WMTP and Different Number of Regular WMTs)**

| Analysis Area | No. of Snowstorms per Season | | Total Direct Costs ($) | | | | | | Total Costs including Delay Costs ($) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | With one WMTP | | Without WMTP | | Yearly Savings | | With one WMTP | | Without WMTP | | Yearly Savings | |
| | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev |
| SE Michigan | 40.5 | 8.66 | 296,129 | 63,401 | 262,268 | 56,152 | (33,861) | 7,249 | 2,049,518 | 441,333 | 3,079,602 | 666,071 | 1,039,084 | 224,738 |
| Mid-Michigan | 39.4 | 10.25 | 298,536 | 77,490 | 251,228 | 65,210 | (47,307) | 12,279 | 952,154 | 247,149 | 1,305,866 | 338,961 | 353,712 | 91,812 |
| West Michigan | 51.1 | 13.21 | 431,592 | 110,407 | 395,883 | 101,271 | (35,713) | 9,136 | 1,724,659 | 441,187 | 2,482,288 | 634,998 | 757,629 | 193,810 |
| Flint/Tri-City Area | 51.4 | 9.88 | 358,898 | 69,280 | 303,191 | 58,532 | (55,706) | 10,754 | 1,462,126 | 282,268 | 2,083,294 | 402,187 | 621,167 | 119,918 |
| North/Upper Peninsula | 80.2 | 16.67 | 681,174 | 140,219 | 594,408 | 594,408 | (86,766) | 17,860 | 979,195 | 201,567 | 1,075,276 | 221,345 | 96,080 | 19,778 |

**Table 5.31: Cost-Benefit of Using one WMTPs on Rural Six-Lane Expressway (121 Lane Miles) – Modified Equipment Configuration**

| Analysis Area | No. of Snowstorms per Season | | Yearly Savings Based on Total Direct Costs | |
|---|---|---|---|---|
| | Average | Std. Dev | Average ($) | Std. Dev ($) |
| SE Michigan | 40.5 | 8.66 | 21, 473 | 4,644 |
| Mid-Michigan | 39.4 | 10.25 | 20,546 | 5,309 |
| West Michigan | 51.1 | 13.21 | 35,959 | 9,198 |
| Flint/Tri-City Area | 51.4 | 9.88 | 21,210 | 4,094 |
| North/Upper Peninsula | 80.2 | 16.67 | 43,408 | 8,873 |

As shown in Figure 5.53, the number of winter storms in a given season is normally distributed. This distribution was applied to the annual cost savings as a result of using the modified equipment configuration. Figures 5.54 to 5.58 show the distribution of anticipated annual savings when using the modified equipment configuration in different regions of the state.

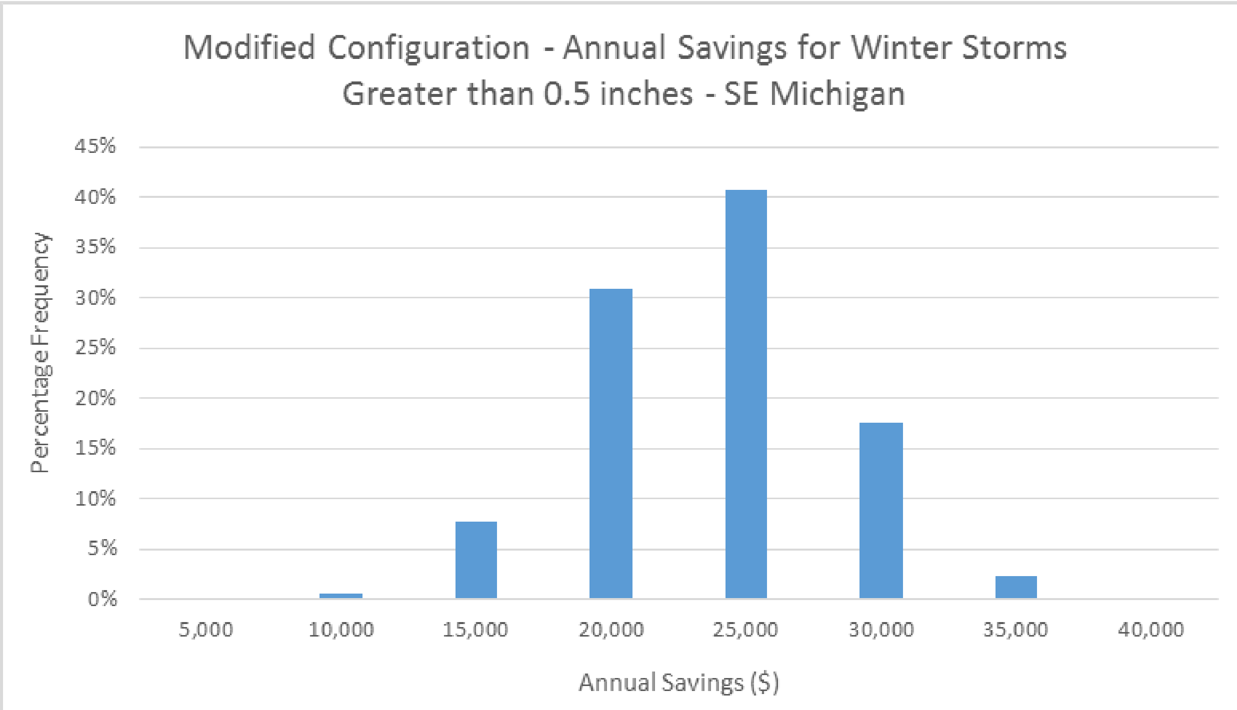


**Figure 5.54: Distribution of the Annual Cost Savings Due to Modified Equipment Configuration for Six-Lane Expressways – SE Michigan**

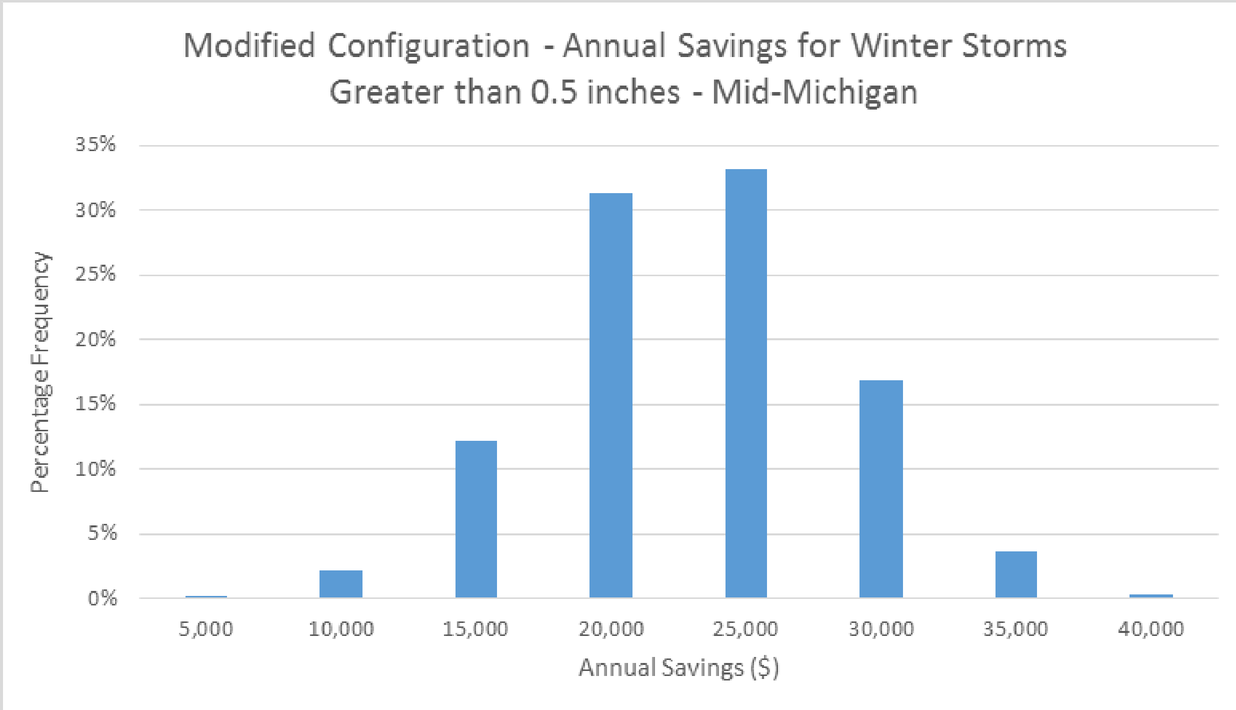


**Figure 5.55: Distribution of the Annual Cost Savings Due to Modified Equipment Configuration for Six-Lane Expressways – Mid-Michigan**

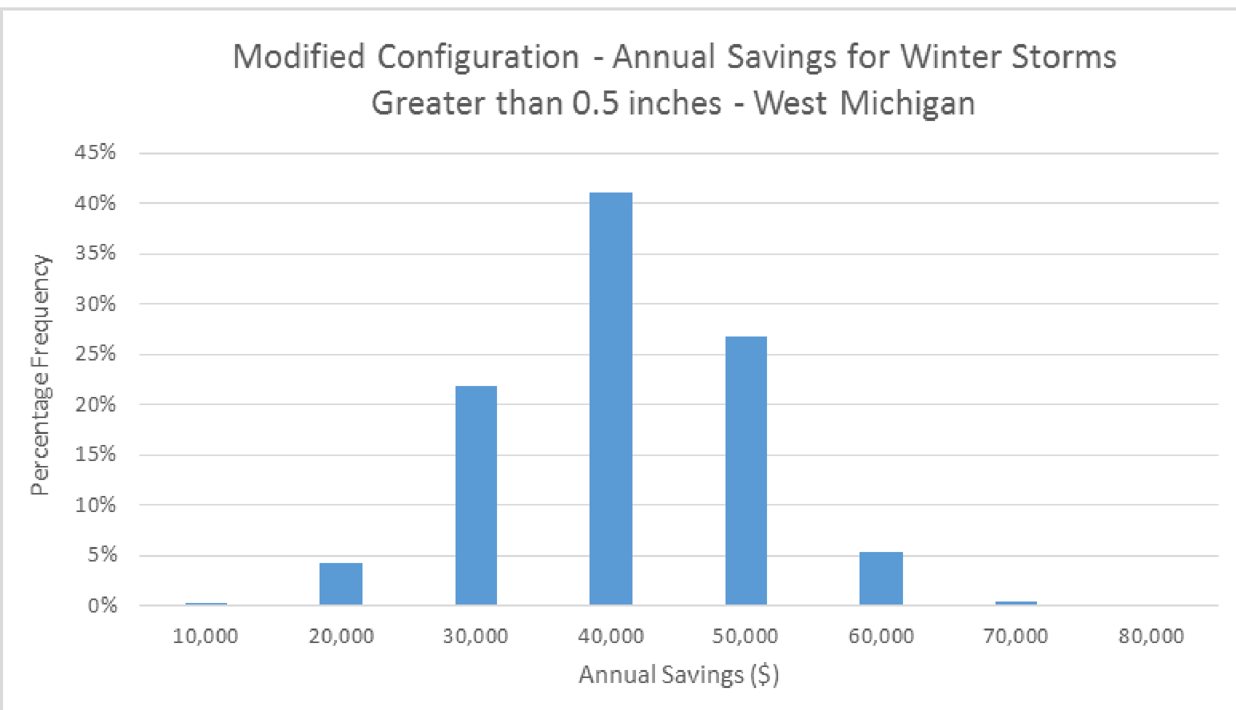


**Figure 5.56: Distribution of the Annual Cost Savings Due to Modified Equipment Configuration for Six-Lane Expressways – West Michigan**

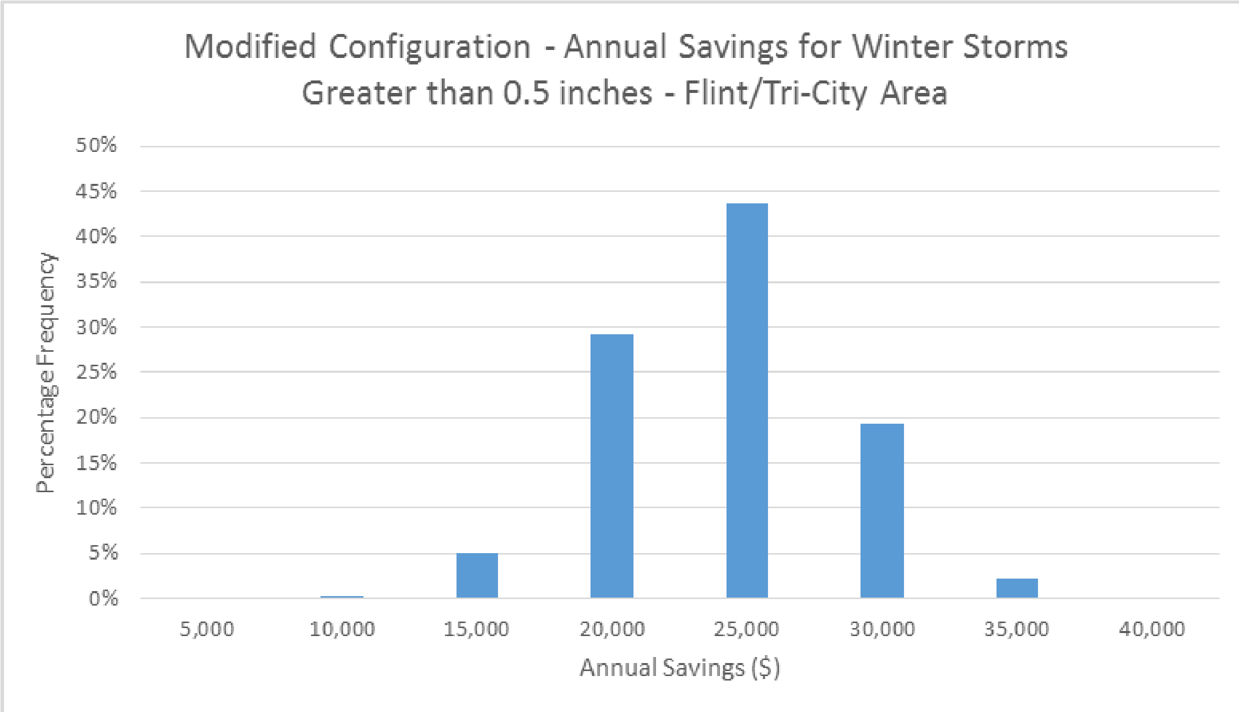


**Figure 5.57: Distribution of the Annual Cost Savings Due to Modified Equipment Configuration for Six-Lane Expressways – Flint/Tri-City Area**

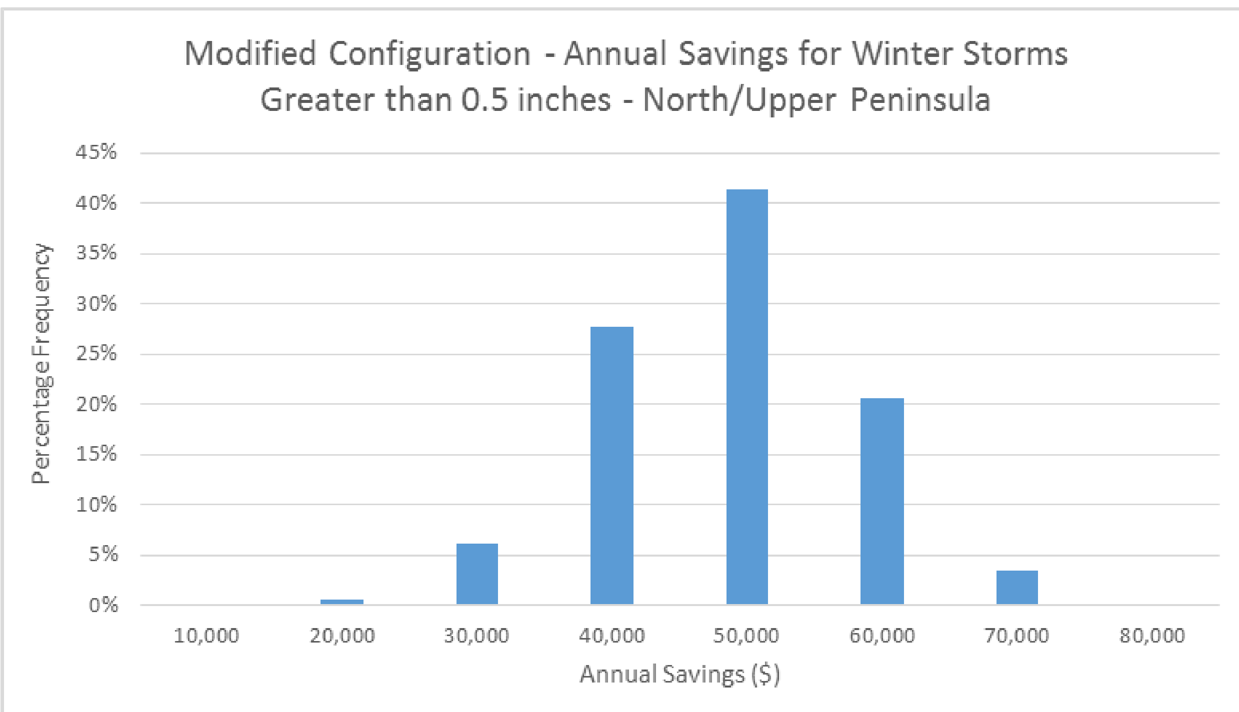


**Figure 5.58: Distribution of the Annual Cost Savings Due to Modified Equipment Configuration for Six-Lane Expressways – North/Upper Peninsula**

#### 5.5.2.2 Cost-Benefit of Using One Tow Plow Combo Unit (WMTP) on Rural Four-Lane Expressways

In Section 5.5.2.1, the cost-benefit of using a WMTP on rural six-lane expressways was determined. The same methodology was applied to rural four-lane expressways using the relationships developed for US-23 in Brighton and I-69 in Charlotte. The US-23 analysis shows the cost-benefit of using the current equipment configuration. The I-69 analysis incorporates the modified equipment configuration developed by MDOT for the Charlotte maintenance garage. In this case, the developed relationships for labor, salt, and equipment costs were used to calculate the total cost of winter maintenance.

The modified configuration includes one WMTP and several regular WMTs in the fleet. These savings were compared to no WMTPs in the equipment fleet with a varying number of WMTs. This methodology was then applied to selected roadways in other counties. Adjustment factors were implemented to incorporate Annual Average Daily Traffic (AADT) volume (Table 5.32).

**Table 5.32: AADT Adjustment Factors for Different Areas of the State**

| Analysis Area | Selected Route and County | AADT (in 2014) | AADT Adjustment Factor for Delay Calculations |
|---|---|---|---|
| SE Michigan | M-39 in Wayne | 105,641 | 4.22 |
| Mid-Michigan | I-69 in Eaton | 25,021 | 1.00 |
| West Michigan | US-131 in Kent | 61,450 | 2.46 |
| Flint/Tri-City Area | I-69 in Genesee | 44,994 | 1.80 |
| North/Upper Peninsula | I-75 in Cheboygan | 8,754 | 0.35 |

The results of the cost-benefit analyses for the current and modified equipment configurations are shown in Tables 5.33 and 5.34.

**Table 5.33: Cost-Benefit of Using WMTPs on Rural Four-Lane Expressways (98 Lane Miles) – Current Equipment Configuration (One WMTP and Different Number of Regular WMTs)**

| | No. of Snow Storms per Season | | Total Direct Costs ($) | | | | | | Total Costs including Delay Costs ($) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | With one WMTP | | Without WMTP | | Yearly Savings | | With one WMTP | | Without WMTP | | Yearly Savings | |
| Analysis Area | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev |
| SE Michigan | 40.5 | 8.66 | 259,851 | 56,093 | 194,690 | 42,027 | (65,161) | 14,066 | 735,822 | 158,838 | 2,761,326 | 592,775 | 2,082,223 | 435,399 |
| Mid-Michigan | 39.4 | 10.25 | 266,504 | 69,276 | 194,385 | 50,529 | (72,119) | 18,747 | 501,208 | 130,285 | 1,465,158 | 380,856 | 963,950 | 250,571 |
| West Michigan | 51.1 | 13.21 | 379,995 | 97,628 | 290,278 | 74,578 | (89,716) | 23,050 | 797,841 | 204,980 | 2,552,657 | 655,826 | 1,754,816 | 450,846 |
| Flint/Tri-City Area | 51.4 | 9.88 | 319,412 | 62,224 | 233,436 | 45,475 | (85,976) | 16,749 | 548,884 | 106,927 | 1,475,884 | 287,513 | 926,999 | 180,586 |
| Northern-Michigan/Upper Peninsula | 80.2 | 16.67 | 597,066 | 125,593 | 443,597 | 93,310 | (153,469) | 32,282 | 685,746 | 144,247 | 923,748 | 194,310 | 238,001 | 50,063 |

**Table 5.34: Cost-Benefit of Using WMTPs on Rural Four-Lane Expressways (142 Lane Miles) – Modified Equipment Configuration (One WMTP and Different Number of Regular WMTs)**

| Analysis Area | No. of Snowstorms per Season | | Total Direct Costs ($) | | | | | | Total Costs including Delay Costs ($) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | With one WMTP | | Without WMTP | | Yearly Savings | | With one WMTP | | Without WMTP | | Yearly Savings | |
| | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev | Average | Std. Dev |
| SE Michigan | 40.5 | 8.66 | 131,978 | 28,230 | 246,843 | 52,800 | 114,865 | 24,570 | 2,015,835 | 433,807 | 3,799,101 | 817,656 | 1,783,266 | 383,758 |
| Mid-Michigan | 39.4 | 10.25 | 128,851 | 33,781 | 255,806 | 67,065 | 126,955 | 33,284 | 585,531 | 152,610 | 1,094,312 | 285,218 | 508,781 | 132,607 |
| West Michigan | 51.1 | 13.21 | 203,312 | 52,721 | 361,991 | 93,868 | 158,678 | 41,147 | 1,917,367 | 497,192 | 3,576,696 | 927,472 | 1,659,329 | 430,280 |
| Flint/Tri-City Area | 51.4 | 9.88 | 162,023 | 31,544 | 313,201 | 60,977 | 151,178 | 29,433 | 1,099,215 | 214,004 | 2,066,959 | 402,413 | 967,744 | 188,408 |
| Northern-Michigan/Upper Peninsula | 80.2 | 16.67 | 320,911 | 66,145 | 591,587 | 121,938 | 270,676 | 55,792 | 722,328 | 148,887 | 1,304,141 | 268,810 | 581,813 | 119,924 |

The distribution of the number of winter storms in a given season was applied to the annual cost savings when using the modified equipment configuration on four-lane expressways. Figures 5.59 to 5.63 show the distribution of anticipated annual savings for different regions of the state.

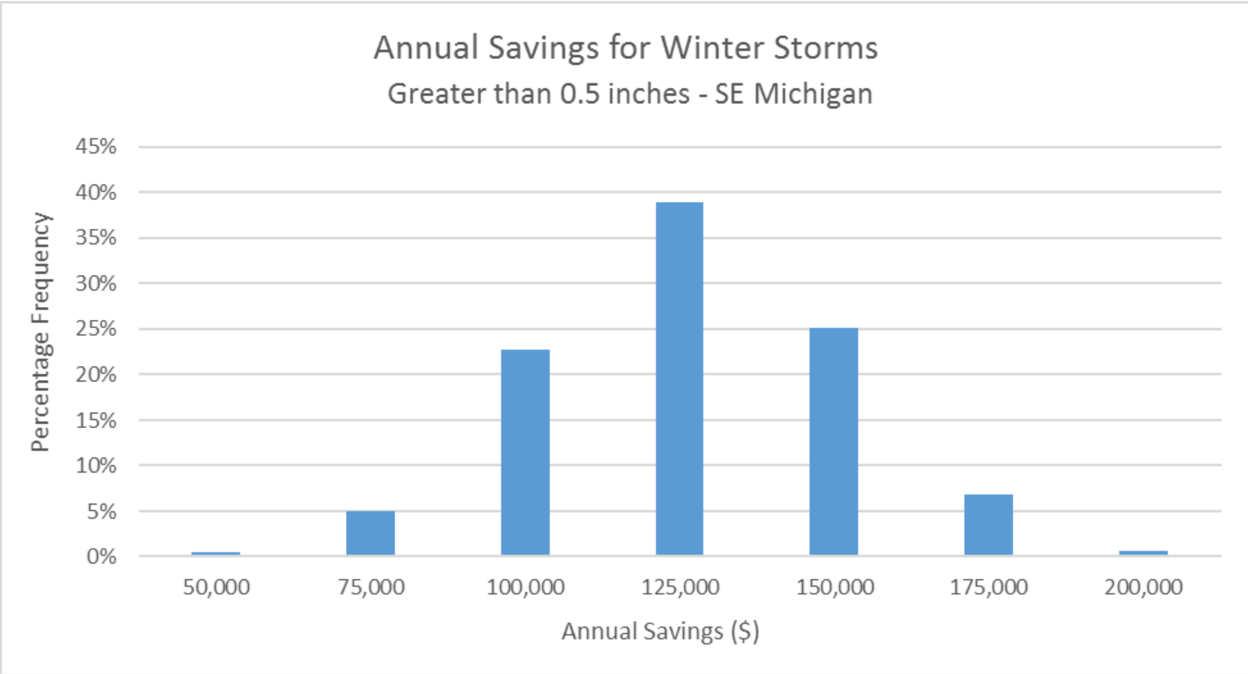


**Figure 5.59: Distribution of the Annual Cost Savings Due to Modified Equipment Configurations for Four-Lane Expressways – SE Michigan**

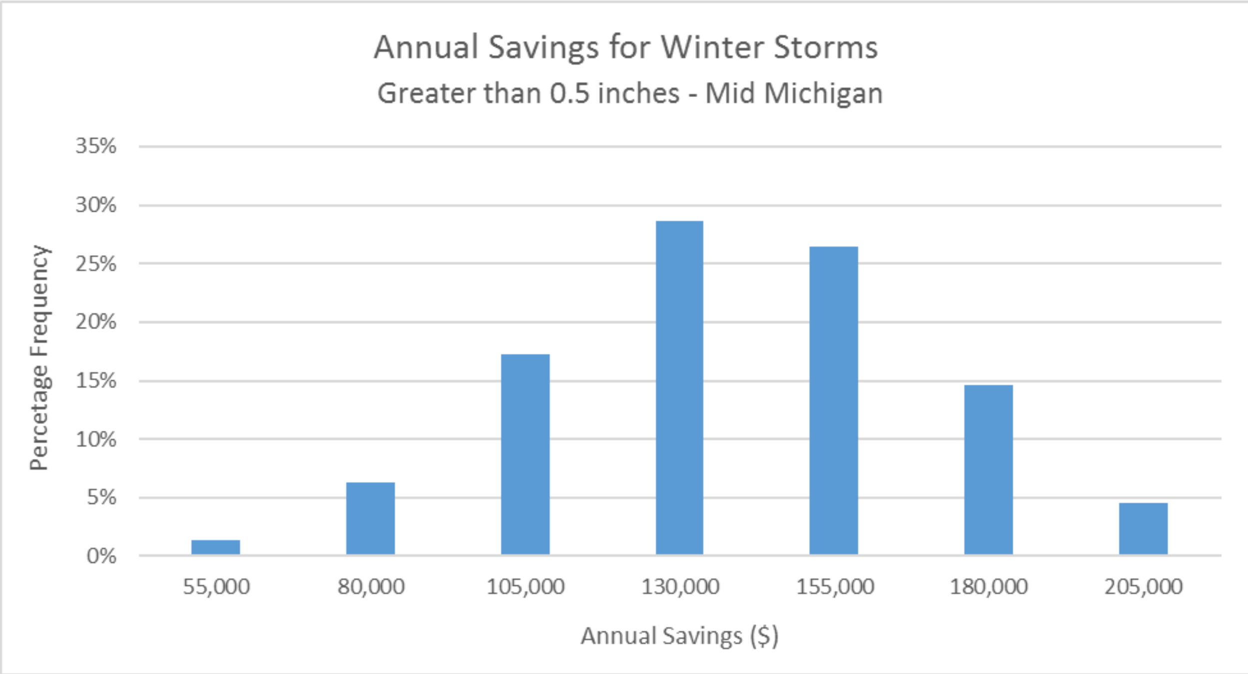


**Figure 5.60: Distribution of the Annual Cost Savings Due to Modified Equipment Configurations for Four-Lane Expressways – Mid-Michigan**

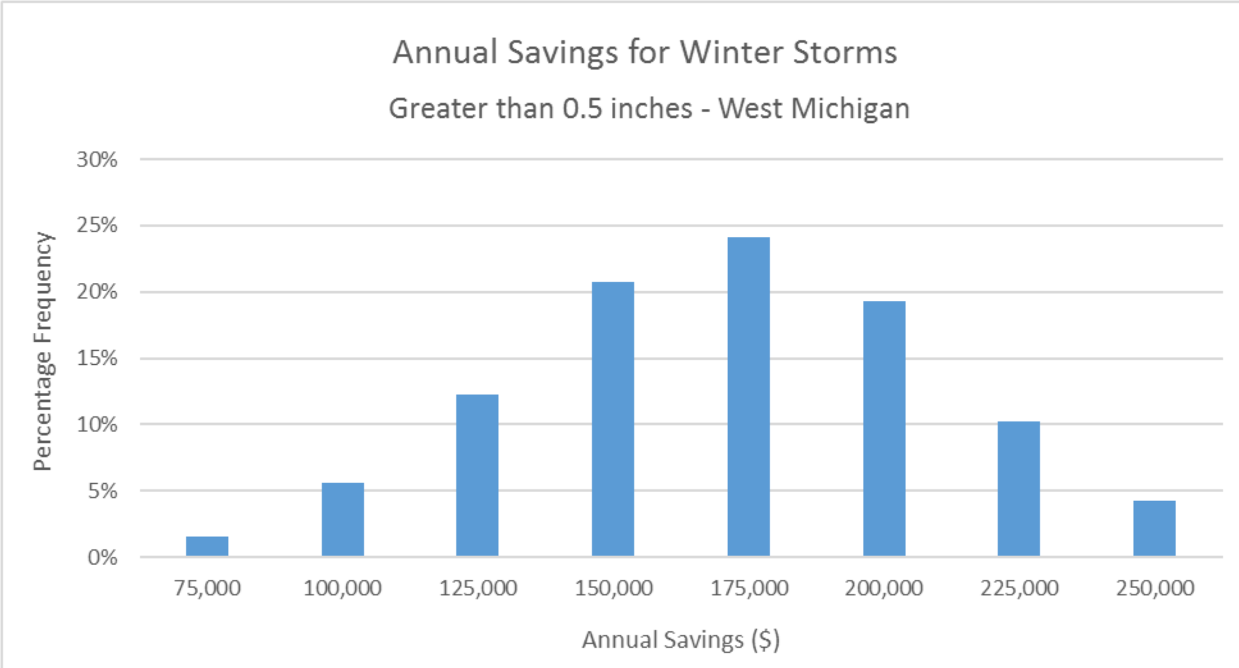


**Figure 5.61: Distribution of the Annual Cost Savings Due to Modified Equipment Configurations for Four-Lane Expressways – West Michigan**

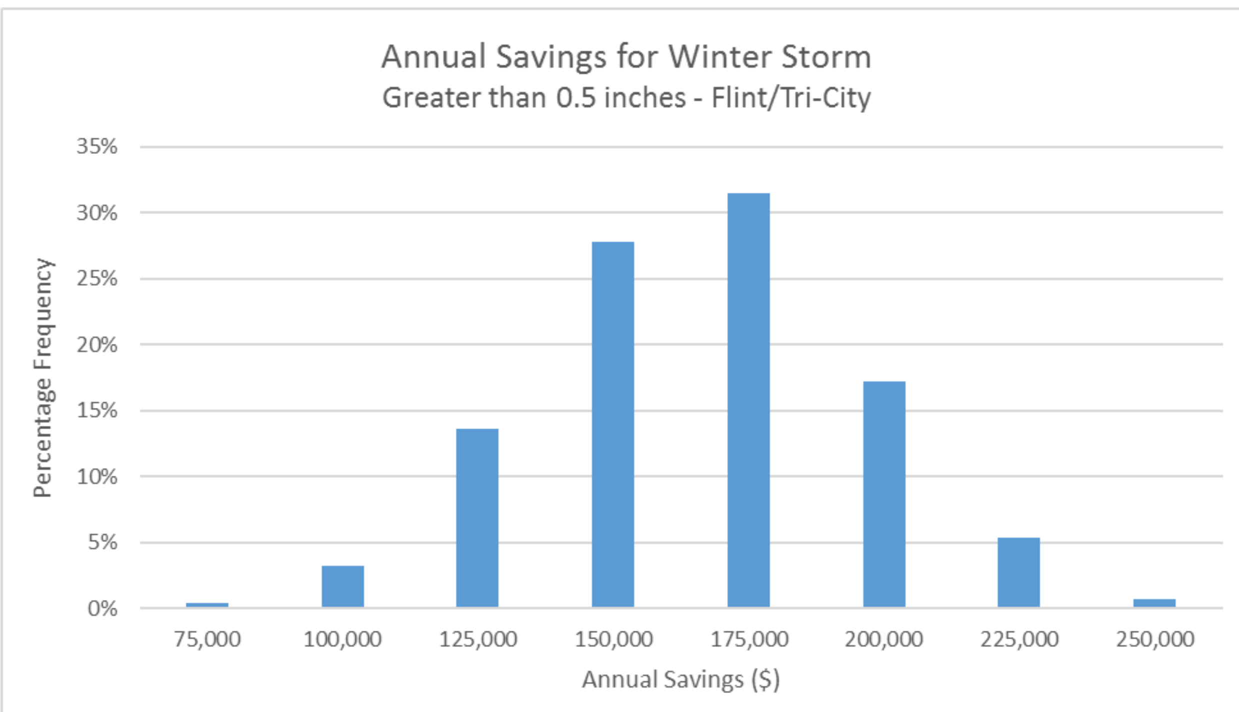


**Figure 5.62: Distribution of the Annual Cost Savings Due to Modified Equipment Configurations for Four-Lane Expressways – Flint/Tri-City Area**

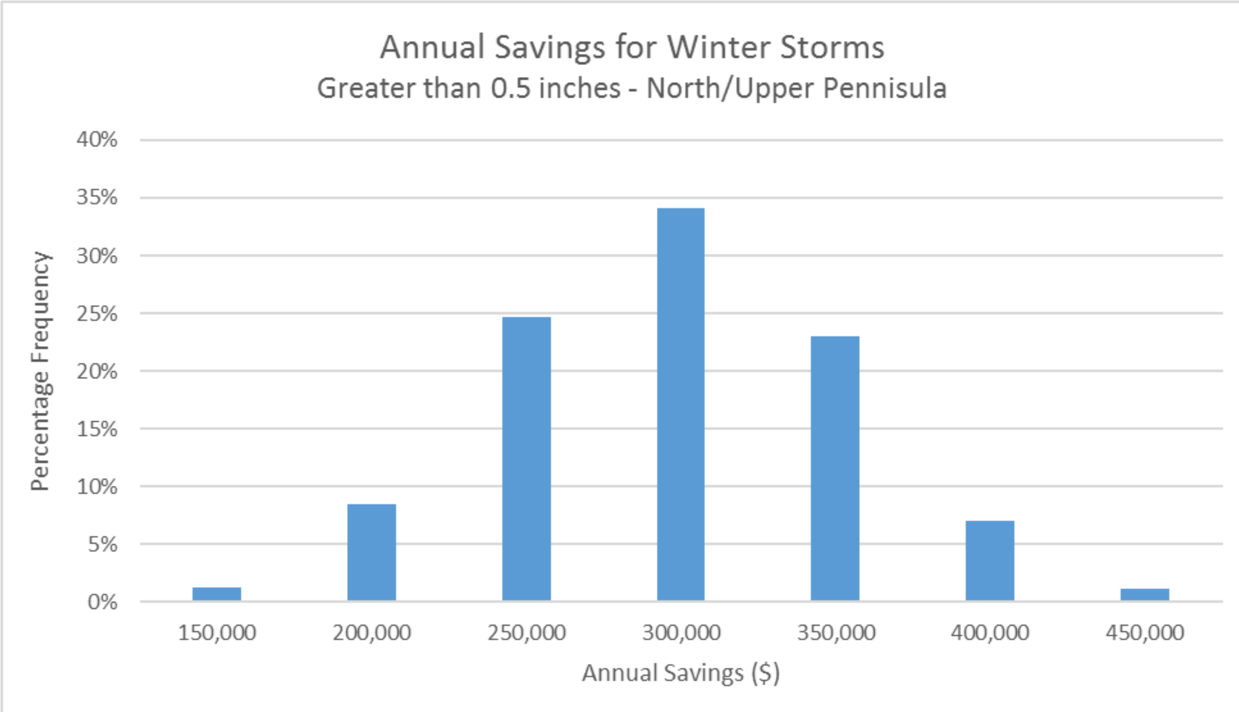


**Figure 5.63: Distribution of the Annual Cost Savings Due to Modified Equipment Configurations for Four-Lane Expressways – North/Upper Peninsula**

As seen in Table 5.34 and Figures 5.59 to 5.63, the modified equipment configurations show positive direct cost savings for rural four-lane expressways. These direct cost savings are comparatively higher than the six-lane expressways savings. This may be due to the insufficient number of data point used in the developed cost models. ***Therefore, reanalyzing the related cost data and updating the developed cost models are recommended.*** The total cost analysis shows a significant overall cost savings by including one WMTP in the equipment fleet. These savings apply to rural four-lane expressways in all areas of Michigan undergoing winter maintenance.

## 5.6 Recommendations on Optimal Tow Plow Combo Unit (WMTP) Usage Per MDOT Region and Expected Annual Savings

Table 5.35 lists the expected annual savings calculated using the developed cost analysis procedure described in Section 5.5. This table includes savings for four-lane and six-lane expressways if WMTPs are incorporated into the MDOT winter maintenance fleet. If 17 WMTPs are acquired and distributed among the seven listed MDOT regions, MDOT can save over $1.9 million annually. Over $4.7 million annually can be saved if 42 WMTPs are used by other winter maintenance agencies maintaining MDOT four and six-lane expressways. The use of additional WMTPs on other routes may provide further savings.

**Table 5.35: Recommendations for Optimal Tow Plow (WMTP) Usage Per MDOT Region and Expected Annual Savings**

| MDOT Region | Freeway Type | Lane Miles | | Total Annual Savings when using WMTPs ($) | | Recommended Number of WMTP Units | |
|---|---|---|---|---|---|---|---|
| | | MDOT Maintained | Other Maintained | MDOT Maintained | Other Maintained | MDOT Maintained | Other Maintained |
| Superior | Four-Lane | 92.72 | 107.27 | 176,736 | 204,475 | 1 | 1 |
| | Six-Lane | 11.15 | 11.66 | N/A | N/A | N/A | N/A |
| North | Four-Lane | 0.00 | 696.31 | N/A | 1,327,281 | N/A | 5 |
| | Six-Lane | 0.00 | 89.42 | N/A | 32,077 | N/A | 1 |
| Grand | Four-Lane | 301.67 | 878.28 | 337,098 | 981,432 | 2 | 6 |
| | Six-Lane | 37.88 | 279.21 | N/A | 82,976 | N/A | 2 |
| Bay | Four-Lane | 174.29 | 999.25 | 185,553 | 1,063,833 | 1 | 7 |
| | Six-Lane | 81.15 | 331.36 | 14,225 | 58,084 | 1 | 3 |
| Southwest | Four-Lane | 550.73 | 183.40 | 615,411 | 204,943 | 4 | 1 |
| | Six-Lane | 291.38 | 31.60 | 86,592 | N/A | 2 | N/A |
| University | Four-Lane | 529.18 | 531.59 | 473,109 | 475,268 | 4 | 4 |
| | Six-Lane | 255.70 | 344.02 | 43,418 | 58,414 | 2 | 3 |
| Metro | Four-Lane | 0.00 | 129.64 | N/A | 104,867 | N/A | 1 |
| | Six-Lane | 0.00 | 1,013.20 | N/A | 179,805 | N/A | 8 |
| **State-wide** | **Four-Lane** | **1,648.58** | **3,525.74** | **1,787,908** | **4,362,098** | **12** | **25** |
| | **Six-Lane** | **677.25** | **2,100.45** | **144,235** | **415,537** | **5** | **17** |
| ***State-wide*** | ***All Expressways*** | ***2,325.83*** | ***5,526.19*** | ***1,932,143*** | ***4,777,636*** | ***17*** | ***42*** |

N/A – Not Applicable

# CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The benefits and costs of using TPs in Michigan were evaluated in this research project. The project was divided into several tasks as shown below.

1. Perform a comprehensive literature review.
2. Survey State Departments of Transportation and other user groups.
3. Evaluate TP usage in the field along different types of roadways.
4. Analyze cost data of winter maintenance with and without WMTPs.
5. Analyze vehicle speed data during winter storms.
6. Analyze cost-benefits and determine the most efficient equipment configuration for different snow routes.
7. Develop training materials for WMTP operators.

The comprehensive literature review provided the framework for the analysis of winter maintenance through the use of different methodologies. The review also produced information regarding previous TP usage evaluations, winter maintenance performance measures, and cost-benefit analyses of winter maintenance activities.

The State Departments of Transportation and other agencies in snowy regions were surveyed using an online “Survey Monkey” web tool. Forty-eight different survey responses from 32 agencies were received. The results of the survey provided information on how different agencies use TPs for winter maintenance activities as well as road type, tow truck (WMT) type, tow truck engine capacity, hydraulic capacity, hitch plate capacity, and different upgrades performed on the TP and the WMT.

## 6.1 Conclusions

### 6.1.1 Field Evaluation Results

The TP field evaluation included driving behind the TPs and regular WMTs along different snow routes during multiple winter storms of varying severity levels. Visual pavement condition, pavement friction behind the TPs and the WMTs, plow operating speeds, and traffic conditions behind the plows were evaluated to determine the effectiveness of the winter maintenance capabilities of different plow configurations.

At the conclusion of the field evaluation, results indicated that there were no statistical differences between pavement conditions behind the TPs and pavement conditions behind regular WMTs. These results were supported by statistically analyzing hundreds of winter pavement condition data and related pavement friction values measured behind both winter fleet configurations.

In terms of operating speed, both the regular WMT and WMTP were in the same speed range. Although the traffic conditions behind the WMTP during winter maintenance operations were generally congested, the overall vehicle delay along the route during winter events was significantly less than when only the regular WMTs were used for winter maintenance operations. This conclusion was obtained by analyzing vehicle speed data during winter events.

In addition to the routine field evaluations of the TP, byproduct-type observations were made and are reported in Appendix C. These observations include performance measures for winter maintenance based on visual winter pavement condition and pavement friction levels.

### 6.1.2 Cost-Benefit Analysis of Tow Plow Combo Unit (WMTP) Usage

#### 6.1.2.1 Winter Maintenance Cost Analysis

Provided by MDOT, winter maintenance cost data for different snow routes were evaluated. Initially, only the snow routes maintained by MDOT's Brighton maintenance garage were included in the analysis. However, based on discussions with MDOT staff, the snow routes were further expanded to include garage routes in: Williamston, Grand Ledge, Reed City, and Charlotte. Winter maintenance costs were obtained from MDOT form 14100 which was filled out by plow drivers after their shift. This form provided the following information: number of hours worked, amount of salt and other materials used, truck number, and other details related to the winter storm.

After analyzing winter maintenance data, relationships were developed between snowstorm severity versus winter maintenance cost using one WMTP in the equipment fleet as well as not using WMTPs in the equipment fleet. Further, regular WMT to WMTP equivalency, based on the snowstorm severity, was also developed for different types of routes. These relationships were then used to develop guidelines for WMTP usage in different snow routes, including when and where to use WMTPs to make the winter maintenance operations more effective.

Based on the developed winter maintenance cost relationships for six-lane and four-lane expressways in the Brighton area and four-lane expressways in the Charlotte area, the cost-benefit of using the WMTP in the equipment fleet in different parts of the state was analyzed considering winter storm frequencies and traffic levels. The following observations were made.

1. The total direct cost (labor, salt, and equipment) of winter maintenance using a WMTP in the equipment fleet with the current configuration for six-lane and four-lane highways was high. However, if delay costs are included, the total cost of winter maintenance was significantly less when a WMTP was included in the equipment fleet. Therefore, significantly less travel delays were observed during winter storm events when a WMTP

was included in the equipment fleet. As a result, the traveling public drove more safely and enjoyed reduced travel times.

2. By applying the analysis of four-lane and six-lane expressway cost data to current WMTP usage, the total cost (direct cost and travel delay cost) savings was 62.5%. This savings includes 65% for four-lane expressways and 27% for six-lane expressways.
3. The total direct costs of winter maintenance with a WMTP in the equipment fleet can be modified to yield positive direct cost savings for both six-lane and four-lane expressways. The following tables show the recommended number of regular WMTs with one WMTP for different winter storm severity levels. When the snowstorm severity is equal to or less than 0.5 inches, the use of regular WMTs for snow clearing operations is recommended.

**Table 6.1: Recommended Number of Regular WMTs with One WMTP for Six-Lane Rural Expressways (Based on 121 Lane Miles)**

| Snowstorm Severity (Inches) | Number of WMTs | Number of WMTP |
|---|---|---|
| 0.5 | 2 | 0 |
| 1.0 | 2 | 1 |
| 1.5 | 3 | 1 |
| 2.0 | 3 | 1 |
| 2.5 | 3 | 1 |
| 3.0 | 3 | 1 |
| 4.0 | 3 | 1 |
| 6.0 | 4 | 1 |
| 8.0 | 4 | 1 |
| 10.0 | 4 | 1 |
| 12.0 | 4 | 1 |

*These recommendations are purely based on direct cost calculations and MDOT should consider their equipment limitations when using these equipment configurations.

**Table 6.2: Recommended Number of Regular WMTs with One WMTP for Four-Lane Rural Expressways (Based on 142 Lane Miles)**

| Snowstorm Severity (inches) | Number of WMTs | Number of WMTPs |
|---|---|---|
| 0.5 | 2 | 0 |
| 1.0 | 2 | 1 |
| 1.5 | 3 | 1 |
| 2.0 | 3 | 1 |
| 2.5 | 3 | 1 |
| 3.0 | 3 | 1 |
| 4.0 | 3 | 1 |
| 6.0 | 3 | 1 |
| 8.0 | 3 | 1 |
| 10.0 | 3 | 1 |
| 12.0 | 3 | 1 |

*These recommendations are purely based on direct cost calculations and MDOT should consider their equipment limitations when using these equipment configurations.

The above-recommended equipment configurations for six-lane expressways can be further modified to obtain further cost savings using an aggressive equipment configuration. MDOT staff at the Charlotte maintenance garage applied this configuration to a four-lane expressway.

### 6.1.2.2 Vehicle Speed Data Analysis

Vehicle speed data during winter storms were obtained from RITIS databases. Vehicle speed data combined with vehicle operating costs and traffic volumes were used to calculate vehicle delay costs during winter storms. These delay costs were then used to calculate winter maintenance total costs when using a WMTP in the equipment fleet and only using regular WMTs in the equipment fleet. The total cost analysis shows that the use of one WMTP in the equipment fleet yields substantial cost savings when compared to only regular WMT usage in the equipment fleet.

When further analyzed, the speed data yielded additional byproduct relationships between different speed parameters and snowstorm severity levels. These byproduct results include a performance measure for winter maintenance using speed parameters. These speed parameters include: Average Winter Speed (AWS), Minimum Winter Speed (MWS), and the newly developed AREA and +AREA parameters. Appendix E of this report provides more details relative to this byproduct information.

### 6.1.2.3 Safety Benefit Analysis

Winter weather-related accident data were obtained from the Michigan Traffic Crash Facts (MTCF) online database and were analyzed to determine any significant changes in winter weather accident rates after inclusion of the TP for winter maintenance operation. Since only 2 years of WMTP usage data were included in the analysis, safety benefits of using a WMTP to regular WMTs in terms of accident costs were difficult to obtain. More data is needed to determine statistically significant accident cost changes due to the use of the WMTP.

## 6.2 Recommendations

The recommendations of using WMTPs for winter maintenance operations on MDOT roadways are given below.

1. MDOT should consider purchasing three more Tow Plow Combo Units (WMTP) to increase the current fleet to 17 and distribute those Tow Plows among MDOT regions as given in the following table:

**Table 6.3: Recommended Number of WMTP Units to Maintain MDOT Maintained Six-Lane and Four-Lane Expressways**

| MDOT Region | Recommended Number of WMTP Units |
|---|---|
| Superior | 1 |
| North | 0 |
| Grand | 2 |
| Bay | 2 |
| Southwest | 6 |
| University | 6 |
| Metro | 0 |
| ***Total*** | ***17*** |

2. The WMTP units listed in Table 6.3 should be distributed among six-lane and four-lane MDOT maintained expressways as shown in Table 5.35 of this report.
3. Agencies maintaining MDOT roadways should purchase WMTP units as recommended in the Table 5.35 of this report.
4. MDOT should explore use of the WMTP units on other roadways such as divided multi-lane highways, undivided multi-lane highways and highways with wide paved shoulders.
5. The cost-benefit analysis of six-lane and four-lane expressways should be revisited after a few more years of WMTP usage to optimize the WMTP usage recommendations.
6. Safety benefits and fuel usage benefits of using WMTP for winter maintenance should be conducted after a more few years of WMTP usage.

### 6.3 Training Material for Tow Plow (TP) Operators

Development of a training document for TP operators was one of the tasks of this research project. However, during the course of this project, MDOT developed a training document to train their TP operators. Discussions with MDOT PM and RAP members revealed that a development of training *video* would be valuable for future TP training programs. With the help of Lawrence Technological University's eLearning Services group, the research team developed a training video as part of this research project. A screenshot of this video is shown in Figure 6.1.


**Figure 6.1: A Screenshot of the TP Training Video**

A link to the Tow Plow training video is given below.

https://youtu.be/Upn9x3WMWh4

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# APPENDIX A

# TOW PLOW USAGE SURVEY

# AND

# ADDITIONAL COMMENTS

# Survey of Tow Plow Usage for Winter Maintenance

**Introduction:**

Lawrence Technological University is conducting a survey for the Michigan Department of Transportation (MDOT) to gather details on the use of the Tow Plow in winter maintenance operations.

We would appreciate your assistance in completing this survey about your agency's experience on Tow Plow usage for winter maintenance operations.

**Name of the Respondent:**

**Agency:**

**Telephone:**

**E-mail:**

**Are you willing to allow us to contact you again if we need further information:** Yes/No

1. For snow and ice control operations, does your agency use: (Please check all that apply)

   □ Internal Staff

   □ Other governmental agencies

   □ Private Contractors

   □ Contractors with other governmental agencies

2. Are you familiar with the Tow Plow technology?

   □ Yes □ No

3. Does your agency own Tow Plows?

   □ Yes □ No

   If Yes, How many units?..................... and Purchased year/s…………………..

4. If you are not using internal staff for winter operations, does your contractor use Tow Plows?

   □ Yes □ No

   If Yes, please name the contractor and contact details

   Phone Number:

   Email address:

5. Does your agency plan to purchase/lease Tow Plows in the future?

   □ Yes □ No

   If Yes, how many units?............................... and When ………………………

**PLEASE PROCEED TO PAGE 6, IF YOU DO NOT OWN TOW PLOWS.**

## TOW PLOW RELATED QUESTIONS

### TOW TRUCK

6. Towing truck type ……………………..
7. Towing truck horse power capacity…………………
8. Towing truck hydraulic capacity……………………..
9. Hitch plate capacity……………………..
10. Salt distribution system of the truck…………………………………
11. Plow Configuration
    - □ Front
    - □ Underbody
    - □ Other please list……………………………
12. Plow Blades
    - □ Carbide
    - □ Wear Plates
    - □ Triple Blade
    - □ Underbody Blade
    - □Tow Blade
    - □ Double/Triple Edge
    - □ 14+ Foot
    - □ Other please list……………………………

12. Please list any modification made to the towing truck and their costs

| Modification | Approximate Cost ($) |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

13. Who made the modifications?
    - □ Internal Staff
    - □ Outside Garage
    - □ Other please list……………………………

**TOW PLOW**

14. Do you have a poly tank for pre-wetting salt
    □ Yes □ No
    If yes, capacity of the poly tank…………………
15. Do you have a hopper with a spreader
    □ Yes □ No
    If yes, capacity of the hopper………………….
16. Do you have or tried to use a camera at the rear of the Tow Plow to view traffic behind the unit?
    □ Yes □ No
17. Do you have a laser alignment system and being used by the operator to define the edge of the plow?
    □ Yes □ No
18. Do you have a hubodometer or other system on the trailer for tracking Tow Plow usage?
    □ Yes □ No
19. Plow Blades
    □ Carbide
    □ Wear Plates
    □ Triple Blade
    □ Underbody Blade
    □Tow Blade
    □ Double/Triple Edge
    □ 14+ Foot
    □ Other please list……………………………
20. Please list any modification made to the Tow Plow and their costs

| Modification | Approximate Cost ($) |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

21. Who made the modifications?
    □ Internal Staff
    □ Manufacturer
    □ Other          please list……………………………

## TOW PLOW AND REGULAR PLOW OPERATING COSTS

22. Fuel efficiency and operational speed of plow trucks

| Equipment | Tow truck/Tow Plow | Regular Plow |
|---|---|---|
| Fuel Efficiency (mpg) | | |
| Operational Speed (mph) | | |

23. Maintenance costs of plow trucks

| Maintenance cost item | Tow truck+Tow Plow | Regular Plow |
|---|---|---|
| Engine Oil Changes | | |
| Tire Changes | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

24. Estimated annual cost of maintenance for the Tow Plow:…………………

    Estimated annual cost of maintenance for a regular plow:…………………

## TOW PLOW USAGE

25. Please list types of roads the Tow Plow is regularly deployed for winter operations.

    □ Urban multi-lane interstates and expressways

    □ Rural multi-lane interstates and expressways

    □ Rural divided highways

    □Tow-lane roads with paved shoulders

    □Alternating passing lanes routes

□Congested urban areas with left turn lanes, islands and commercial entrances

□ Other, please specify………………………………………………

26. Are there any restrictions in your state related to Tow Plow usage (types of roads, percent grade etc)?

□ Yes □ No

If yes, please specify…………………

27. Do you have training activities for Tow Plow operators?

□ Yes □ No

If yes, please specify…………………

28. How often do you conduct these training courses?

29. Plow operators opinion on Tow Plows

□ Efficient and cost effective
□ Good Investment
□ Expensive
□ Waste of money
□ Way to reduce staff
□ Other, please specify……………………………………..

30. Did you receive any complaints from the public related to Tow Plow usage for winter operations?

□ Yes □ No

If yes, please specify…………………

31. Did your agency conduct any research on Tow Plow?

□ Yes
□ No
□ Currently being conducted

Please provide details ……………………………………………………………….

32. Please include any other information related to your experience with Tow Plow.

## WINTER MAINTENANCE PRACTICES

33. Do you use Level of Service (LOS) classifications for winter maintenance activities?
    □ Yes □ No
    If YES, please list your agency's LOS classifications (PLEASE CHECK ALL THAT APPLY)
    □ Time to bare pavement
    □ Time to wet pavement
    □ Time to return to a reasonably, near-normal winter condition
    □ Time to provide one wheel track
    □ Friction
    □ Level of service based on traffic flow
    □ Travel speed during storm
    □ Traffic volume during storm
    □ Time for traffic volume to return to "normal" after storm
    □ Fuel usage
    □ Lane miles plowed
    □ Personnel hours
    □ Overtime hours
    □ Tons of materials used
    □ Amount of equipment deployed
    □ Cost of winter operations per lane-mile
    □ Other, please specify

34. What are the performance measures/levels used to determine the above selected LOS classifications?

35. Who monitors these performance measures and how often are they measured?

36. What are the three most critical objectives for snow and ice control operations in your state?
    a.
    b.
    c.

37. Are different performance measures used for different road classifications and different storm events?

    □ Yes □ No

    If YES, please describe your agency's performance measures

38. Do you have a method to characterize different storm events?

    □ Yes □ No

    If YES, please describe.

39. What technologies have you used or tried to use for measuring performance and please describe your experience with these technologies.

# Tow Plow Usage Survey

## Additional Comments

| Agency | Additional Information |
| --- | --- |
| Colorado Department of Transportation | They are great! |
| Pennsylvania Department of Transportation | worked with the end users to develop an iformational bulletin outlining the best practices in "setting" up the units. Items such as installing bed vibrators and intregal tailgate spreaders raised the outlet of the spreader thus providing more area above the trailer tongue so the bed can be raised higher. |
| Massachusetts Department of Transportation | The cost benefit for each plow is approximatly 6 or 7:1 Each tow plow allows us to elliminate a private plow truck at a significant savings to the Commonwealth. Plus each tow plow opperator can do the work of two. Stretching our limited resources. The truck and tow plow can be paid off in two years with a moderate winter. |
| Nebraska Department of Roads | Operators were worried at first, but after operating the tow plow they would not want to go back to single plow truck. |
| Brunway Highway Operations, Inc. | Good investment, 1 operator with 2 plows., |
| North Dakota Department of Transportation | The operators that have them view them like when we added wings. They make your truck more efficient. They feel helpless like they're not getting anything accomplished if they don't have the tow plow. Ours run 24/7 in some urban areas with night crews. It makes a big difference when the morning crew comes in. They love them. Our current target for tow plow is 64 total. Like I stated earlier, we are currently approved for 32. Having the anti-ice tanks is expanding our anti-ice program. Districts not using anti-icing practices started once they received the towplows because they were hooked up and in the field already. Experimented with turning the liquid on and were amazed with the results. Districts use them all over now for anti-icing, de-icing, and plowing. Some also used in summer operations for washing bridge decks. |
| Snow King Technologies | Most all with will comment on their right hand TPs. There are 5 left hand TPs in the field with 2 in Kansas City and the next generation will be in the future. I will be providing the system to plow left or right where rural interstates will be able to be plowed in 2 passes instead of 4 or 5 passes. And provide a means to cut across when needed to plow down wind. This should reduce plowing costs by 60% or more. |
| Ohio Department of Transportation | Parts needs limited to OEM supply are not locally available. |
| Missouri Department of Transportation | Our towplows have allowed us to remove snow more efficiently than in the past. The towplow allows one driver to clear two lanes with only one truck. Maintenance on the towplow is expected to be be minimal due to lack of power train. |
| Eau Clair County Highway Department | We do not use the tow plow unless there will be more than two inches of snow or if the rate of snow is more than an inch per hour. The plow is a floater on all our divided highways. It goes where the need is the most. Call if you would like to discuss how we use the plow and where I have found it to be very helpful in improving our level of service. |

# APPENDIX B

## SAMPLE OF COLLECTED DATA

# APPENDIX B

## SUMMARY OF COLLECTED DATA

Data reported in Appendix B include:

- Winter storm number, snowfall amount and category classification, and storm date.
- Data collection starting and ending points.
- Lanes plowed.
- Operating speed.
- Friction data.[1]
- Pavement surface condition and respective friction values.[2]
- Representative photographs showing pavement surface conditions.[3]

As discussed in Chapter 2.1.8, four winter storm categories were identified:

1. Trace snowfall – Up to 0.5 inches of total accumulation
2. Light snowfall - Between 0.5 and 1.5 inches of total accumulation
3. Moderate snowfall - Between 1.5 and 5.5 inches of total accumulation
4. Heavy snowfall - Greater than 5.5 inches of total accumulation

Lane direction acronyms include:

- EB – Eastbound
- NB – Northbound
- SB – Southbound
- WB – Westbound

The acronym WMTP refers to a tow truck and a Tow Plow unit. This unit is also known as the Tow Plow Combo Unit. Tow trucks and regular plows are also referred to as winter maintenance trucks (WMTs).

### B.1: Winter Storm 1 (Moderate Snowfall – 5.3 inches (dry snow)) – January 1, 2014

Tow Plow data collected during this storm are summarized in Table B.1.

[1] All average friction values were collected for 500-foot long segments measured at 1000-foot intervals.
[2] All pavement surface conditions were recorded at 500-foot intervals.
[3] Pavement surface condition photographs were recorded at 500-foot intervals.

**Table B.1: Tow Plow Summary Data**

| | |
|---|---|
| Tow Plow Data Collection Starting Point | NB US-23 ramp to WB I-96 in Brighton, MI |
| Tow Plow Data Collection Ending Point | M-59 bridge over I-96 in Howell, MI |
| Lanes Plowed | WB I-96 Middle Lane and Slow Lane |
| Tow Plow Operating Speed (mph) | 38.2 |

Average friction values collected behind the Tow Plow are shown in Figure B.1.

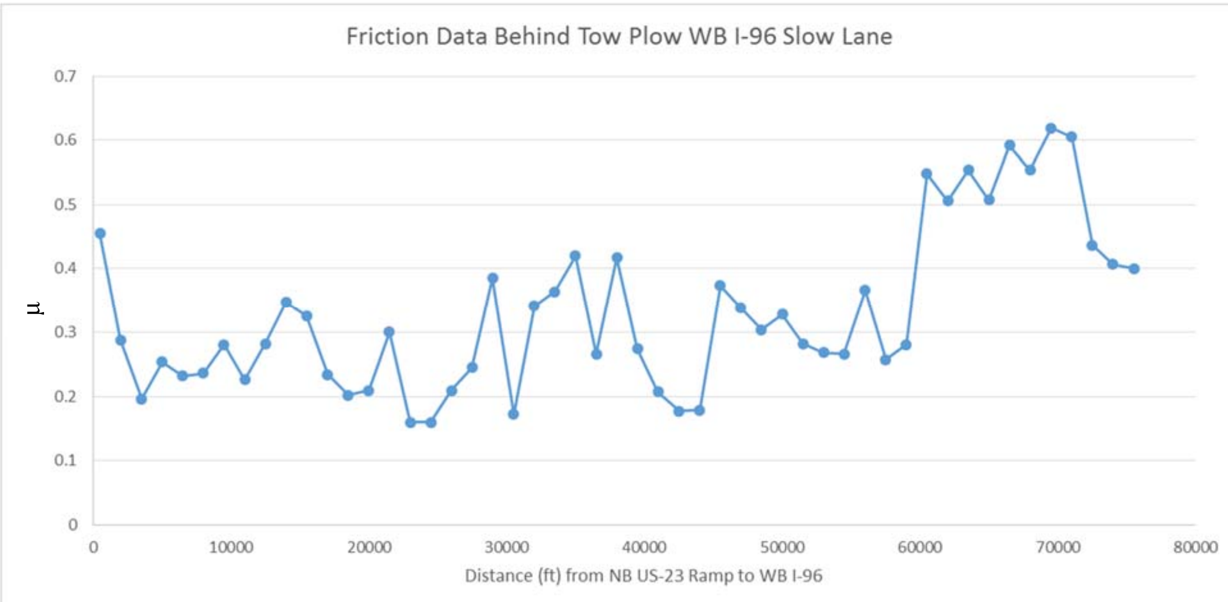


**Figure B.1: Friction Data behind Tow Plow WB I-96 for Winter Storm on 1/1/2014**

Both lanes (middle lane and slow lane) showed "Wheel Track Bare" surface conditions at 94% of the area and "Loose Snow" surface condition of 6% area immediately behind the Tow Plow and tow truck. Table B.2 shows average friction values for different pavement conditions observed behind the Tow Plow (slow lane). Sample pictures follow the table.

**Table B.2: Pavement Condition and Average Friction Values for Winter Storm on 1/1/2014 behind Tow Plow**

| Pavement Condition | Area (%) Middle & Slow Lane | Average Friction Value (µ) Slow Lane | Standard Deviation of µ Slow Lane |
|---|---|---|---|
| Wheel Track Bare (WTB) | 94 | 0.34 | 0.12 |
| Loose Snow (LS) | 6 | 0.16 | 0.01 |

**Figure B.2: 1,584 feet from NB US-23 Ramp on WB I-96 for Winter Storm on 1/1/2014**

**Figure B.3: 11,088 feet from NB US-23 Ramp on WB I-96 for Winter Storm on 1/1/2014**

**Figure B.4: 41,712 feet from NB US-23 Ramp to WB I-96 for Winter Storm on 1/1/2014**

A summary of data collected during this storm behind the regular plow is shown in the following table.

**Table B.3: Winter Storm 1 Summary Data behind Regular Plow**

| | |
|---|---|
| Regular Plow Data Collection Starting Point | M-59 bridge over I-96 in Howell, MI |
| Regular Plow Data Collection Ending Point | First turnaround after US-23 in Brighton, MI |
| Lanes Plowed | Fast Lane and Left Shoulder with the wing |
| Regular Plow Operating Speed (mph) | 34.5 |

Average friction values are shown in Figure B.5.

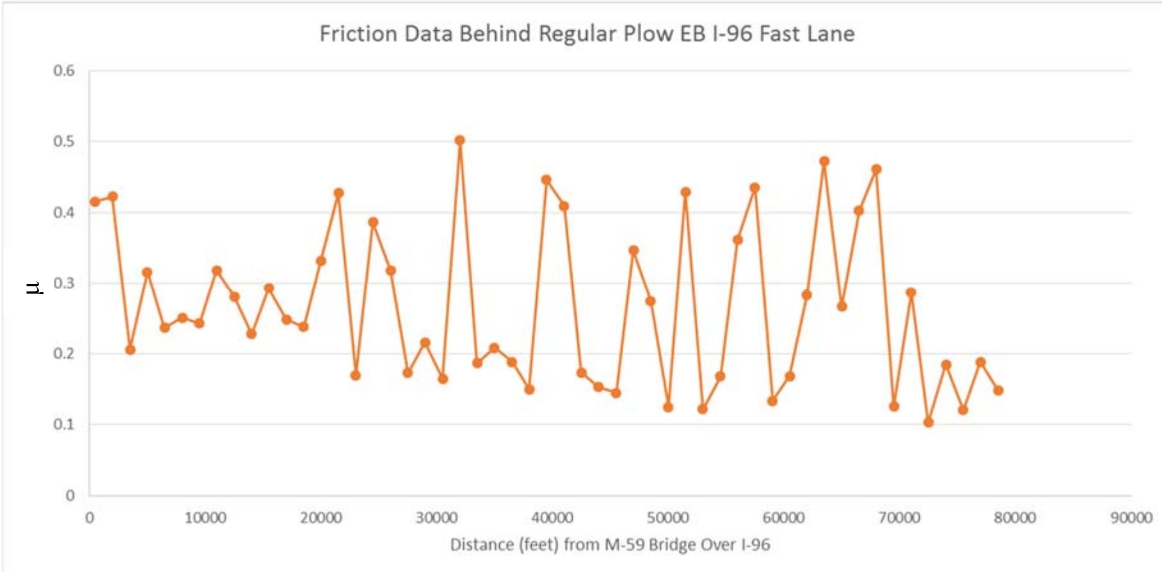


**Figure B.5: Friction Data behind Regular Plow EB I-96 for Winter Storm on 1/1/2014**

The fast lane of EB I-96 showed "Wheel Track Bare" surface conditions at 84.9% of the area and "Loose Snow" surface conditions at 15.1% of the area immediately behind the regular plow. Table B.4 shows average friction values for these pavement conditions observed behind the regular plow. Sample pictures follow the table.

**Table B.4: Pavement Condition and Average Friction Values for Winter Storm on 1/1/2014 behind Regular Plow**

| Pavement Condition | Area (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 84.9 | 0.28 | 0.11 |
| Loose Snow (LS) | 15.1 | 0.16 | 0.03 |

**Figure B.6: 1,584 feet from M-59 Bridge over I-96 EB I-96 for Winter Storm on 1/1/2014**

**Figure B.7: 7,362 feet from M-59 Bridge over I-96 EB I-96 for Winter Storm on 1/1/2014**

**Figure B.8: 25,344 feet from M-59 Bridge over I-96 EB I-96 for Winter Storm on 1/1/2014**

**Figure B.9: 41,184 feet from M-59 Bridge over I-96 EB I-96 for Winter Storm on 1/1/2014**

**B.2: Winter Storm 2 (Heavy Snowfall – 10.2 inches) – January 5, 2014**

Data collected behind the WMTP during this storm are shown in the following table.

**Table B.5: Winter Storm 2 Summary Data behind Tow Plow Combo Unit (WMTP)**

| | |
|---|---|
| WMTP Data Collection Starting Point | Livingston/Oakland County Line |
| WMTP Collection Ending Point | M-59 bridge over I-96 in Howell, MI |
| Lanes Plowed | WB I-96 Slow Lane and Outside Shoulder |
| WMTP Operating Speed (mph) | 38.6 |

Average friction values measured behind the tow truck are shown in Figure B.10.

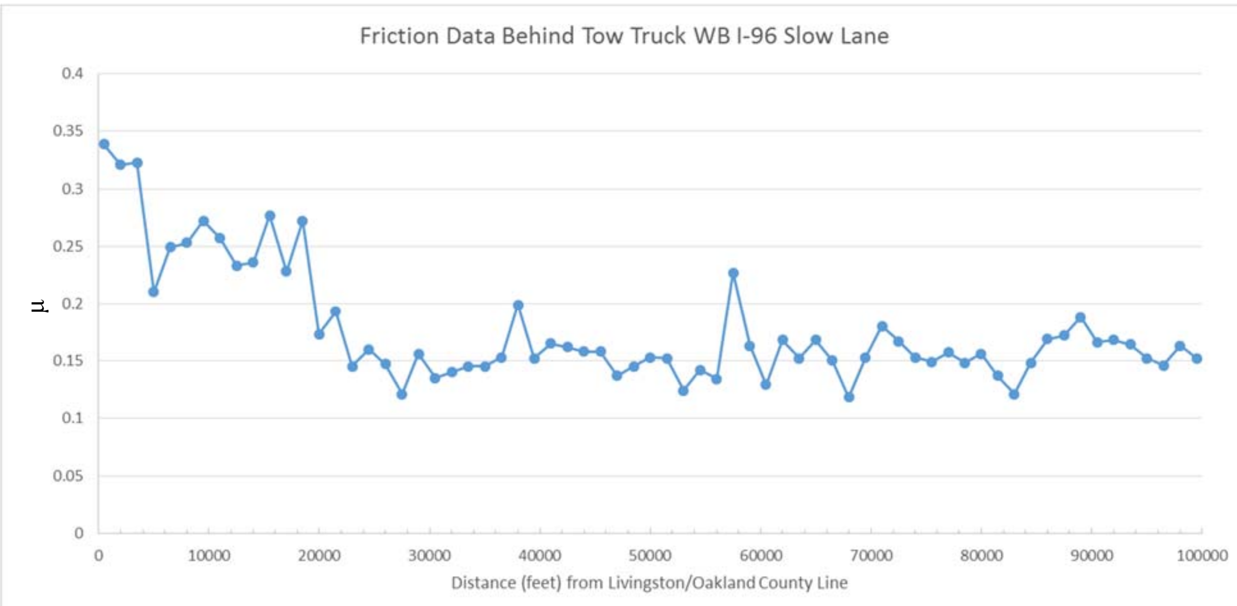


**Figure B.10: Friction Data behind Tow Truck WB I-96 for Winter Storm on 1/5/2014**

The slow lane of WB I-96 showed "Wheel Track Bare" surface conditions immediately behind the tow truck. The shoulder pavement of WB I-96 immediately behind Tow Plow had "Wheel Track Bare" conditions at 43% of the length, "Loose Snow" at 43% of the length and "Centerline Bare" at the remaining 14% of the length. Table B.6 shows average friction values for different pavement conditions observed behind the tow truck.

**Table B.6: Pavement Condition and Average Friction Values for Winter Storm on 1/5/2014 behind Tow Truck**

| Pavement Condition | Length (%) Slow Lane/Shoulder | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 100/43 | 0.18 | 0.05 |
| Loose Snow (LS) | 0/43 | N/A | N/A |
| Centerline Bare (CLB) | 0/14 | N/A | N/A |

Some sample pictures are shown below.

**Figure B.11: 8,057 feet from Livingston/Oakland County Line WB I-96 for Winter Storm on 1/5/2014**

**Figure B.12: 72,511 feet from Livingston/Oakland County Line WB I-96 for Winter Storm on 1/5/2014**

**Figure B.13: 88,579 feet from Livingston/Oakland County Line WB I-96 for Winter Storm on 1/5/2014**

A summary of the data collected behind the regular plow is shown in the following table.

**Table B.7: Winter Storm 2 Summary Data behind Regular Plow**

| | |
|---|---|
| Regular Plow Data Collection Starting Point | Mile Marker 137 in Howell, MI |
| Regular Plow Data Collection Ending Point | Under Kensington Road bridge in Brighton, MI |
| Lanes Plowed | Fast Lane and Left Shoulder with the wing |
| Regular Plow Operating Speed (mph) | 35.4 |

Average friction values taken behind the regular plow are shown in Figure B.14.

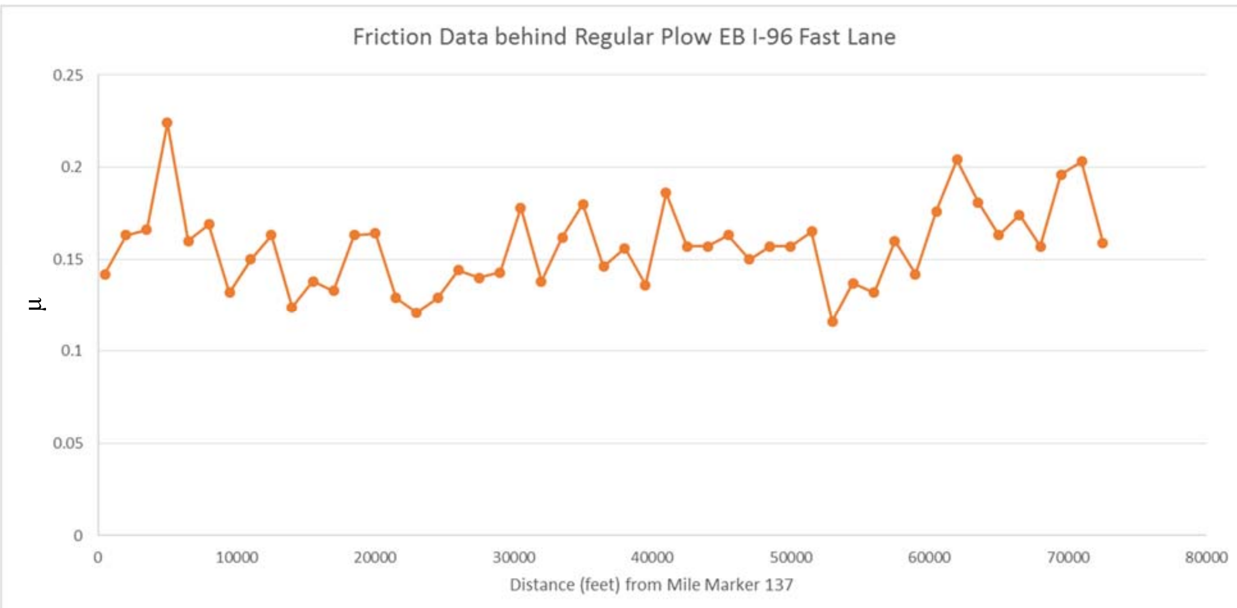


**Figure B.14: Friction Data behind Regular Plow EB I-96 for Winter Storm on 1/5/2014**

The fast lane of EB I-96 showed "Loose Snow" pavement conditions immediately behind the regular plow. Sample pavement surface condition photographs are shown below. Table B.8 shows average friction values for different pavement conditions observed behind the regular plow.

**Table B.8: Pavement Condition and Average Friction Values for Winter Storm on 1/5/2014 behind Regular Plow**

| Pavement Condition | Area (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Loose Snow (LS) | 100 | 0.15 | 0.02 |

**Figure B.15: 6,865 feet from Mile Marker 137 EB I-96 for Winter Storm on 1/5/2014**

**Figure B.16: 12,210 feet from Mile Marker 137 EB I-96 for Winter Storm on 1/5/2014**

**Figure B.17: 26,710 feet from Mile Marker 137 EB I-96 for Winter Storm on 1/5/2014**

**Figure B.18: 67,832 feet from Mile Marker 137 EB I-96 for Winter Storm on 1/5/2014**

**B.3: Winter Storm 3 (Heavy Snowfall – 7.4 inches) – February 1, 2014**

During this storm, data were collected along EB I-96 behind the Tow Plow, WB I-96 behind a regular plow, and WB I-96 behind the tow truck of the Tow Plow.

A summary of data collected behind the Tow Plow during this storm event is shown in the following table.

**Table B.9: Winter Storm 3 Summary Data behind Tow Plow**

| | |
|---|---|
| Tow Plow Data Collection Starting Point | Mile Marker 134 in Howell, MI |
| Tow Plow Data Collection Ending Point | Kensington Road Bridge over I-96 in Brighton, MI |
| Lanes Plowed | EB I-96 Middle Lane and Slow Lane |
| Tow Plow Operating Speed (mph) | 37.4 |

Average friction values taken behind the Tow Plow are shown in Figure B.19.

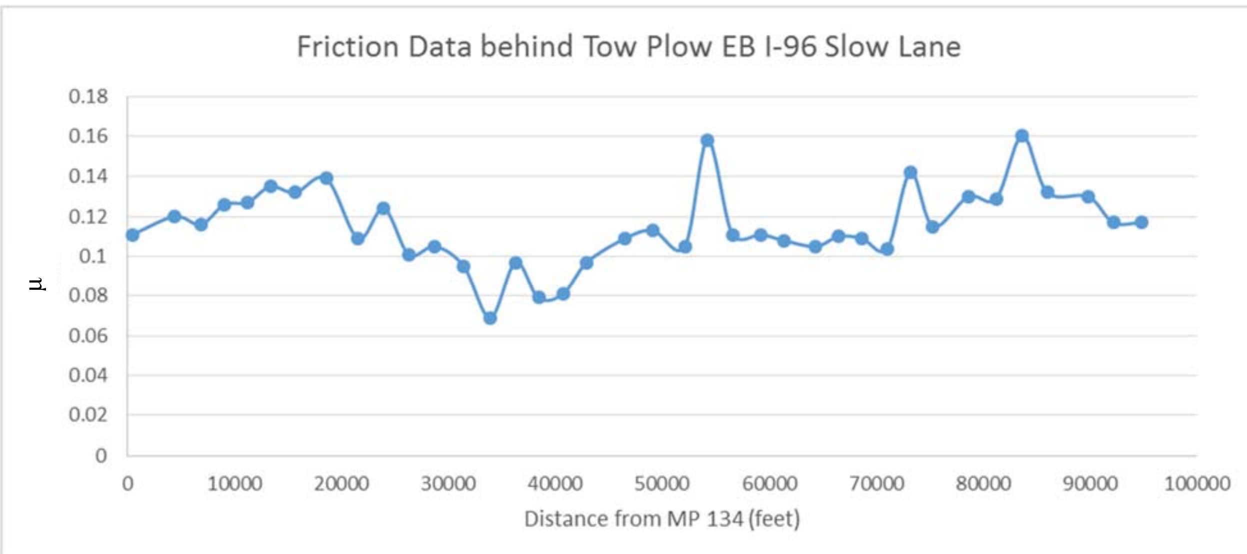


**Figure B.19: Friction Data behind Tow Plow EB I-96 for Winter Storm on 2/1/2014**

The middle lane of EB I-96 showed "Loose Snow" at 74% of the length and "Wheel Track Bare" at 26% of the length immediately behind the tow truck. Surface conditions for the slow lane of EB I-96 were "Loose Snow" at 89.5% of the length and "Wheel Track Bare" at 10.5% of the length. Sample pavement condition pictures are shown after Table B.10. Table B.10 shows average friction values for different pavement conditions observed along EB I-96 behind the Tow Plow.

**Table B.10: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2014 behind Tow Plow along EB I-96**

| Pavement Condition | Length (%) Middle Lane/Slow Lane | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 26/10.5 | 0.14 | 0.01 |
| Loose Snow (LS) | 74/89.5 | 0.11 | 0.02 |

**Figure B.20: 6,640 feet from Mile Marker 134 EB I-96 for Winter Storm on 2/1/2014**

**Figure B.21: 20,657 feet from Mile Marker 134 EB I-96 for Winter Storm on 2/1/2014**

**Figure B.22: 94,813 feet from Mile Marker 134 EB I-96 for Winter Storm on 2/1/2014**


**Figure B.23: Near Kensington Road Exit EB I-96 for Winter Storm on 2/1/2014**

A summary of the data collected during this storm behind the regular plow is shown in the following table.

**Table B.11: Winter Storm 3 Summary Data behind Regular Plow**

| | |
|---|---|
| Regular Plow Data Collection Starting Point | Under Kensington Road bridge in Brighton, MI |
| Regular Plow Data Collection Ending Point | M-59 Bridge over I-96 in Howell, MI |
| Lanes Plowed | Fast Lane and Left Shoulder with the wing |
| Regular Plow Operating Speed (mph) | 37.8 |

The average friction values taken behind the regular plow are shown in Figure B.24.

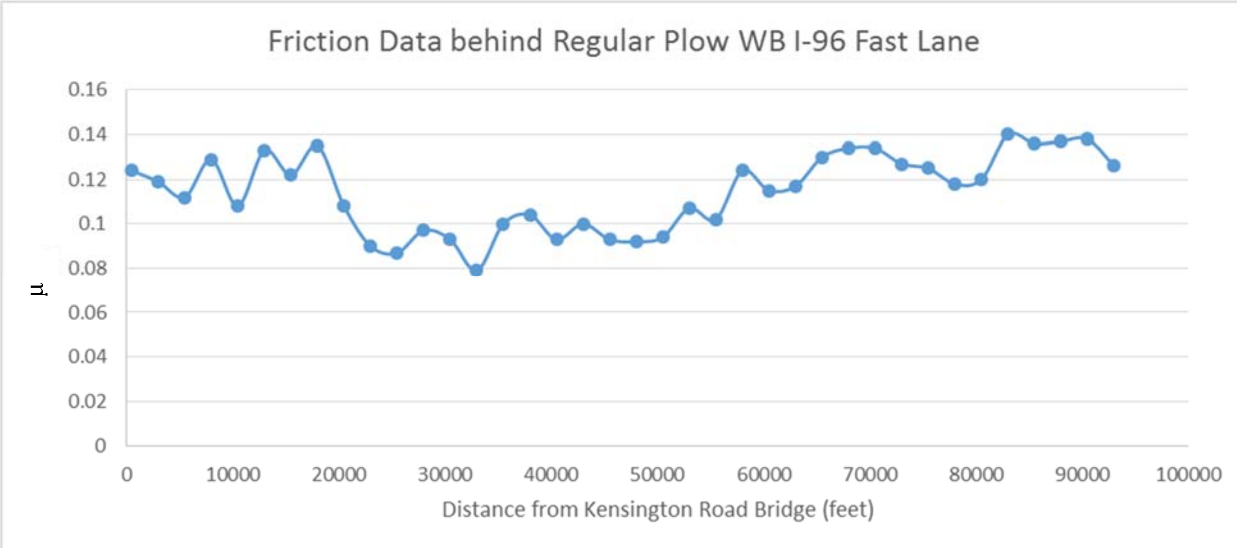


**Figure B.24: Friction Data behind Regular Plow WB I-96 for Winter Storm on 2/1/2014**

The fast lane of WB I-96 showed "Loose Snow" at 84.2% of the length and "Wheel Track Bare" at 15.8 % of the length immediately behind the regular plow. Sample pictures are shown below. Table B.12 shows average friction values for different pavement conditions observed along WB I-96 behind a regular plow.

**Table B.12: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2014 behind Regular Plow along WB I-96**

| Pavement Condition | Length (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 15.8 | 0.12 | 0.01 |
| Loose Snow (LS) | 84.2 | 0.11 | 0.02 |

**Figure B.25: 0 feet from Kensington Road Bridge WB I-96 for Winter Storm on 2/1/2014**

**Figure B.26: 16,110 feet from Kensington Road Bridge WB I-96 for Winter Storm on 2/1/2014**

**Figure B.27: 38,079 feet from Kensington Road Bridge WB I-96 for Winter Storm on 2/1/2014**

**Figure B.28: 68,103 feet from Kensington Road Bridge WB I-96 for Winter Storm on 2/1/2014**

The following table summarizes the data collected during Winter Storm 3 behind the tow truck of the Tow Plow.

**Table B.13: Winter Storm 3 Summary Data behind Tow Truck**

| | |
|---|---|
| Tow Truck Data Collection Starting Point | Under Kensington Road bridge in Brighton, MI |
| Tow Truck Data Collection Ending Point | M-59 Bridge over I-96 in Howell, MI |
| Lanes Plowed | Slow Lanes of WB I-96 and Shoulder |
| Tow Truck Operating Speed (mph) | 35.8 |

The average friction values are shown in Figure B.29.

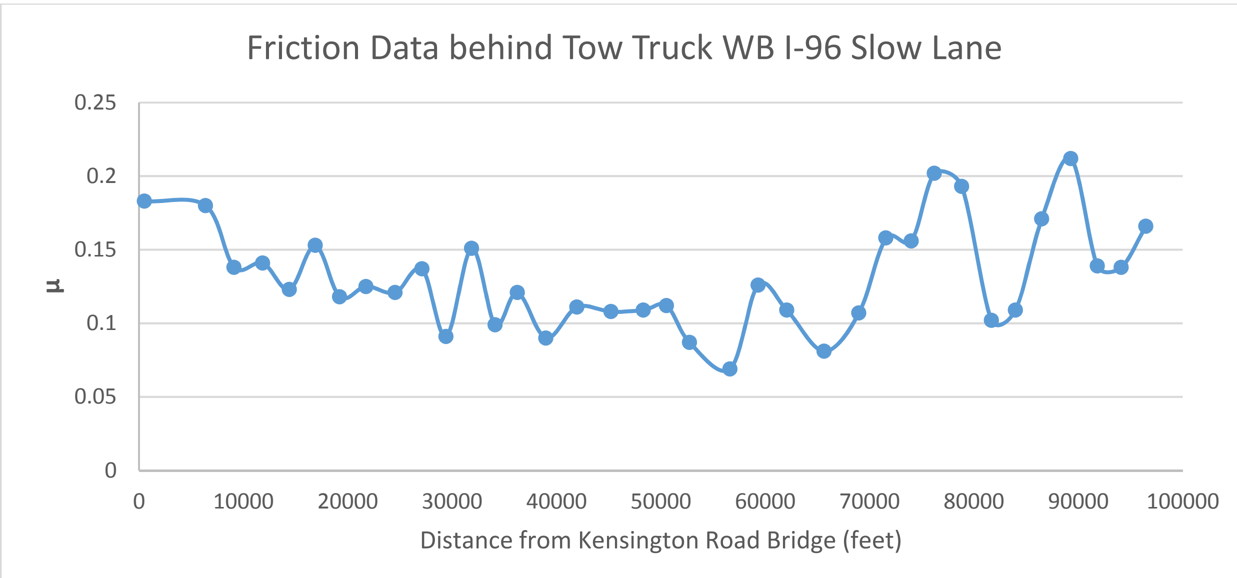


**Figure B.29: Friction Data behind Tow Truck along WB I-96 for Winter Storm on 2/1/2014**

The slow lane of WB I-96 showed "Loose Snow" at 72.2% of the length and "Wheel Track Bare" at 27.8 % of the length immediately behind the tow truck. Sample pictures from this event are shown below. Table B.14 reports the average friction values for different pavement conditions observed behind the tow truck travelling along WB I-96.

**Table B.14: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2014 behind Tow Truck along WB I-96**

| Pavement Condition | Length (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 27.8 | 0.15 | 0.03 |
| Loose Snow (LS) | 72.2 | 0.12 | 0.03 |

**Figure B.30: WB I-96 42,722 feet from Kensington Road Bridge for Winter Storm on 2/1/2014**

**Figure B.31: WB I-96 30,536 feet from Kensington Road Bridge for Winter Storm on 2/1/2014**

**Figure B.32: WB I-96 50,316 feet from Kensington Road Bridge for Winter Storm on 2/1/2014**

**Figure B.33: WB I-96 70,095 feet from Kensington Road Bridge for Winter Storm on 2/1/2014**

### B.4: Winter Storm 4 (Moderate Snowfall – 2.5 inches) – January 21, 2015

During this storm, data were collected behind the Tow Plow along EB I-96 and WB I-96. The following table reports information for the EB I-96 slow lane.

**Table B.15: Winter Storm 4 Summary Data behind Tow Plow along EB I-96 Slow Lane**

| | |
|---|---|
| Tow Plow Data Collection Starting Point | M-59 Bridge over I-96 in Howell, MI |
| Tow Plow Data Collection Ending Point | Kent Lake Road Bridge over I-96 in Brighton, MI |
| Lanes Plowed | EB I-96 Middle Lane and Slow Lane |
| Tow Plow Operating Speed (mph) | 41.1 |

Average friction values are shown in Figure B.34.

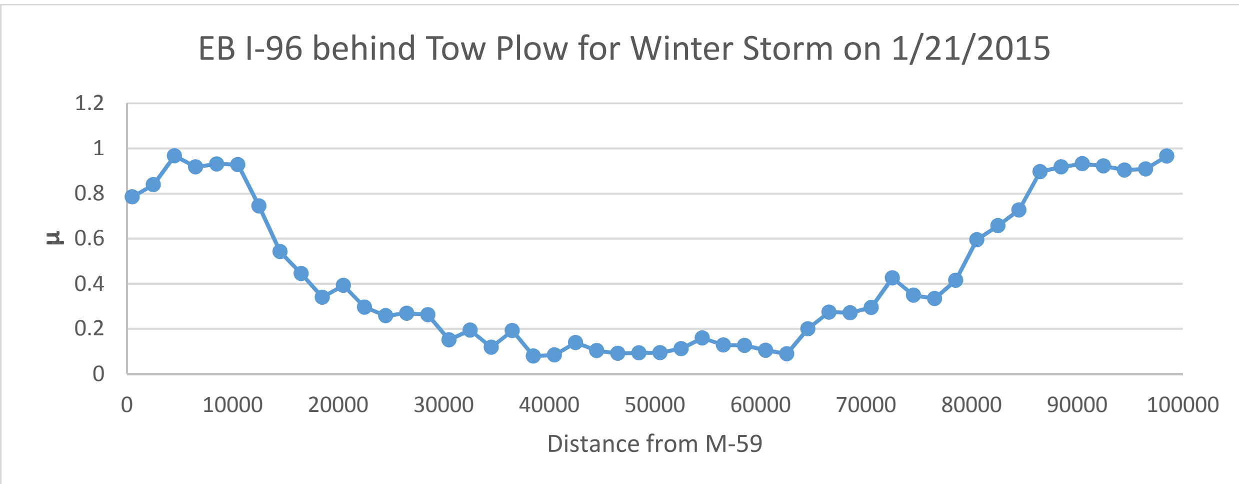


**Figure B.34: Friction Data behind Tow Plow EB I-96 for Winter Storm on 1/21/2015**

The slow lane of EB I-96 showed "Bare" surface conditions at 48% of the length, "Centerline Bare" surface conditions at 22% of the length, "Wheel Track Bare" surface conditions at 10% of the length and "Loose Snow" surface conditions at 20% of the length immediately behind the Tow Plow. Sample pictures are shown following the table. Table B.16 shows average friction values for different pavement conditions observed behind the Tow Plow along EB I-96.

**Table B.16: Pavement Condition and Average Friction Values for Winter Storm on 1/21/2015 behind Tow Plow along EB I-96**

| Pavement Condition | Length (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Bare (B) | 48 | 0.72 | 0.23 |
| Centerline Bare (CLB) | 22 | 0.25 | 0.09 |
| Wheel Track Bare (WTB) | 10 | 0.14 | 0.03 |
| Loose Snow (LS) | 20 | 0.11 | 0.03 |

**Figure B.35: EB I-96 20,500 feet from M-59 Bridge over I-96 for Winter Storm on 1/21/2015**

**Figure B.36: EB I-96 32,500 feet from M-59 Bridge over I-96 for Winter Storm on 1/21/2015**

**Figure B.37: EB I-96 56,500 feet from M-59 Bridge over I-96 for Winter Storm on 1/21/2015**

A summary of data collected during this storm behind the Tow Plow along the WB I-96 slow lane is shown in the following table.

**Table B.17: Winter Storm 4 Summary Data behind Tow Plow along WB I-96 Slow Lane**

| | |
|---|---|
| Tow Plow Data Collection Starting Point | Kent Lake Road Bridge over I-96 in Brighton, MI |
| Tow Plow Data Collection Ending Point | M-59 Bridge over I-96 in Howell, MI |
| Lanes Plowed | WB I-96 Middle Lane and Slow Lane |
| Tow Plow Operating Speed (mph) | 42.0 |

Figure B.38 shows the average friction values collected behind the Tow Plow.

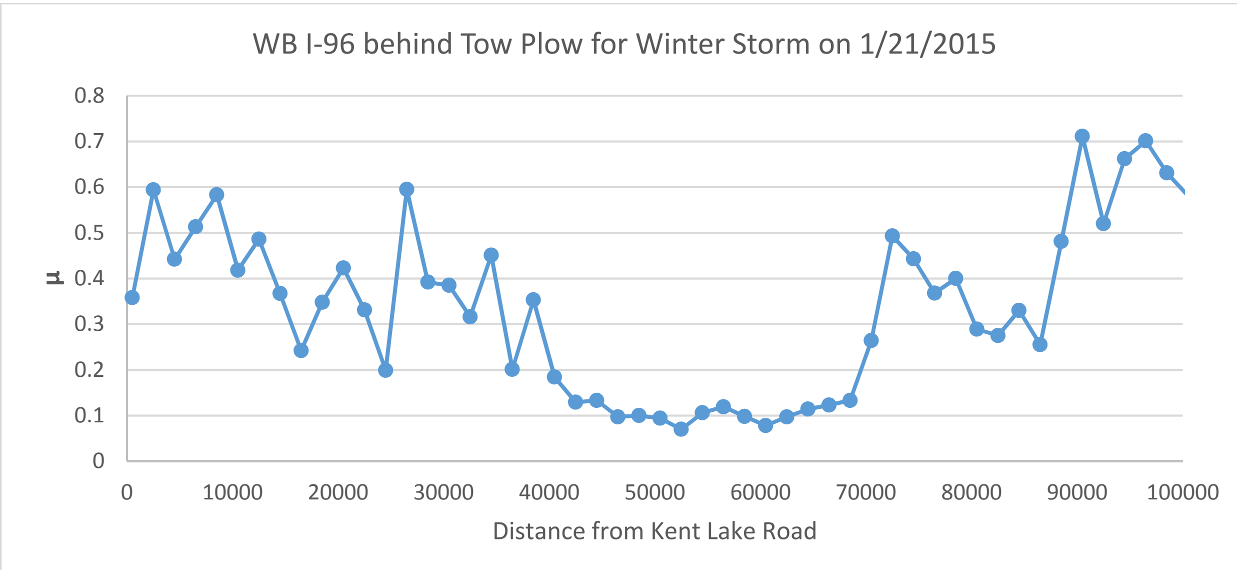


**Figure B.38: Friction Data behind Tow Plow WB I-96 for Winter Storm on 1/21/2015**

The slow lane of WB I-96 showed "Bare" surface conditions at 72.5% of the length, "Centerline Bare" surface conditions at 7.8% of the length, and "Wheel Track Bare" surface conditions at 19.6% of the length immediately behind the Tow Plow. No sample pictures were available for this research area. Table B.18 shows average friction values for different pavement conditions observed behind the Tow Plow along WB I-96.

**Table B.18: Pavement Condition and Average Friction Values for Winter Storm on 1/21/2015 behind Tow Plow along WB I-96**

| Pavement Condition | Length (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Bare (B) | 72.5 | 0.40 | 0.16 |
| Centerline Bare (CLB) | 7.8 | 0.31 | 0.15 |
| Wheel Track Bare (WTB) | 19.6 | 0.10 | 0.02 |

**B.5: Winter Storm 5 (Heavy Snowfall – 17 inches in 2 Days) - February 1, 2015**

During this storm, data were collected along the EB I-96 slow lane behind the Tow Plow, the EB I-96 slow lane behind the tow truck of the Tow Plow, and the WB I-96 slow lane behind the tow truck travelling near the Williamston Garage area.

A summary of data collected during this storm behind the Tow Plow along the EB I-96 slow lane is shown in the following table.

**Table B.19: Winter Storm 5 Summary Data behind Tow Plow along EB I-96 Slow Lane**

| | |
|---|---|
| Tow Plow Data Collection Starting Point | D-19 Entering Ramp in Howell, MI |
| Tow Plow Data Collection Ending Point | First Turn Around After US-23 in Brighton, MI |
| Lanes Plowed | EB I-96 Middle Lane and Slow Lane |
| Tow Plow Operating Speed (mph) | 37.8 |

Average friction values for 500-foot segments measured at 1000-foot intervals behind the Tow Plow are shown in Figure B.39.

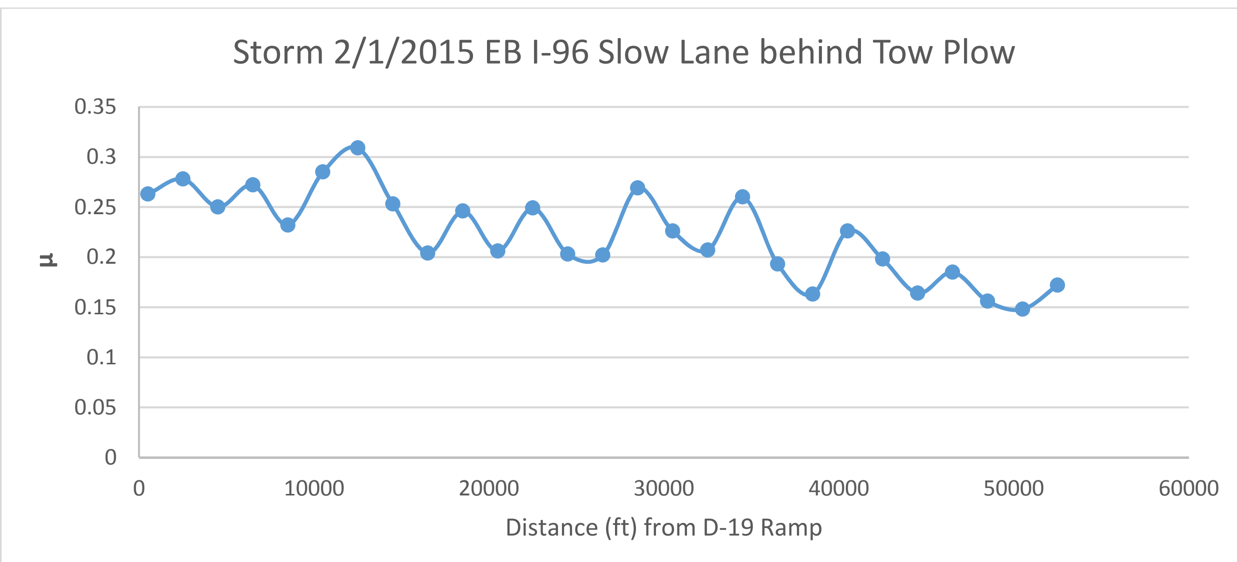


**Figure B.39: Friction Data behind Tow Plow EB I-96 for Winter Storm on 2/1/2015**

The slow lane of EB I-96 showed "Centerline Bare" surface conditions at 14.8% of the length and "Wheel Track Bare" surface condition at 85.2% of the length immediately behind the Tow Plow. The middle lane of EB I-96 showed "Wheel Track Bare" surface conditions at 88.9% of the length and "Loose Snow" surface conditions at 11.1% of the length immediately behind the tow truck of the Tow Plow. Sample pictures follow Table B.20. Table B.20 shows the average friction values for different pavement conditions observed behind the Tow Plow along EB I-96.

**Table B.20: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2015 behind Tow Plow along EB I-96**

| Pavement Condition | Length (%) Slow Lane/Middle Lane | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Centerline Bare (CLB) | 14.8/11.1 | 0.24 | 0.22 |
| Wheel Track Bare (WTB) | 85.2/88.9 | 0.06 | 0.04 |

**Figure B.40: EB I-96 20,500 feet from D-19 Entrance Ramp for Winter Storm on 2/1/2015**

**Figure B.41: EB I-96 38,500 feet from D-19 Entrance Ramp for Winter Storm on 2/1/2015**

A summary of data collected during this storm behind the tow truck of the Tow Plow along EB I-96 slow lane is shown in the following table.

**Table B.21: Winter Storm 5 Summary Data behind Tow Truck of the Tow Plow along EB I-96 Slow Lane**

| | |
|---|---|
| Tow Truck Data Collection Starting Point | M-59 Entering Ramp in Howell, MI |
| Tow Truck Data Collection Ending Point | Grand River Exit Ramp in Brighton, MI |
| Lanes Plowed | EB I-96 Slow Lane and Shoulder |
| Tow Plow Operating Speed (mph) | 35.7 |

The average friction values taken behind the tow truck are shown in Figure B.42.

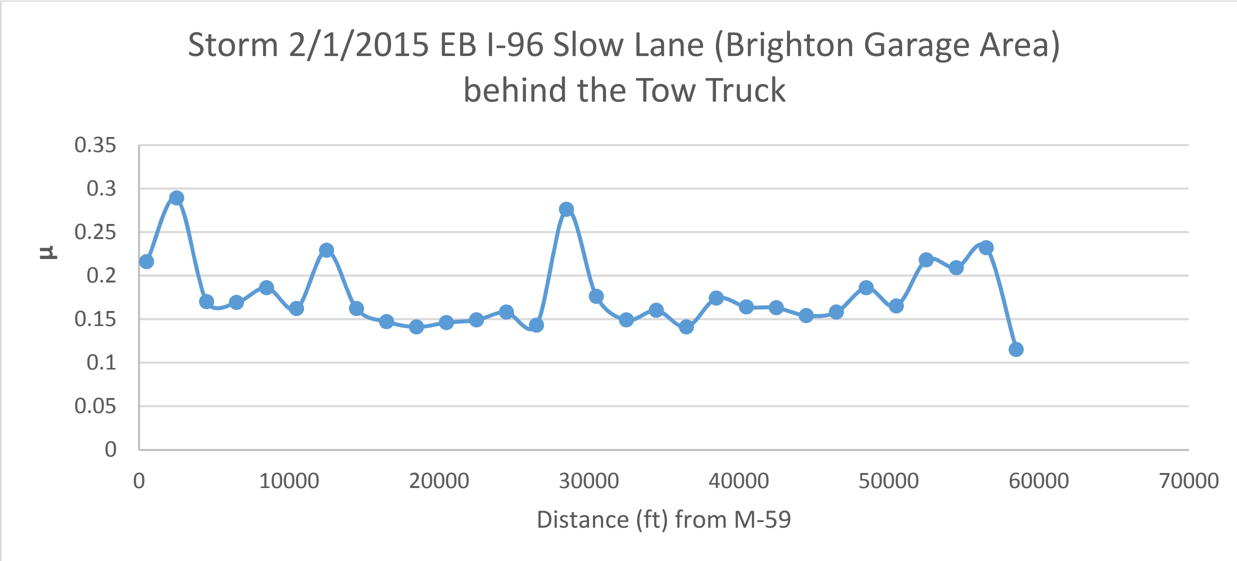


**Figure B.42: Friction Data behind Tow Truck EB I-96 for Winter Storm on 2/1/2015**

The slow lane of EB I-96 showed "Wheel Track Bare" surface conditions at 40% of the length and "Loose Snow" surface condition at 60% of the length immediately behind the tow truck. Sample pictures are shown following the average friction values. Table B.22 shows average friction values for different pavement conditions observed behind the tow truck along EB I-96.

**Table B.22: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2015 behind Tow Truck along EB I-96**

| Pavement Condition | Length (%) | Average Friction Value (µ) | Standard Deviation of µ |
|---|---|---|---|
| Wheel Track Bare (WTB) | 40 | 0.20 | 0.05 |
| Loose Snow (LS) | 60 | 0.16 | 0.03 |

**Figure B.43: EB I-96 2500 feet from M-59 Entrance Ramp for Winter Storm on 2/1/2015**

**Figure B.44: EB I-96 16500 feet from M-59 Entrance Ramp for Winter Storm on 2/1/2015**

Data collected during this storm behind the tow truck of the Tow Plow along the WB I-96 slow lane in the Williamston Garage area are summarized in the following table.

**Table B.23: Winter Storm 5 Summary Data behind Tow Truck of the Tow Plow along WB I-96 Slow Lane, Williamston Garage Area**

| | |
|---|---|
| Tow Truck Data Collection Starting Point | M-59 Entering Ramp in Howell, MI |
| Tow Truck Data Collection Ending Point | Exit 125 |
| Lanes Plowed | WB I-96 Slow Lane and Shoulder |
| Tow Plow Operating Speed (mph) | 32.1 |

Average friction values for 500-foot segments measured at 1000-foot intervals behind the tow truck are shown in Figure B.45.

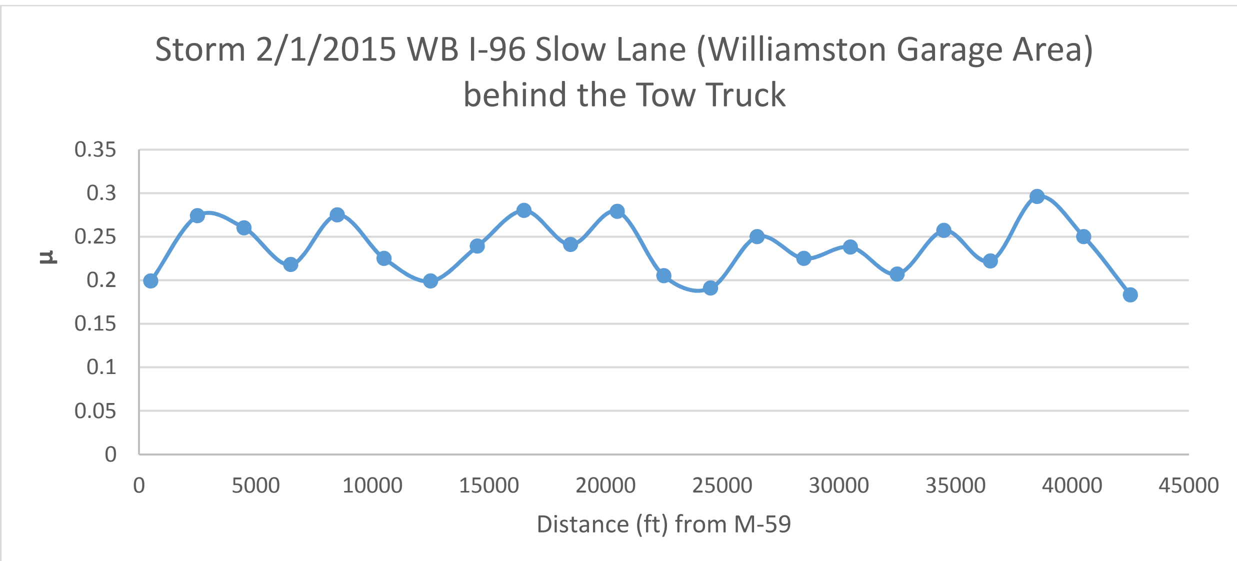


**Figure B.45: Friction Data behind Tow Truck WB I-96 (Williamston Garage) for Winter Storm on 2/1/2015**

The slow lane of WB I-96 showed "Centerline Bare" surface conditions at 42.9% of the length and "Wheel Track Bare" surface conditions at 57.1% of the length immediately behind the tow truck. Sample pictures are shown below. Table B.24 shows average friction values for different pavement conditions observed behind the tow truck along WB I-96.

**Table B.24: Pavement Condition and Average Friction Values for Winter Storm on 2/1/2015 behind Tow Truck along WB I-96 (Williamston Garage Area)**

| Pavement Condition | Length (%) | Average Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| Centerline Bare (CLB) | 42.9 | 0.23 | 0.03 |
| Wheel Track Bare (WTB) | 57.1 | 0.23 | 0.03 |

**Figure B.46: EB I-96 22,500 feet from M-59 Entrance Ramp for Winter Storm on 2/1/2015**


**Figure B.47: EB I-96 36,500 feet from M-59 Entrance Ramp for Winter Storm on 2/1/2015**

### B.6: Winter Storm 6 (Moderate Snowfall – 2.2 inches) - February 14, 2015

During this storm, data were collected along the NB US-23 slow lane behind the tow truck of the Tow Plow.

A summary of the data collected during this storm behind the tow truck along NB US-23 slow lane is shown in the following table.

**Table B.25: Winter Storm 6 Summary Data behind Tow Truck along NB US-23 Slow Lane**

| | |
|---|---|
| Tow Truck Data Collection Starting Point | I-96 EB bridge over US-23 in Howell, MI |
| Tow Truck Data Collection Ending Point | White Lake Road Exit |
| Lanes Plowed | NB US-23 Slow Lane and Shoulder |
| Tow Plow Operating Speed (mph) | 36.8 |

The average friction values measured behind the tow truck are shown in Figure B.48.

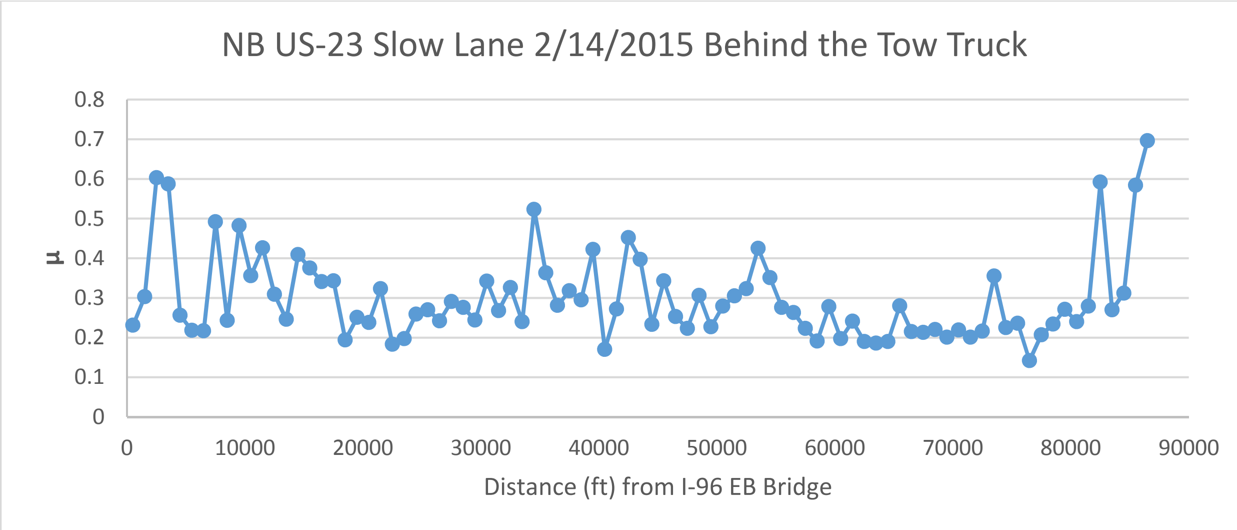


**Figure B.48: Friction Data behind Tow Truck NB US-23 for Winter Storm on 2/14/2015**

The slow lane of NB US-23 showed "Centerline Bare" surface conditions at 32.2% of the length and "Wheel Track Bare" surface conditions at 67.8% of the length immediately behind the tow truck. Sample pictures are shown below the following table. Table B.26 shows average friction values for different pavement conditions observed behind the tow truck along NB US-23.

**Table B.26: Pavement Condition and Average Friction Values for Winter Storm on 2/14/2015 behind Tow Truck along NB US-23**

| Pavement Condition | Length (%) | Average Friction Value (µ) | Standard Deviation of µ |
|---|---|---|---|
| Centerline Bare (CLB) | 32.2 | 0.38 | 0.13 |
| Wheel Track Bare (WTB) | 67.8 | 0.26 | 0.07 |

**Figure B.49: NB US-23 22,500 feet from EB I-96 Bridge for Winter Storm on 2/14/2015**

**Figure B.50: NB US-23 39,500 feet from EB I-96 Bridge for Winter Storm on 2/14/2015**

**Figure B.51: NB US-23 48,500 feet from EB I-96 Bridge for Winter Storm on 2/14/2015**

### B.7: Winter Storm 7 (Light Snowfall – 1.1 inches) – March 3, 2015

During this storm, data were collected along NB US-23, SB US-23 and WB I-96 behind the WMTP. However, the friction tester was not operating accurately during this storm and only the visual pavement condition data were collected.

A summary of data collected during this storm behind the WMTP along WB I-96 is shown in the following table.

**Table B.27: Winter Storm 7 Summary Data behind WMTP along WB I-96**

| | |
|---|---|
| WMTP Data Collection Starting Point | Oakland County Line |
| WMTP Data Collection Ending Point | Brighton Exit |
| Lanes Plowed | WB I-96 Middle Lane and Slow Lane |

The middle lane of WB I-96 showed "Centerline Bare" surface conditions at 11% of the length and "Loose Snow" surface conditions at 89% of the length immediately behind the tow truck. The slow lane of WB I-96 showed "Centerline Bare" surface conditions at 12.7% of the length and "Loose Snow" surface conditions at 87.3% of the length immediately behind the Tow Plow.

Sample pictures of WB I-96 taken during the snowstorm on 3/3/2015 are found below.


**Figure B.52: WB I-96 near Kensington Road Exit for Winter Storm on 3/3/2015**


**Figure B.53: WB I-96 near SB US-23 Exit for Winter Storm on 3/3/2015**

A summary of data collected during this storm behind the WMTP along NB US-23 is shown in the following table.

**Table B.28: Winter Storm 7 Summary Data behind WMTP along NB US-23**

| | |
|---|---|
| WMTP Data Collection Starting Point | I-96 |
| WMTP Data Collection Ending Point | North County Line |
| Lanes Plowed | NB US-23 Slow Lane and Outside Shoulder |

The slow lane of NB US-23 showed “Centerline Bare” surface conditions at 14.1% of the length, “Wheel Track Bare” surface conditions at 48.4% of the length and “Loose Snow” surface conditions at 37.5% of the length immediately behind the tow truck. The shoulder lane of NB US-23 showed “Wheel Track Bare” surface conditions at 7.8% of the length and “Loose Snow” surface conditions at 92.2% of the length immediately behind the Tow Plow.

Sample pictures of NB US-23 taken during the snowstorm on 3/3/2015 are shown below.

**Figure B.54: NB US-23 near Clyde Road Exit for Winter Storm on 3/3/2015**

**Figure B.55: NB US-23 near North County Line for Winter Storm on 3/3/2015**

A summary of data collected during this storm behind the WMTP along SB US-23 is shown in the following table.

**Table B.29: Winter Storm 7 Summary Data behind WMTP along SB US-23**

| | |
|---|---|
| WMTP Data Collection Starting Point | North County Line |
| WMTP Data Collection Ending Point | M-59 Ramp |
| Lanes Plowed | Slow Lane and Outside Shoulder |

The slow lane of SB US-23 showed "Centerline Bare" surface conditions at 75.7% of the length, "Wheel Track Bare" surface conditions at 10.8% of the length, and "Loose Snow" surface conditions at 13.5% of the length immediately behind the tow truck. The outside shoulder of SB US-23 showed "Centerline Bare" surface conditions at 2.7% of the length, "Wheel Track Bare" surface conditions at 29.7% of the length and "Loose Snow" surface conditions at 67.6% of the length immediately behind the Tow Plow.

Sample pictures of SB US-23 during the snowstorm on 3/3/2015 are shown in the following pictures.


**Figure B.56: SB US-23 near White Lake Road Exit for Winter Storm on 3/3/2015**


**Figure B.57: SB US-23 5280 feet from Clyde Road Exit for Winter Storm on 3/3/2015**

# APPENDIX C

# RELATIONSHIPS BETWEEN WINTER STORM PAVEMENT SURFACE CONDITIONS AND PAVEMENT FRICTION VALUES

# APPENDIX C

# RELATIONSHIPS BETWEEN WINTER STORM PAVEMENT SURFACE CONDITIONS AND PAVEMENT FRICTION VALUES

## C.1: Comparison of Winter Pavement Friction Values to Wet Pavement Friction Values

Tire-pavement friction is drastically reduced during winter storm events. Loss of tire-pavement friction during winter storms causes a severe safety hazard to the motoring public. Every year more than 117,000 people are injured and more than 1,300 people die on snowy, slushy, or icy roadways (FHWA, 2015). The coefficient of friction (μ) between a vehicle tire and pavement can be dramatically increased by winter maintenance activities such as snow plowing, deicing, anti-icing, and sanding of the roadway.

### C.1.1: Wet Friction and Winter Friction Data

For this study, wet pavement friction values were collected during the summer months. These values were compared to friction values collected during winter storm events. Table C.1 shows a summary of the wet friction values for each direction (eastbound (EB), northbound (NB), southbound (SB), and westbound (WB)), of I-96 in Brighton, US-23 in Brighton, and I-96 in Williamston.

The friction testing along I-96 in the Brighton area (three-lane section) was performed at an average speed of 50 mph. All other roadways were tested at an average speed of 40 mph.

**Table C.1: Summary Wet Friction Data**

| Roadway/Direction | Lane | Average Wet Friction Value (μ) | Standard Deviation of μ |
|---|---|---|---|
| I-96 Brighton/EB | Outside Lane (Lane 1) | 0.66 | 0.09 |
| | Middle Lane (Lane 2) | 0.72 | 0.07 |
| I-96 Brighton/WB | Outside Lane (Lane 1) | 0.66 | 0.12 |
| | Middle Lane (Lane 2) | 0.72 | 0.08 |
| US-23 Brighton/NB | Outside Lane (Lane 1) | 0.80 | 0.08 |
| | Inside Lane (Lane 2) | 0.83 | 0.09 |
| US-23 Brighton/SB | Outside Lane (Lane 1) | 0.76 | 0.10 |
| | Inside Lane (Lane 2) | 0.80 | 0.09 |
| I-96 Williamston/EB | Outside Lane (Lane 1) | 0.80 | 0.05 |
| | Inside Lane (Lane 2) | 0.75 | 0.07 |
| I-96 Williamston/WB | Outside Lane (Lane 1) | 0.78 | 0.06 |
| | Inside Lane (Lane 2) | 0.74 | 0.06 |

Figures C.1 to C.6 show the wet friction data for each direction of the respective roadway as well as collected winter storm friction data. When reading the legends, wet pavement condition friction results show only the lane number, e.g. Lane 1. The winter storm friction data, as seen within the legend, show the direction, road identifier, lane number, and storm date, e.g. EB I-96 Lane 3 1/1/2014.

### C.1.1.1: I-96 in Brighton Friction Data

Figure C.1 shows the friction values collected along EB I-96. Due to variations in pavement contaminants (snow, ice), the friction values collected during the winter storms were highly variable when compared to the wet pavement condition friction data. For example, during the winter storm on 1/21/2015, the first and last 10,000 feet of EB I-96 exceeded wet pavement friction values.

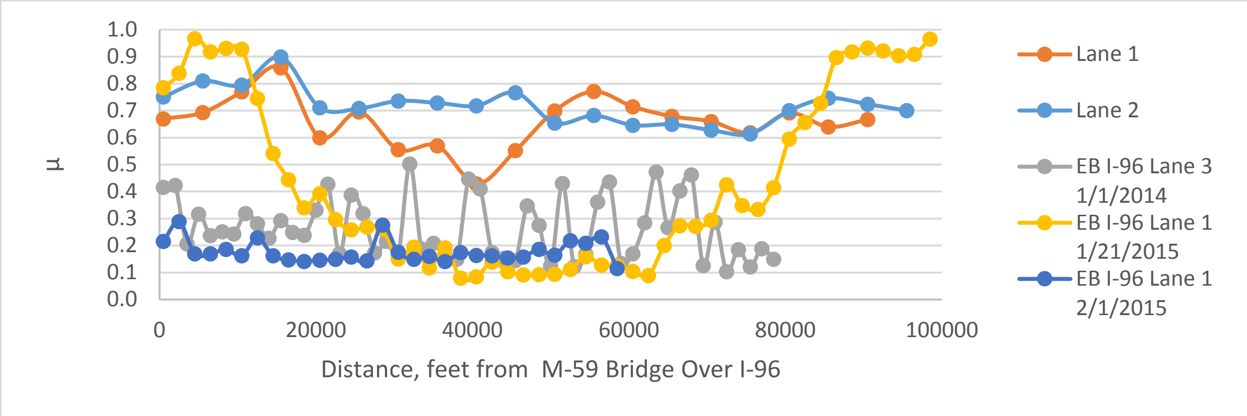


**Figure C.1: EB I-96 Brighton Wet Friction Data with Winter Storm Friction Data**

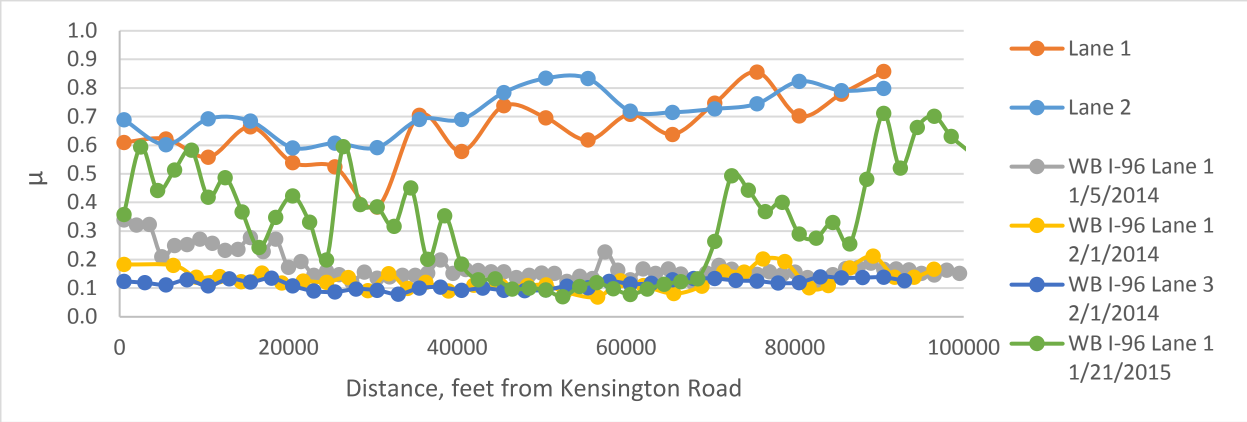


**Figure C.2: WB I-96 Brighton Wet Friction Data with Winter Storm Friction Data**

### C.1.1.2: US-23 in Brighton Friction Data

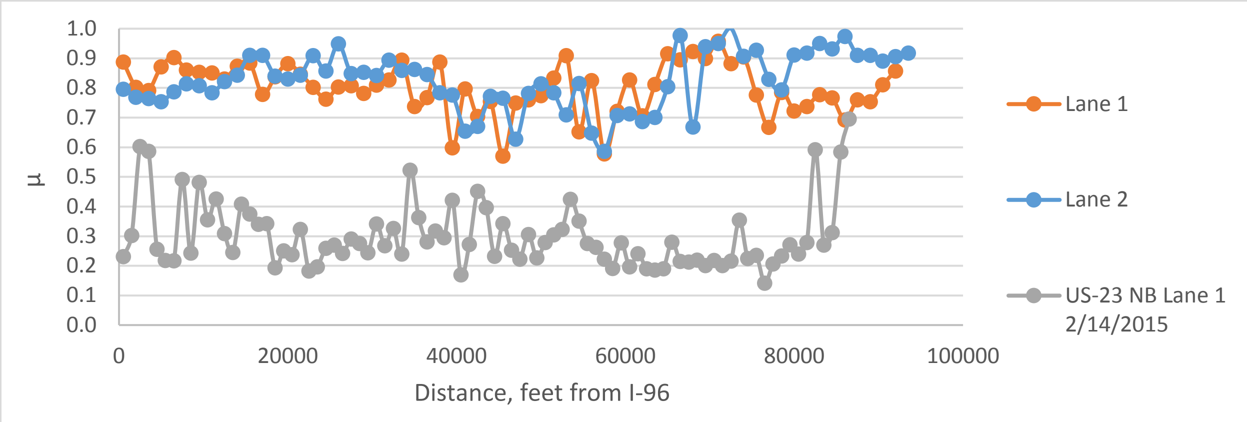


**Figure C.3: NB US-23 Brighton Wet Friction data with Winter Storm Friction Data**

Friction data taken during the winter storms were not available for SB US-23; only wet pavement friction data are shown in Figure C.4.

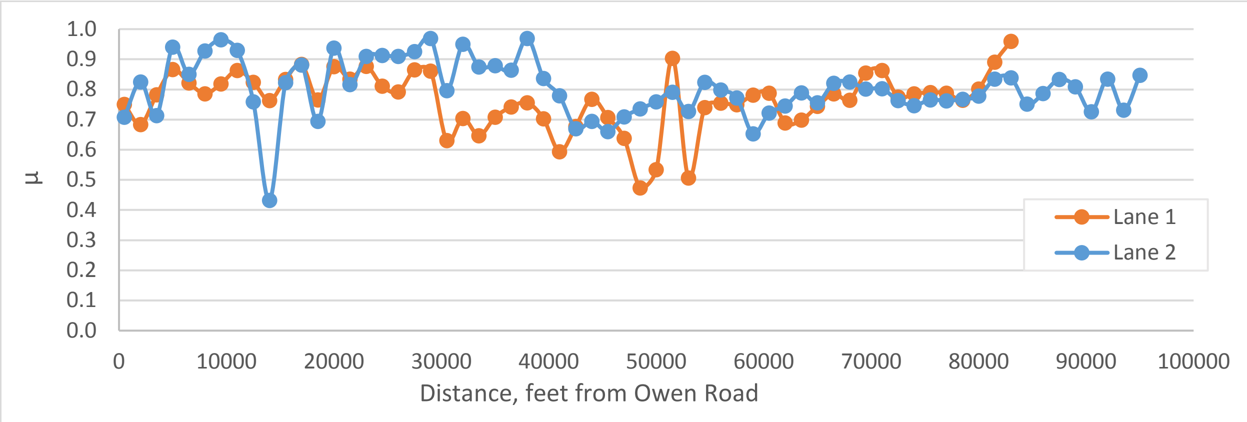


**Figure C.4: SB US-23 Brighton Wet Friction data**

### C.1.1.3: I-96 in Williamston Friction Data

Friction data taken during the winter storms were not available for EB I-96 in Williamston. Only wet pavement friction data are shown in Figure C.5.

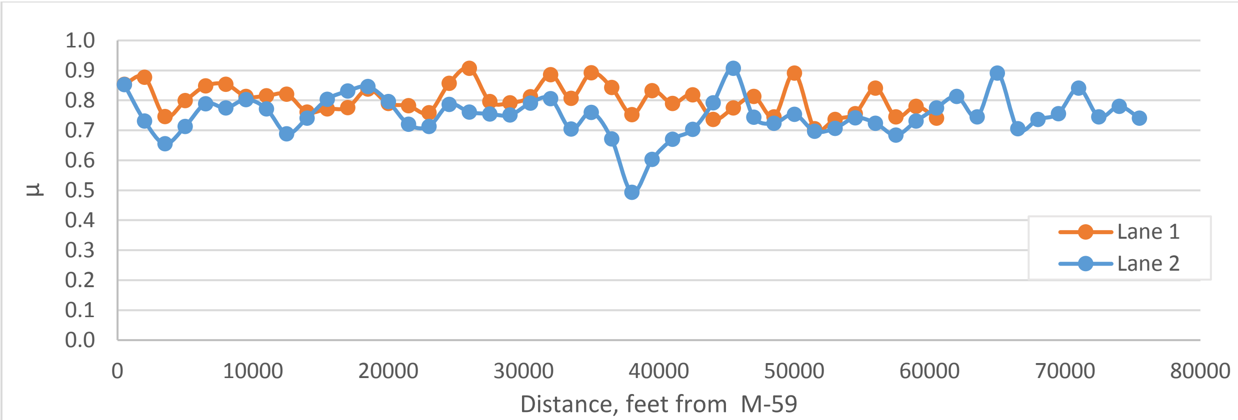


**Figure C.5: EB I-96 Williamston Wet Friction data**

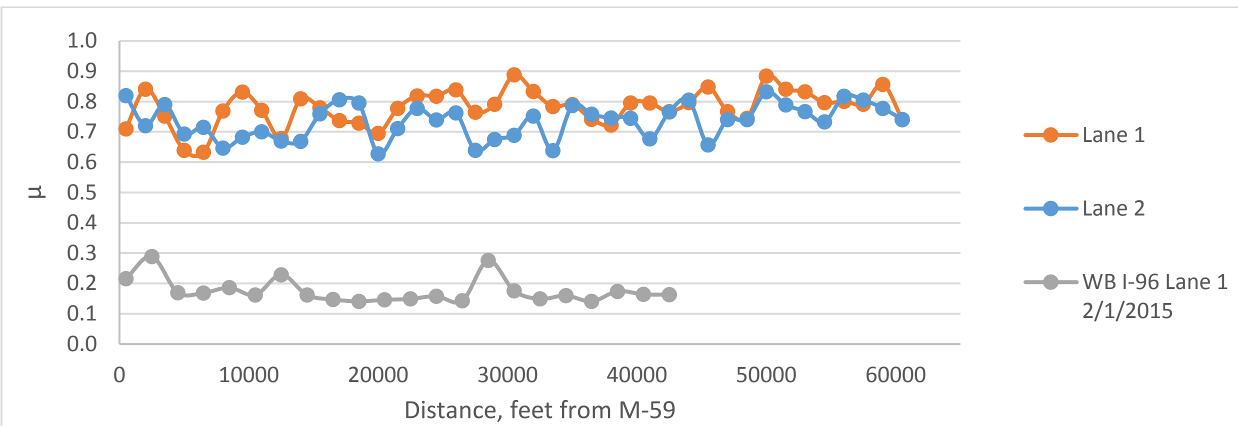


**Figure C.6: WB I-96 Williamston Wet Friction data**

### C.2: Winter Friction Values and Winter Pavement Conditions

In most cases, a significant reduction of friction values was observed between the wet pavement friction values and winter storm pavement friction values. Since winter storm pavement friction levels are dependent upon the variability of the winter storm pavement surface condition, a correlation was developed between the winter pavement surface conditions and observed friction values. The winter storm surface conditions are defined in Figure 4.3 of this report. This relationship is based on collected friction values during all winter storms for all data collection routes during the 2013-2015 winter seasons. Table C.2 and Figure C.7 show the average friction values at different winter storm pavement conditions for the winter seasons (2013-2015).

**Table C.2: Friction Statistics for different Winter Pavement Surface Conditions**

| Winter Pavement Surface Condition | Average Friction Value μ | Standard Deviation of μ | Maximum μ | Minimum μ | Number of Observations |
|---|---|---|---|---|---|
| Bare (B) | 0.53 | 0.25 | 0.97 | 0.10 | 61 |
| Centerline Bare (CLB) | 0.31 | 0.12 | 0.70 | 0.09 | 57 |
| Wheel Track Bare (WTB) | 0.25 | 0.11 | 0.62 | 0.07 | 242 |
| Loose Snow (LS) | 0.13 | 0.03 | 0.23 | 0.07 | 141 |
| Snow Covered (S) | No data | No data | No data | No data | No data |

The average friction values for each condition type are graphed along with ± 1 Standard Deviation in Figure C.7.

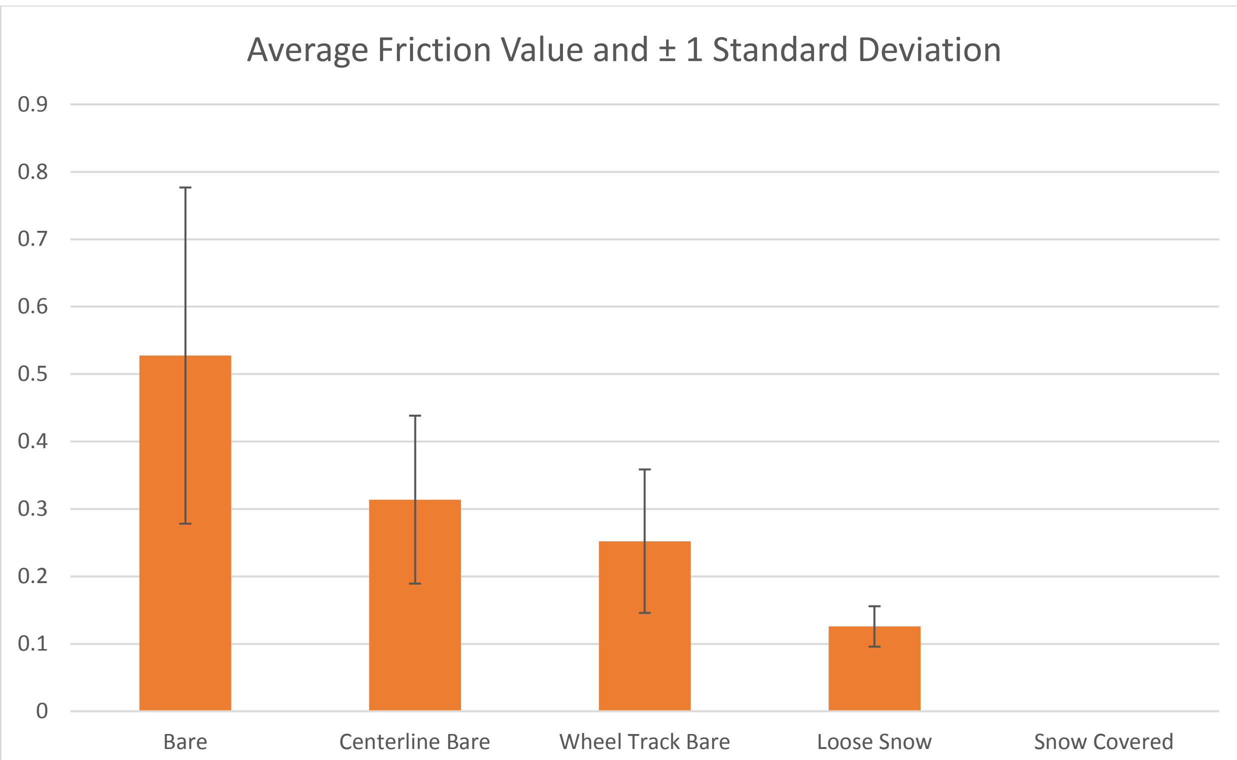


**Figure C.7: Correlation between Pavement Condition and Friction Values**

Differences between the average friction values for each observed winter pavement surface condition are clearly visible. A statistical analysis was performed to see whether there was a statistically significant difference in observed friction values relative to winter pavement surface conditions.

The statistical analysis was performed by comparing the absolute difference between adjacent pavement condition mean friction values based on the method described in Section 4.3.

**Table C.3: Statistical Analysis Results for Average Friction Values and Winter Storm Pavement Conditions**

| Parameter | Between B and CLB | | Between CLB and WTB | | Between WTB and LS | |
|---|---|---|---|---|---|---|
| | **B** | **CLB** | **CLB** | **WTB** | **WTB** | **LS** |
| μ | 0.527 | 0.314 | 0.314 | 0.252 | 0.252 | 0.126 |
| Std. Dev (S) | 0.249 | 0.124 | 0.124 | 0.106 | 0.106 | 0.030 |
| Sample size (n) | 61 | 57 | 57 | 242 | 242 | 141 |
| $S_d$ | 0.0359 | | 0.0179 | | 0.0073 | |
| $\lvert\overline{\mu_1} - \overline{\mu_2}\rvert$ | 0.2140 | | 0.0616 | | 0.1260 | |
| $ZS_d$ for 95% Confidence Level | 0.0704 | | 0.0350 | | 0.0142 | |
| *Result* | *Statistically Different* | | *Statistically Different* | | *Statistically Different* | |

As seen in Table C.3 results, there are statistically significant differences between average friction values for different winter pavement conditions. These friction values and corresponding winter storm pavement condition values can be used as a performance measure for winter maintenance. Since visual pavement conditions influence a driver's response during winter storm events, the visual pavement condition assessment and corresponding friction measurements are objective measurements of roadway safety during these events.  This correlation provides a basic guideline for winter maintenance and performance measurements of this winter maintenance.

### C.3:  Winter Pavement Friction Values and Driving Safety

Pavement friction plays an important role in vehicle stopping distance. Stopping distance along a level road is given in the following equation.

$$\text{Stopping Distance (d)} = \frac{V^2}{2g\mu}$$

Where,

d = Stopping distance in feet
$v$ = Initial vehicle speed in ft/sec
$g$ = Acceleration due to gravity
$\mu$ = Friction coefficient

Figure C.8 shows the stopping distances needed for different friction values at different initial speeds.

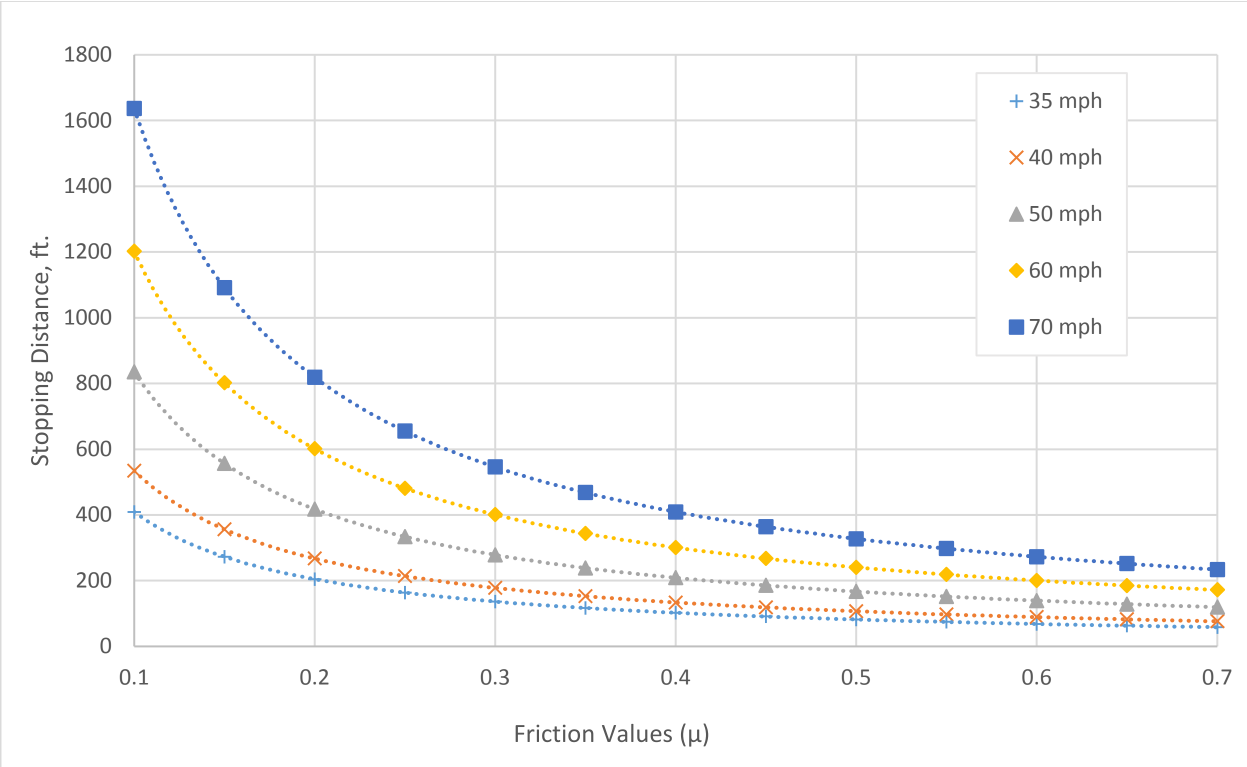


**Figure C.8: Stopping Distance and Pavement Friction**

The American Association of State Highway and Transportation Officials (AASHTO) recommend using 0.35 as a friction value for highway geometric design (AASHTO, 2004). When the friction value dropped below 0.35 due to a winter storm, the stopping distance increased as shown in Figure C.8. This poses real safety hazards for the driving public if they do not adjust to the drop in friction values as a result of a winter storm. DOTs should warn motorists of potentially dangerous driving conditions by using variable message signs and other modes of communication tools such as radio and social media applications.

Table C.4 shows the recommended speeds levels for different posted speed limit roads at different winter storm pavement conditions.

**Table C.4: Recommended Winter Speed Limits**

| Posted Speed Limit (mph) | Winter Pavement Condition Calculated/Recommended Winter Speed Limits (mph) | | |
|---|---|---|---|
| | Centerline Bare (CLB) | Wheel Track Bare (WTB) | Loose Snow (LS) |
| 35 | 33/30 | 30/30 | 21/20 |
| 40 | 38/35 | 34/30 | 24/20 |
| 45 | 42/40 | 38/35 | 27/25 |
| 50 | 47/45 | 42/40 | 30/30 |
| 55 | 52/50 | 46/45 | 34/30 |
| 60 | 56/55 | 51/50 | 37/35 |
| 65 | 61/60 | 55/55 | 40/40 |
| 70 | 66/65 | 59/55 | 43/40 |

The winter speed limits recommended above will provide a safe braking distance for vehicles traveling on roadways with different winter pavement conditions. These recommendations can be posted on changeable message boards along the side of the roadways. Also, these recommendations can be distributed to driving public through social media such as twitter and Facebook.

# APPENDIX D

# WINTER MAINTENANCE DATA FOR 2012-2016 WINTER SEASONS

## APPENDIX D

## WINTER MAINTENANCE DATA FOR 2012-2016 WINTER SEASONS

### Table D-1: Winter Maintenance Data for I-96 Route in Brighton Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/21/2012 | 1.02 | 76.00 | 3,420.00 | 4,525.20 | 4373.06 | 4.42 | 0.00 |
| 12/24/2012 | 0.70 | 47.50 | 1,732.50 | 2,959.20 | 2,085.53 | 4.57 | 0.0 |
| 12/26-12/27/2012 | 4.59 | 59.00 | 4,882.50 | 7,163.55 | 6,184.66 | 6.16 | 0.0 |
| 12/29/2012 | 1.44 | 37.00 | 1,665.00 | 3,661.20 | 3,008.74 | 3.33 | 0.0 |
| 1/21/2013 | 1.50 | 46.00 | 2,070.00 | 2,777.40 | 2,972.02 | 4.43 | 7.0 |
| 1/22/2013 | 0.30 | 13.00 | 585.00 | 135.00 | 818.19 | 3.00 | 0.0 |
| 1/25/2013 | 1.85 | 76.50 | 3,442.50 | 7,320.60 | 4,748.04 | 5.00 | 12.5 |
| 1/27/2013 | 1.87 | 77.50 | 3,487.50 | 7,131.60 | 4,421.33 | 5.00 | 0.0 |
| 2/2/2013 | 1.28 | 36.50 | 1,642.50 | 2,076.30 | 1,739.56 | 3.26 | 0.0 |
| 2/3/2013 | 0.38 | 45.50 | 2,047.50 | 1,695.60 | 2,676.43 | 3.37 | 0.0 |
| 2/4/2013 | 2.03 | 46.00 | 2,070.00 | 3,186.00 | 2,873.71 | 4.21 | 0.0 |
| 2/7-2/8/2013 | 1.85 | 85.30 | 3,757.50 | 5,628.60 | 5,754.26 | 8.27 | 12.0 |
| 2/16/2013 | 1.44 | 12.50 | 562.50 | 496.80 | 725.97 | 4.00 | 0.0 |
| 3/15-3/16/2013 | 1.48 | 60.50 | 2,772.50 | 4,879.80 | 2,258.77 | 2.69 | 0.0 |
| 11/11/2013 | 0.50 | 6.50 | 292.50 | 90.00 | 459.09 | 1.00 | 0.0 |
| 12/11/2013 | 0.30 | 12.00 | 1,507.50 | 2,025.00 | 2,383.08 | 3.89 | 6.0 |
| 12/14/2013 | 6.70 | 58.00 | 2,610.00 | 8,726.40 | 4,924.06 | 3.85 | 22.0 |
| 12/15/2013 | 0.70 | 61.00 | 2,745.00 | 3,641.40 | 3,627.38 | 3.00 | 10.0 |
| 12/16-12/17/2013 | 1.34 | 89.00 | 4,005.00 | 6,428.70 | 6,525.73 | 3.55 | 25.0 |
| 12/25-12/26/2013 | 1.96 | 69.25 | 3,116.25 | 5,269.50 | 4,231.23 | 5.17 | 8.0 |
| 12/31/2013 | 1.22 | 34.00 | 1,530.00 | 3,818.70 | 2,630.17 | 2.98 | 13.0 |
| 1/1-1/2/2014 | 9.04 | 119.00 | 5,355.00 | 9,986.40 | 7,939.22 | 4.36 | 24.0 |
| 1/5-1/6/2014 | 10.20 | 137.00 | 6,165.00 | 6,808.00 | 9,666.12 | 5.02 | 42.5 |
| 1/24-1/25/2014 | 1.54 | 70.00 | 3,150.00 | 4,288.50 | 4,830.66 | 2.91 | 22.5 |
| 1/26/2014 | 1.94 | 46.00 | 2,070.00 | 5,692.50 | 3,652.29 | 2.17 | 24.0 |
| 1/27/2014 | 2.24 | 54.25 | 2,441.25 | 5,510.70 | 3,740.33 | 5.38 | 12.0 |
| 1/30/2014 | 0.60 | 26.00 | 1,170.00 | 998.10 | 1,813.46 | 2.38 | 0.0 |
| 2/1/2014 | 7.42 | 87.50 | 3,937.50 | 6,196.05 | 6,076.78 | 5.48 | 18.0 |
| 2/4-2/5/2014 | 6.45 | 94.00 | 4,230.00 | 9,226.80 | 6,021.53 | 4.93 | 12.0 |
| 2/8-2/9/2014 | 2.41 | 35.00 | 1,575.00 | 3,652.65 | 2,393.36 | 2.47 | 8.5 |
| 2/14/2014 | 0.40 | 12.50 | 562.50 | 585.90 | 770.37 | 1.83 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 41.00 | 2,115.60 | 3,713.40 | 3,571.18 | 4.02 | 19.0 |
| 2/20/2014 | 1.37 | 29.00 | 1,305.00 | 1,125.00 | 1,612.29 | 4.00 | 0.0 |
| 3/12/2014 | 7.06 | 87.50 | 3,937.50 | 6,903.00 | 6,041.03 | 4.55 | 16.0 |
| 4/14-4/15/2014 | 1.41 | 20.00 | 900.00 | 2,563.20 | 1,500.61 | 3.08 | 7.0 |
| 11/16/2014 | 0.60 | 4.00 | 180.00 | 360.00 | 282.52 | 0.33 | 0.0 |
| 11/19/2014 | 1.10 | 64.50 | 2,902.50 | 4,494.60 | 4,479.38 | 2.66 | 10.0 |
| 1/4/2015 | 0.60 | 60.50 | 2,722.50 | 4,071.60 | 3,923.23 | 3.48 | 9.0 |
| 1/6-1/7/2015 | 1.20 | 46.00 | 2,070.00 | 2,752.20 | 3,066.02 | 3.90 | 8.0 |
| 1/8-1/9/2015 | 1.80 | 99.50 | 4,477.50 | 4,205.70 | 7,142.52 | 4.73 | 27.0 |
| 1/11-1/12/2015 | 2.70 | 68.50 | 3,082.50 | 5,975.10 | 4,898.49 | 4.29 | 20.0 |
| 1/14/2015 | 0.20 | 6.00 | 270.00 | 360.00 | 306.48 | 1.60 | 0.0 |
| 1/20/2015 | 0.90 | 19.00 | 855.00 | 1,102.50 | 1,046.36 | 2.38 | 0.0 |
| 1/21/2015 | 2.50 | 46.00 | 2,070.00 | 3,691.80 | 3,067.40 | 3.08 | 12.0 |
| 1/29/2015 | 1.30 | 51.00 | 2,295.00 | 3,676.95 | 3,530.10 | 3.94 | 12.0 |
| 2/1-2/2/2015 | 17.00 | 156.25 | 7,031.25 | 11,450.25 | 11,084.66 | 5.51 | 26.5 |
| 2/3-2/4/2015 | 2.60 | 89.50 | 4,027.50 | 7,905.60 | 6,188.64 | 4.47 | 17.0 |
| 2/13-2/14/2015 | 2.20 | 81.50 | 3,667.50 | 8,239.95 | 5,437.25 | 4.03 | 12.0 |
| 2/21/2015 | 0.50 | 22.50 | 1,012.50 | 1,358.10 | 1,387.45 | 2.91 | 0.0 |
| 2/26/2015 | 0.30 | 26.00 | 1,170.00 | 2,677.50 | 1,598.90 | 3.40 | 0.0 |
| 3/1/2015 | 0.40 | 9.50 | 427.50 | 787.50 | 579.07 | 3.40 | 0.0 |
| 3/3/2015 | 1.10 | 70.00 | 3,150.00 | 7,404.30 | 4,373.06 | 4.72 | 12.0 |
| 11/21/2015 | 8.2 | 82.00 | 3,690.00 | 8,570.70 | 6,038.61 | 4.81 | 16.5 |
| 12/28/2015 | 1.4 | 75.00 | 3,375.00 | 6,838.20 | 5,672.21 | 5.46 | 20.0 |
| 1/10/2016 | 4.3 | 67.50 | 3,037.50 | 6,007.05 | 3,365.75 | 4.85 | 0.00 |
| 2/24/2016 | 10.4 | 115.00 | 5,175.00 | 9,369.90 | 9,628.09 | 5.91 | 65.0 |

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 3/1/2016 | 7.2 | 110.72 | 4,982.40 | 12,776.85 | 8,781.03 | 4.79 | 48.0 |

## Table D-2: Winter Maintenance Data for US-23 Route in Brighton Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 11/11/2013 | 0.50 | 6.50 | 292.50 | 90.00 | 459.09 | 1.00 | 0.0 |
| 12/11/2013 | 0.30 | 24.00 | 1,080.00 | 765.00 | 1,537.86 | 3.50 | 0.0 |
| 12/14/2013 | 6.70 | 59.00 | 2,655.00 | 3,917.70 | 3,332.99 | 3.81 | 0.0 |
| 12/15/2013 | 0.70 | 59.00 | 2,655.00 | 2,685.60 | 3,649.01 | 4.00 | 0.0 |
| 12/16-12/17/2013 | 1.34 | 70.00 | 3,150.00 | 4,061.70 | 4,487.32 | 4.06 | 0.0 |
| 12/25-12/26/2013 | 1.96 | 65.25 | 2,936.25 | 4,991.40 | 3,831.99 | 3.35 | 0.0 |
| 12/31/2013 | 1.22 | 39.50 | 1,777.50 | 5,037.75 | 2,460.66 | 2.72 | 0.0 |
| 1/1-1/2014 | 9.02 | 125.00 | 5,625.00 | 11,248.20 | 6,834.32 | 5.16 | 0.0 |
| 1/5-1/6/2014 | 10.20 | 142.50 | 6,412.50 | 5,351.40 | 8,267.88 | 5.12 | 0.0 |
| 1/24-1/25/2014 | 1.54 | 55.50 | 2,497.50 | 1,824.30 | 3,074.31 | 2.58 | 0.0 |
| 1/26/2014 | 1.94 | 43.50 | 1,957.50 | 2,103.30 | 2,287.87 | 3.31 | 0.0 |
| 1/27/2014 | 2.24 | 39.25 | 1,766.25 | 1,687.50 | 2,282.88 | 3.96 | 0.0 |
| 1/30/2014 | 0.60 | 17.00 | 765.00 | 1,098.00 | 1,103.30 | 1.62 | 0.0 |
| 2/1/2014 | 7.42 | 45.50 | 2,047.50 | 7,174.35 | 2,596.40 | 2.38 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 76.00 | 3,420.00 | 6,315.30 | 4,113.53 | 4.18 | 0.0 |
| 2/8-2/9/2014 | 2.41 | 43.50 | 1,957.50 | 3,517.20 | 2,543.92 | 2.29 | 0.0 |
| 2/14/2014 | 0.40 | 17.00 | 765.00 | 270.00 | 998.96 | 2.17 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 55.50 | 2,497.50 | 3,823.20 | 3,440.55 | 3.68 | 0.0 |
| 2/20/2014 | 1.37 | 22.00 | 990.00 | 1,558.80 | 1,405.12 | 3.00 | 0.0 |
| 3/12/2014 | 7.06 | 60.50 | 2,722.50 | 4,887.90 | 3,545.87 | 3.25 | 0.0 |
| 4/14-4/15/2014 | 1.41 | 20.00 | 900.00 | 1,358.10 | 1,200.73 | 3.08 | 0.0 |
| 11/16/2014 | 0.50 | 7.50 | 337.50 | 450.00 | 765.53 | 0.65 | 7.5 |
| 11/19/2014 | 1.10 | 59.50 | 2,677.50 | 5,481.90 | 4,549.27 | 2.75 | 23.0 |
| 1/4/2015 | 0.60 | 53.00 | 2,385.00 | 3,922.65 | 3,116.41 | 2.91 | 0.0 |
| 1/6-1/7/2015 | 1.20 | 64.00 | 2,880.00 | 3,534.30 | 3,820.54 | 4.41 | 0.0 |
| 1/8-1/9/2015 | 1.80 | 89.00 | 4,005.00 | 4,590.00 | 5,214.27 | 4.48 | 0.0 |
| 1/11-1/12/2015 | 2.70 | 60.00 | 2,700.00 | 4,266.00 | 3,566.75 | 4.71 | 0.0 |
| 1/14/2015 | 0.20 | 2.00 | 90.00 | 180.00 | 129.80 | 0.40 | 0.0 |
| 1/20/2015 | 0.90 | 22.00 | 990.00 | 814.50 | 1,172.66 | 3.00 | 0.0 |
| 1/21/2015 | 2.50 | 50.00 | 2,250.00 | 3,496.50 | 2,679.44 | 3.12 | 0.0 |
| 1/29/2015 | 1.30 | 56.00 | 2,520.00 | 3,125.25 | 3,262.32 | 3.94 | 0.0 |
| 2/1-2/2/2015 | 17.00 | 123.75 | 5,568.75 | 9,117.45 | 8,318.05 | 4.33 | 37.5 |
| 2/3-2/4/2015 | 1.60 | 69.50 | 3,127.50 | 5,703.30 | 4,697.49 | 3.63 | 20.0 |
| 2/13-2/14/2015 | 2.20 | 67.00 | 3,015.00 | 6,409.80 | 4,318.38 | 4.41 | 12.0 |
| 2/21/2015 | 0.50 | 17.00 | 765.00 | 635.40 | 999.48 | 1.42 | 0.0 |
| 2/26/2015 | 0.30 | 27.00 | 1,215.00 | 1,688.40 | 1,402.57 | 3.30 | 0.0 |
| 3/1/2015 | 0.40 | 21.50 | 967.50 | 1,407.60 | 752.34 | 3.30 | 0.0 |
| 3/3/2015 | 1.1 | 34.00 | 1530.00 | 2340.00 | 2565.00 | 3.07 | 12.0 |
| 11/21/15 | 8.2 | 29.50 | 1327.50 | 3788.10 | 2605.88 | 2.02 | 18.0 |
| 12/28/15 | 1.4 | 60.00 | 2700.00 | 4949.10 | 6588.48 | 3.36 | 12.0 |
| 1/10/16 | 4.3 | 60.50 | 2722.50 | 6394.05 | 4196.43 | 2.87 | 11.0 |
| 2/24/16 | 10.4 | 74.00 | 3330.00 | 7273.80 | 5443.94 | 5.03 | 24.0 |
| 3/1/16 | 7.2 | 98.50 | 4432.50 | 8986.50 | 6813.66 | 5.21 | 29.0 |

## Table D-3: Winter Maintenance Data for I-96 East Route (896EST-12) in Williamston Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 1/21/2013 | 1.50 | 12.0 | 540.00 | 1,080.00 | 696.98 | 0.91 | 0 |
| 1/22/2013 | 0.30 | 5.0 | 225.00 | 45.00 | 316.30 | 0.90 | 0 |
| 1/25/2013 | 1.85 | 20.0 | 900.00 | 1,800.00 | 1,121.80 | 1.00 | 0 |
| 1/27/2013 | 1.87 | 13.0 | 585.00 | 900.00 | 729.17 | 1.00 | 0 |
| 2/2/2013 | 1.28 | 13.0 | 585.00 | 540.00 | 884.52 | 0.55 | 0 |
| 2/3/2013 | 0.38 | 10.0 | 450.00 | 495.00 | 680.40 | 1.00 | 0 |
| 2/4/2013 | 2.03 | 13.5 | 607.50 | 540.00 | 805.02 | 0.92 | 0 |
| 2/7-2/8/2013 | 1.85 | 20.5 | 922.50 | 1,890.00 | 1,093.36 | 1.27 | 0 |
| 2/16/2013 | 1.44 | 7.5 | 337.50 | 180.00 | 420.68 | 0.60 | 0 |
| 3/15-3/16/2013 | 1.48 | 19.0 | 855.00 | 1,440.00 | 1,194.02 | 1.11 | 0 |
| 11/11/2013 | 0.50 | 4.0 | 180.00 | 180.00 | 256.36 | 0.28 | 0 |
| 12/11/2013 | 0.30 | 13.0 | 585.00 | 945.00 | 852.92 | 2.00 | 0 |
| 12/14/2013 | 6.70 | 34.0 | 1,530.00 | 3,960.00 | 2,170.36 | 1.87 | 0 |
| 12/15/2013 | 0.70 | 19.0 | 855.00 | 1,620.00 | 1,209.11 | 0.95 | 0 |
| 12/16-12/17/2013 | 1.34 | 37.0 | 1,665.00 | 2,205.00 | 2,170.93 | 1.37 | 0 |
| 12/25-12/26/2013 | 1.96 | 67.5 | 3,037.50 | 3,960.00 | 4,430.70 | 2.16 | 0 |
| 12/31/2013 | 1.22 | 26.5 | 1,192.50 | 2,250.00 | 1,649.16 | 1.76 | 0 |
| 1/1-1/2/2014 | 9.04 | 56.0 | 2,520.00 | 2,925.00 | 2,956.08 | 1.31 | 0 |
| 1/5-1/6/2014 | 10.20 | 82.0 | 3,690.00 | 1,170.00 | 5,341.48 | 2.78 | 0 |
| 1/24-1/25/2014 | 1.54 | 71.0 | 3,195.00 | 1,665.00 | 4,761.56 | 2.11 | 0 |
| 1/26/2014 | 1.94 | 67.0 | 2,430.00 | 3,015.00 | 3,530.76 | 2.46 | 0 |
| 1/27/2014 | 2.24 | 36.0 | 1,620.00 | 1,485.00 | 2,032.28 | 2.70 | 0 |
| 1/30/2014 | 0.60 | 31.0 | 1,395.00 | 1,395.00 | 1,940.22 | 2.33 | 0 |
| 2/1/2014 | 7.42 | 48.0 | 2,160.00 | 1,665.00 | 2,858.88 | 2.57 | 0 |
| 2/4-2/5/2014 | 6.45 | 64.0 | 2,880.00 | 2,160.00 | 12,874.04 | 3.18 | 0 |
| 2/8-2/9/2014 | 2.41 | 42.0 | 1,890.00 | 1,170.00 | 2,835.70 | 1.37 | 0 |
| 2/17-2/18/2014 | 2.57 | 48.5 | 2,182.50 | 2,205.00 | 3,178.00 | 2.93 | 0 |
| 2/20/2014 | 1.37 | 16.0 | 720.00 | 675.00 | 1,088.64 | 2.00 | 0 |
| 3/12/2014 | 7.06 | 48.0 | 2,160.00 | 3,105.00 | 3,143.16 | 2.00 | 0 |
| 4/14-4/15/2014 | 1.41 | 12.5 | 562.50 | 405.00 | 850.50 | 1.00 | 0 |
| 11/16/2014 | 0.60 | 9.0 | 405.00 | 630.00 | 612.36 | 1.00 | 0 |
| 11/19/2014 | 1.10 | 36.5 | 1,642.50 | 3,600.00 | 2,145.16 | 2.56 | 0 |
| 1/4/2015 | 0.60 | 36.0 | 1,620.00 | 2,295.00 | 1,889.28 | 2.00 | 0 |
| 1/11-1/12/2015 | 2.70 | 29.5 | 1,327.50 | 1,170.00 | 1,718.66 | 1.31 | 0 |
| 1/14/2015 | 0.20 | 3.0 | 135.00 | 0.00 | 168.27 | 1.00 | 0 |
| 1/20/2015 | 0.90 | 13.5 | 607.50 | 855.00 | 851.09 | 2.46 | 0 |
| 3/1/2015 | 0.40 | 6.0 | 270.00 | 90.00 | 408.24 | 1.00 | 0 |
| 1/6-1/7/2015 | 1.20 | 53.0 | 2,385.00 | 3,015.00 | 3,489.75 | 2.14 | 12 |
| 1/8-1/9/2015 | 1.80 | 70.0 | 3,150.00 | 3,555.00 | 3,884.76 | 2.54 | 6 |
| 1/21/2015 | 2.50 | 26.0 | 1,170.00 | 1,845.00 | 2,074.10 | 2.03 | 12 |
| 1/29/2015 | 1.30 | 48.0 | 2,160.00 | 1,980.00 | 2,711.85 | 3.22 | 3 |
| 2/1-2/2/2015 | 17.00 | 74.0 | 3,330.00 | 2,745.00 | 5,479.78 | 2.19 | 10 |
| 2/3-2/4/2015 | 2.60 | 85.0 | 3,825.00 | 2,587.50 | 5,378.80 | 4.59 | 24 |
| 2/13-2/14/2015 | 2.20 | 51.5 | 2,317.50 | 4,320.00 | 3,912.42 | 2.98 | 12 |
| 2/26/2015 | 0.30 | 24.0 | 1,080.00 | 2,610.00 | 1,658.96 | 2.67 | 8 |
| 3/3/2015 | 1.10 | 44.0 | 1,980.00 | 3,060.00 | 2,585.64 | 3.10 | 12 |

**Table D-4: Winter Maintenance Data for I-96 West Route (896WST-12) in Williamston Garage**

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 1/21/13 | 1.5 | 19.0 | 855.00 | 1710.00 | 1045.90 | 1.33 | 0.0 |
| 1/22/13 | 0.3 | 5.0 | 225.00 | 45.00 | 316.30 | 0.90 | 0.0 |
| 1/25/13 | 1.85 | 40.0 | 1800.00 | 3375.00 | 2417.40 | 2.08 | 0.0 |
| 1/27/13 | 1.87 | 25.5 | 1147.50 | 3285.00 | 1597.59 | 2.00 | 0.0 |
| 2/2/13 | 1.28 | 22.0 | 990.00 | 1665.00 | 1335.29 | 2.00 | 0.0 |
| 2/3/13 | 0.38 | 13.5 | 607.50 | 1080.00 | 757.21 | 1.24 | 0.0 |
| 2/4/13 | 2.03 | 22.0 | 990.00 | 1260.00 | 1435.30 | 1.35 | 0.0 |
| 2/7-2/8/2013 | 1.85 | 38.5 | 1732.50 | 4545.00 | 2369.90 | 1.83 | 0.0 |
| 2/16/13 | 1.44 | 12.0 | 540.00 | 360.00 | 714.90 | 1.25 | 0.0 |
| 3/15-3/16/2013 | 1.48 | 19.5 | 877.50 | 1800.00 | 1016.79 | 1.84 | 0.0 |
| 11/11/13 | 0.5 | 8.5 | 382.50 | 360.00 | 544.76 | 0.59 | 0.0 |
| 12/11/13 | 0.3 | 8.0 | 360.00 | 810.00 | 544.32 | 1.00 | 0.0 |
| 12/14/13 | 6.7 | 26.5 | 1192.50 | 4185.00 | 1755.26 | 1.15 | 0.0 |
| 12/15/13 | 0.7 | 25.0 | 1125.00 | 2295.00 | 1641.25 | 1.39 | 0.0 |
| 12/16-12/17/2013 | 1.34 | 47.0 | 2115.00 | 3105.00 | 3162.03 | 1.57 | 0.0 |
| 12/25-12/26/2013 | 1.96 | 42.5 | 1912.50 | 2205.00 | 2866.58 | 1.09 | 0.0 |
| 12/31/13 | 1.22 | 17.0 | 765.00 | 1755.00 | 1156.68 | 1.00 | 0.0 |
| 1/1/14-1/2/14 | 9.04 | 49.0 | 2205.00 | 3375.00 | 3296.28 | 1.40 | 0.0 |
| 1/5-1/6/2014 | 10.2 | 44.0 | 1980.00 | 1260.00 | 2674.20 | 1.00 | 0.0 |
| 1/24-1/25/2014 | 1.54 | 43.0 | 1935.00 | 1620.00 | 2888.04 | 1.21 | 0.0 |
| 1/26/14 | 1.94 | 23.0 | 1035.00 | 1260.00 | 1530.38 | 1.10 | 0.0 |
| 1/27/14 | 2.24 | 20.0 | 900.00 | 990.00 | 1114.56 | 1.00 | 0.0 |
| 1/30/14 | 0.6 | 20.0 | 900.00 | 630.00 | 1184.20 | 1.42 | 0.0 |
| 2/1/14 | 7.42 | 24.5 | 1102.50 | 1530.00 | 1666.98 | 1.01 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 28.0 | 1260.00 | 1215.00 | 1880.00 | 1.12 | 0.0 |
| 2/8-2/9/2014 | 2.41 | 31.0 | 1395.00 | 1080.00 | 2071.56 | 1.62 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 24.0 | 1080.00 | 1530.00 | 1620.40 | 1.06 | 0.0 |
| 2/20/14 | 1.37 | 8.0 | 360.00 | 315.00 | 519.20 | 1.00 | 0.0 |
| 3/12/14 | 7.06 | 36.0 | 1620.00 | 3690.00 | 2449.44 | 1.50 | 0.0 |
| 4/14-4/15/2014 | 1.41 | 11.5 | 517.50 | 585.00 | 782.46 | 1.00 | 0.0 |
| 11/16/14 | 0.6 | 7.0 | 315.00 | 180.00 | 476.28 | 1.67 | 0.0 |
| 11/19/14 | 1.1 | 22.0 | 990.00 | 1035.00 | 1496.88 | 0.71 | 0.0 |
| 1/4/15 | 0.6 | 23.5 | 1057.50 | 2205.00 | 2398.64 | 1.00 | 23.5 |
| 1/6-1/7/2015 | 1.2 | 35.0 | 1575.00 | 1080.00 | 2660.13 | 1.35 | 11.0 |
| 1/8-1/9/2015 | 1.8 | 34.0 | 1530.00 | 1485.00 | 2925.90 | 1.21 | 18.0 |
| 1/11-1/12/2015 | 2.7 | 21.5 | 967.50 | 1350.00 | 1784.32 | 2.24 | 10.5 |
| 1/14/15 | 0.2 | 3.0 | 135.00 | 0.00 | 204.12 | 1.00 | 0.0 |
| 1/20/15 | 0.9 | 11.0 | 495.00 | 720.00 | 850.53 | 2.04 | 3.0 |
| 1/21/15 | 2.5 | 23.0 | 1035.00 | 1350.00 | 1505.17 | 1.85 | 0.0 |
| 1/29/15 | 1.3 | 18.5 | 832.50 | 1125.00 | 1616.05 | 1.75 | 10.5 |
| 2/1-2/2/2015 | 17 | 38.0 | 1710.00 | 1080.00 | 2946.48 | 1.12 | 12.0 |
| 2/3-2/4/2015 | 2.6 | 25.5 | 1147.50 | 2295.00 | 2450.86 | 1.41 | 9.5 |
| 2/13-2/14/2015 | 2.2 | 33.0 | 1485.00 | 2070.00 | 2197.92 | 1.21 | 0.0 |
| 2/26/15 | 0.3 | 12.0 | 540.00 | 1125.00 | 952.60 | 1.00 | 4.0 |
| 3/1/15 | 0.4 | 6.0 | 270.00 | 90.00 | 612.42 | 0.50 | 6.0 |
| 3/3/15 | 1.1 | 4.5 | 202.50 | 450.00 | 1075.26 | 0.76 | 0.0 |

## Table D-5: Winter Maintenance Data for I-69 (I6900-19) Route in Grand Ledge Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/14/2013 | 6.70 | 25.0 | 1,125.00 | 2,250.00 | 1,826.47 | 1.46 | 6.0 |
| 12/15/2013 | 0.70 | 16.0 | 720.00 | 540.00 | 748.44 | 1.37 | 0.0 |
| 12/16-12/17/2013 | 1.34 | 33.0 | 1,485.00 | 3,690.00 | 2,463.32 | 1.47 | 8.0 |
| 12/25-12/26/2013 | 1.96 | 13.5 | 607.50 | 1,800.00 | 918.54 | 0.28 | 0.0 |
| 12/31/2013 | 1.22 | 12.5 | 562.50 | 1,485.00 | 1,184.26 | 0.52 | 7.0 |
| 1/1-1/2/2014 | 9.04 | 20.0 | 900.00 | 630.00 | 1,546.02 | 1.04 | 6.0 |
| 1/5-1/6/2014 | 10.20 | 16.0 | 720.00 | 315.00 | 665.16 | 0.39 | 6.0 |
| 1/24-1/25/2014 | 1.54 | 21.0 | 945.00 | 1,575.00 | 1,875.96 | 0.56 | 11.0 |
| 1/26/2014 | 1.94 | 4.0 | 180.00 | 540.00 | 224.36 | 0.17 | 0.0 |
| 1/27/2014 | 2.24 | 9.5 | 427.50 | 450.00 | 598.58 | 0.40 | 0.0 |
| 1/30/2014 | 0.60 | 8.5 | 382.50 | 675.00 | 721.51 | 0.65 | 5.5 |
| 2/1/2014 | 7.42 | 22.0 | 990.00 | 1,440.00 | 1,281.78 | 0.55 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 26.0 | 1,170.00 | 405.00 | 1,796.92 | 0.90 | 4.0 |
| 2/8-2/9/2014 | 2.41 | 18.0 | 810.00 | 1,125.00 | 1,224.72 | 0.43 | 0.0 |
| 2/14/2014 | 0.40 | 2.0 | 90.00 | 270.00 | 148.12 | 1.00 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 12.0 | 540.00 | 1,035.00 | 408.24 | 0.25 | 0.0 |
| 2/20/2014 | 1.37 | 18.5 | 832.50 | 900.00 | 1,156.86 | 2.42 | 0.0 |
| 3/12/2014 | 7.06 | 16.0 | 720.00 | 720.00 | 890.56 | 0.70 | 4.0 |
| 11/16/2014 | 0.60 | 4.0 | 180.00 | 720.00 | 259.60 | 0.27 | 0.0 |
| 11/19/2014 | 1.10 | 4.0 | 180.00 | 720.00 | 443.44 | 0.24 | 4.0 |
| 1/4/2015 | 0.60 | 42.0 | 1,890.00 | 4,050.00 | 3,114.60 | 1.75 | 6.0 |
| 1/6-1/7/2015 | 1.20 | 59.0 | 2,655.00 | 1,440.00 | 4,954.48 | 2.32 | 6.0 |
| 1/8-1/9/2015 | 1.80 | 96.0 | 4,320.00 | 5,535.00 | 6,519.88 | 3.50 | 12.0 |
| 1/11-1/12/2015 | 2.70 | 44.0 | 1,980.00 | 2,385.00 | 2,348.48 | 2.51 | 12.0 |
| 1/29/2015 | 1.30 | 59.0 | 2,655.00 | 4,140.00 | 4,517.70 | 2.45 | 16.0 |
| 2/1-2/2/2015 | 17.00 | 63.0 | 2,835.00 | 2,070.00 | 4,591.40 | 2.36 | 8.0 |
| 2/3-2/4/2015 | 2.60 | 70.0 | 3,150.00 | 2,970.00 | 5,124.50 | 3.59 | 14.0 |
| 2/13-2/14/2015 | 2.20 | 47.5 | 2,137.50 | 4,185.00 | 3,648.92 | 1.87 | 12.0 |
| 2/26/2015 | 0.30 | 11.0 | 495.00 | 630.00 | 712.59 | 1.60 | 0.0 |
| 3/1/2015 | 0.40 | 6.5 | 292.50 | 765.00 | 442.26 | 1.19 | 0.0 |
| 3/3/2015 | 1.10 | 53.5 | 2,407.50 | 4,275.00 | 3,806.03 | 3.55 | 12.0 |

**Table D-6: Winter Maintenance Data for EB I-496 (8E49600) Route in Grand Ledge Garage**

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/11/2013 | 6.70 | 45.0 | 2,025.00 | 8,010.00 | 2,758.56 | 3.51 | 6.0 |
| 12/14/2013 | 0.70 | 36.0 | 1,620.00 | 3,510.00 | 2,306.04 | 1.71 | 0.0 |
| 12/15/2013 | 1.34 | 32.0 | 1,440.00 | 2,295.00 | 2,100.52 | 1.91 | 0.0 |
| 12/16-12/17/2013 | 1.96 | 51.0 | 2,295.00 | 3,645.00 | 3,121.09 | 1.89 | 0.0 |
| 12/25-12/26/2013 | 1.22 | 39.0 | 1,755.00 | 3,015.00 | 2,223.40 | 1.85 | 0.0 |
| 12/31/2013 | 9.04 | 43.0 | 1,935.00 | 2,475.00 | 1,244.96 | 0.44 | 0.0 |
| 1/1-1/2/2014 | 10.20 | 77.0 | 3,465.00 | 135.00 | 4,771.80 | 2.10 | 6.0 |
| 1/5-1/6/2014 | 1.54 | 46.0 | 2,070.00 | 1,890.00 | 2,570.28 | 1.52 | 0.0 |
| 1/24-1/25/2014 | 1.94 | 43.5 | 1,957.50 | 2,790.00 | 2,243.29 | 2.61 | 0.0 |
| 1/26/2014 | 2.24 | 42.0 | 1,890.00 | 3,915.00 | 2,056.14 | 3.03 | 0.0 |
| 1/27/2014 | 0.60 | 12.0 | 540.00 | 135.00 | 447.12 | 0.60 | 0.0 |
| 1/30/2014 | 7.42 | 46.0 | 2,070.00 | 2,610.00 | 3,412.18 | 2.38 | 12.0 |
| 2/1/2014 | 6.45 | 62.0 | 2,790.00 | 2,295.00 | 3,420.16 | 2.31 | 6.0 |
| 2/4-2/5/2014 | 2.41 | 43.5 | 1,957.50 | 2,250.00 | 2,394.82 | 2.43 | 0.0 |
| 2/8-2/9/2014 | 0.40 | 16.0 | 720.00 | 495.00 | 759.36 | 2.17 | 0.0 |
| 2/14/2014 | 2.57 | 49.0 | 2,205.00 | 1,890.00 | 2,731.76 | 2.42 | 4.0 |
| 2/17-2/18/2014 | 1.37 | 20.0 | 900.00 | 495.00 | 1,008.84 | 2.00 | 0.0 |
| 2/20/2014 | 7.06 | 42.0 | 1,890.00 | 2,250.00 | 2,358.04 | 1.97 | 6.0 |
| 3/12/2014 | 0.60 | 12.5 | 562.50 | 585.00 | 781.94 | 1.24 | 0.0 |
| 11/16/2014 | 1.10 | 43.5 | 1,957.50 | 3,645.00 | 2,500.52 | 3.16 | 0.0 |
| 11/19/2014 | 0.60 | 38.0 | 1,710.00 | 3,375.00 | 2,322.62 | 1.57 | 0.0 |
| 1/4/2015 | 1.20 | 73.0 | 3,285.00 | 2,385.00 | 2,974.15 | 2.21 | 4.0 |
| 1/6-1/7/2015 | 1.80 | 64.5 | 2,902.50 | 3,015.00 | 3,550.00 | 1.72 | 0.0 |
| 1/8-1/9/2015 | 2.70 | 22.0 | 1,260.00 | 1,260.00 | 746.80 | 3.00 | 0.0 |
| 1/11-1/12/2015 | 0.20 | 4.0 | 180.00 | 247.50 | 265.88 | 0.34 | 0.0 |
| 1/14/2015 | 0.90 | 27.0 | 1,215.00 | 1,620.00 | 1,636.45 | 2.49 | 4.0 |
| 1/20/2015 | 2.50 | 32.0 | 1,440.00 | 2,790.00 | 1,691.44 | 3.52 | 4.0 |
| 1/21/2015 | 1.30 | 58.5 | 2,632.50 | 4,230.00 | 3,347.58 | 2.30 | 7.5 |
| 1/29/2015 | 17.00 | 80.5 | 3,622.50 | 2,835.00 | 5,048.85 | 2.95 | 14.0 |
| 2/1-2/2/2015 | 2.60 | 72.0 | 3,240.00 | 3,375.00 | 3,816.05 | 3.11 | 4.0 |
| 2/3-2/4/2015 | 2.20 | 44.0 | 1,980.00 | 3,510.00 | 2,334.00 | 2.11 | 0.0 |
| 2/13-2/14/2015 | 0.30 | 16.0 | 720.00 | 1,890.00 | 771.92 | 2.00 | 0.0 |
| 2/26/2015 | 0.40 | 9.0 | 405.00 | 1,350.00 | 561.42 | 1.50 | 0.0 |
| 3/1/2015 | 1.10 | 43.0 | 1,935.00 | 4,815.00 | 2,673.22 | 2.71 | 5.0 |
| 3/3/2015 | 6.70 | 45.0 | 2,025.00 | 8,010.00 | 2,758.56 | 3.51 | 6.0 |

## Table D-7: Winter Maintenance Data for WB I-496 (8W49600) Route in Grand Ledge Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/11/2013 | 0.30 | 15.0 | 675.00 | 1,350.00 | 774.36 | 1.87 | 0.0 |
| 12/14/2013 | 6.70 | 49.0 | 2,205.00 | 8,010.00 | 4,040.06 | 3.31 | 5.0 |
| 12/15/2013 | 0.70 | 50.0 | 2,250.00 | 4,590.00 | 3,372.90 | 3.15 | 12.0 |
| 12/16-12/17/2013 | 1.34 | 46.0 | 2,070.00 | 4,815.00 | 2,827.08 | 2.48 | 0.0 |
| 12/25-12/26/2013 | 1.96 | 55.0 | 2,475.00 | 3,645.00 | 3,328.14 | 2.35 | 0.0 |
| 12/31/2013 | 1.22 | 31.0 | 1,395.00 | 2,295.00 | 1,979.22 | 2.01 | 0.0 |
| 1/1-1/2/2014 | 9.04 | 74.0 | 3,330.00 | 5,625.00 | 4,344.50 | 1.92 | 0.0 |
| 1/5-1/6/2014 | 10.20 | 81.0 | 3,645.00 | 0.00 | 4,438.08 | 2.30 | 6.0 |
| 1/24-1/25/2014 | 1.54 | 84.0 | 3,780.00 | 4,545.00 | 5,247.46 | 2.90 | 8.0 |
| 1/26/2014 | 1.94 | 25.0 | 1,125.00 | 1,260.00 | 1,054.62 | 1.83 | 0.0 |
| 1/27/2014 | 2.24 | 44.0 | 1,980.00 | 3,105.00 | 3,014.92 | 2.71 | 10.0 |
| 1/30/2014 | 0.60 | 29.0 | 1,305.00 | 1,035.00 | 1,935.48 | 2.70 | 0.0 |
| 2/1/2014 | 7.42 | 62.0 | 2,790.00 | 3,150.00 | 3,733.95 | 2.55 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 55.0 | 2,475.00 | 1,305.00 | 3,012.52 | 2.40 | 6.0 |
| 2/8-2/9/2014 | 2.41 | 42.0 | 1,890.00 | 1,980.00 | 2,746.99 | 2.43 | 0.0 |
| 2/14/2014 | 0.40 | 8.0 | 360.00 | 360.00 | 472.62 | 1.03 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 44.5 | 2,002.50 | 1,935.00 | 3,442.01 | 2.32 | 4.0 |
| 2/20/2014 | 1.37 | 11.0 | 495.00 | 765.00 | 603.34 | 1.58 | 0.0 |
| 3/12/2014 | 7.06 | 46.0 | 2,070.00 | 2,385.00 | 2,884.12 | 1.96 | 6.0 |
| 11/16/2014 | 0.60 | 13.5 | 607.50 | 540.00 | 844.31 | 1.43 | 0.0 |
| 11/19/2014 | 1.10 | 31.0 | 1,395.00 | 2,610.00 | 1,788.26 | 1.87 | 0.0 |
| 1/4/2015 | 0.60 | 45.0 | 2,025.00 | 5,220.00 | 3,040.14 | 1.87 | 9.0 |
| 1/6-1/7/2015 | 1.20 | 85.0 | 3,825.00 | 3,780.00 | 4,605.27 | 3.44 | 4.0 |
| 1/8-1/9/2015 | 1.80 | 50.0 | 2,250.00 | 1,980.00 | 3,358.04 | 1.30 | 0.0 |
| 1/11-1/12/2015 | 2.70 | 31.0 | 1,395.00 | 1,575.00 | 1,996.60 | 1.30 | 4.0 |
| 1/14/2015 | 0.20 | 12.0 | 540.00 | 405.00 | 803.92 | 0.99 | 0.0 |
| 1/20/2015 | 0.90 | 28.0 | 1,260.00 | 1,125.00 | 1,268.55 | 3.05 | 4.0 |
| 1/21/2015 | 2.50 | 40.0 | 1,800.00 | 4,050.00 | 2,036.19 | 2.26 | 4.0 |
| 1/29/2015 | 1.30 | 58.0 | 2,610.00 | 3,645.00 | 3,780.56 | 2.83 | 4.0 |
| 2/1-2/2/2015 | 17.00 | 93.0 | 4,185.00 | 3,015.00 | 5,506.48 | 2.79 | 6.0 |
| 2/3-2/4/2015 | 2.60 | 47.5 | 2,137.50 | 2,970.00 | 3,023.96 | 2.41 | 4.0 |
| 2/13-2/14/2015 | 2.20 | 35.0 | 1,575.00 | 3,735.00 | 2,664.40 | 1.30 | 9.0 |
| 2/21/2015 | 0.50 | 8.0 | 360.00 | 0.00 | 519.20 | 1.00 | 0.0 |
| 2/26/2015 | 0.30 | 15.0 | 675.00 | 810.00 | 774.36 | 1.87 | 0.0 |
| 3/1/2015 | 0.40 | 8.5 | 382.50 | 900.00 | 551.91 | 1.06 | 0.0 |
| 3/3/2015 | 1.10 | 29.0 | 1,305.00 | 3,105.00 | 2,192.40 | 1.21 | 6.0 |

## Table D-8: Winter Maintenance Data for M-155 (OM115) Route in Reed City Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/11/2013 | 0.30 | 30.00 | 1,350.00 | 0.00 | 1,853.30 | 1.74 | 0.0 |
| 12/14/2013 | 6.70 | 62.50 | 2,812.50 | 900.00 | 3,505.63 | 1.22 | 0.0 |
| 12/15/2013 | 0.70 | 36.00 | 1,620.00 | 810.00 | 2,019.24 | 0.87 | 0.0 |
| 12/16-12/17/2013 | 1.34 | 56.00 | 2,520.00 | 1,170.00 | 3,141.04 | 0.78 | 0.0 |
| 12/25-12/26/2013 | 1.96 | 25.00 | 1,125.00 | 630.00 | 1,402.25 | 0.61 | 0.0 |
| 12/31/2013 | 1.22 | 8.00 | 360.00 | 0.00 | 448.72 | 0.33 | 0.0 |
| 1/1-1/2/2014 | 9.04 | 28.00 | 1,260.00 | 855.00 | 2,030.32 | 3.00 | 10.0 |
| 1/24-1/25/2014 | 1.54 | 36.00 | 1,620.00 | 180.00 | 2,019.24 | 1.00 | 0.0 |
| 1/26/2014 | 1.94 | 12.00 | 540.00 | 0.00 | 673.08 | 1.00 | 0.0 |
| 1/27/2014 | 2.24 | 9.00 | 405.00 | 90.00 | 504.81 | 1.38 | 0.0 |
| 1/30/2014 | 0.60 | 12.00 | 540.00 | 270.00 | 673.08 | 1.00 | 0.0 |
| 2/1/2014 | 7.42 | 21.00 | 945.00 | 270.00 | 1,177.89 | 1.61 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 12.00 | 540.00 | 0.00 | 224.36 | 1.50 | 0.0 |
| 2/8-2/9/2014 | 2.41 | 16.00 | 720.00 | 945.00 | 897.44 | 1.44 | 0.0 |
| 2/14/2014 | 0.40 | 23.00 | 1,035.00 | 765.00 | 1,290.07 | 1.80 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 47.00 | 2,115.00 | 1,710.00 | 2,636.23 | 0.95 | 0.0 |
| 2/20/2014 | 1.37 | 28.00 | 1,260.00 | 2,115.00 | 1,570.52 | 0.90 | 0.0 |
| 11/16/14 | 0.60 | 6.00 | 270.00 | 225.00 | 336.54 | 1.50 | 0.0 |
| 11/19/2014 | 1.10 | 18.00 | 1,710.00 | 990.00 | 2,131.42 | 2.23 | 0.0 |
| 1/4/2015 | 0.60 | 28.00 | 1,260.00 | 495.00 | 1,570.52 | 0.89 | 0.0 |
| 1/6-1/7/2015 | 1.20 | 64.00 | 2,880.00 | 0.00 | 4,739.26 | 1.35 | 25.0 |
| 1/8-1/9/2015 | 1.80 | 33.00 | 1,485.00 | 0.00 | 2,448.71 | 1.06 | 13.0 |
| 1/11-1/12/2015 | 2.70 | 22.00 | 990.00 | 270.00 | 1,877.70 | 1.11 | 14.0 |
| 1/14/2015 | 0.20 | 6.00 | 270.00 | 0.00 | 612.42 | 1.00 | 6.0 |
| 1/20/2015 | 0.90 | 8.00 | 360.00 | 405.00 | 448.72 | 0.50 | 0.0 |
| 1/21/2015 | 2.50 | 8.00 | 360.00 | 360.00 | 448.72 | 0.31 | 0.0 |
| 1/29/2015 | 1.30 | 14.00 | 630.00 | 765.00 | 1,061.14 | 0.89 | 6.0 |
| 2/1-2/2/2015 | 17.00 | 32.00 | 1,440.00 | 90.00 | 3,266.24 | 0.65 | 32.0 |
| 2/3-2/4/2015 | 2.60 | 35.00 | 1,575.00 | 225.00 | 3,572.45 | 0.59 | 35.0 |
| 2/13-2/14/2015 | 2.20 | 29.00 | 1,305.00 | 0.00 | 2,960.03 | 0.69 | 29.0 |
| 2/21/2015 | 0.50 | 5.00 | 225.00 | 90.00 | 280.45 | 1.50 | 0.0 |
| 2/26/2015 | 0.30 | 1.00 | 45.00 | 0.00 | 102.07 | 1.00 | 1.0 |
| 3/3/2015 | 1.10 | 40.65 | 1,827.90 | 1,485.00 | 3,778.24 | 1.20 | 0.0 |

## Table D-9: Winter Maintenance Data for M-66 (OM66) Route in Reed City Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/11/2013 | 0.30 | 15 | 675.00 | 0.00 | 841.35 | 1.51 | 0.0 |
| 12/14/2013 | 6.70 | 34 | 1,530.00 | 0.00 | 1,907.06 | 0.58 | 0.0 |
| 12/15/2013 | 0.70 | 35 | 1,575.00 | 315.00 | 1,963.15 | 0.73 | 0.0 |
| 12/16-12/17/2013 | 1.34 | 92 | 4,140.00 | 945.00 | 5,160.28 | 1.29 | 0.0 |
| 12/25-12/26/2013 | 1.96 | 12 | 540.00 | 270.00 | 673.08 | 0.45 | 0.0 |
| 12/31/2013 | 1.22 | 3 | 135.00 | 0.00 | 168.27 | 0.12 | 0.0 |
| 1/24-1/25/2014 | 1.54 | 16 | 720.00 | 180.00 | 897.44 | 0.35 | 0.0 |
| 1/26/2014 | 1.94 | 8 | 360.00 | 0.00 | 448.72 | 0.27 | 0.0 |
| 1/27/2014 | 2.24 | 8 | 360.00 | 0.00 | 448.72 | 0.29 | 0.0 |
| 1/30/2014 | 0.60 | 8 | 360.00 | 0.00 | 448.72 | 0.50 | 0.0 |
| 2/1/2014 | 7.42 | 8 | 360.00 | 90.00 | 448.72 | 0.50 | 0.0 |
| 2/4-2/5/2014 | 6.45 | 10 | 450.00 | 0.00 | 341.20 | 1.00 | 0.0 |
| 2/14/2014 | 0.40 | 3 | 135.00 | 180.00 | 168.27 | 0.20 | 0.0 |
| 2/17-2/18/2014 | 2.57 | 23 | 1,035.00 | 720.00 | 1,290.07 | 1.20 | 0.0 |
| 2/20/2014 | 1.37 | 15 | 675.00 | 495.00 | 841.35 | 0.80 | 0.0 |
| 11/16/2014 | 0.60 | 8 | 360.00 | 180.00 | 224.36 | 0.50 | 0.0 |
| 11/19/2014 | 1.10 | 5 | 225.00 | 0.00 | 280.45 | 0.23 | 0.0 |
| 1/4/2015 | 0.60 | 21 | 945.00 | 22.50 | 1,177.89 | 0.82 | 0.0 |
| 1/6-1/7/2015 | 1.20 | 42 | 1,890.00 | 0.00 | 2,723.62 | 0.86 | 8.0 |
| 1/8-1/9/2015 | 1.80 | 28 | 1,260.00 | 0.00 | 2,306.20 | 1.07 | 16.0 |
| 1/11-1/12/2015 | 2.70 | 20 | 900.00 | 225.00 | 1,305.72 | 0.89 | 4.0 |
| 1/14/2015 | 0.20 | 6 | 270.00 | 0.00 | 336.54 | 1.00 | 0.0 |
| 1/20/2015 | 0.90 | 24 | 1,080.00 | 540.00 | 1,714.00 | 1.67 | 8.0 |
| 1/21/2015 | 2.50 | 10 | 450.00 | 720.00 | 560.90 | 0.90 | 0.0 |
| 1/29/2015 | 1.30 | 16 | 720.00 | 360.00 | 1,265.28 | 0.61 | 8.0 |
| 2/1-2/2/2015 | 17.00 | 17 | 765.00 | 90.00 | 1,735.19 | 0.35 | 17.0 |
| 2/3-2/4/2015 | 2.60 | 24 | 1,080.00 | 270.00 | 2,449.68 | 0.41 | 24.0 |
| 2/13-2/14/2015 | 2.20 | 13 | 585.00 | 0.00 | 1,326.91 | 0.31 | 13.0 |
| 2/21/2015 | 0.50 | 5 | 225.00 | 45.00 | 510.35 | 0.50 | 5.0 |
| 3/3/2015 | 1.10 | 28 | 1,260.00 | 1,575.00 | 2,490.12 | 0.38 | 0.0 |

## Table D-10: Winter Maintenance Data for I-69 (NI69 and SI69) Route in Charlotte Garage

| Date | Snow Amount (in) | Total Labor Hours | Labor Cost ($) | Salt Cost ($) | Equipment Cost ($) | No. Total Plows | Tow Plow Hours |
|---|---|---|---|---|---|---|---|
| 12/25-12/26 2013 | 2.4 | 56.0 | 2,520.00 | 4,275.00 | 3,216.56 | 4.00 | 0.0 |
| 12/31/2013-1/2/2014 | 3.8 | 107.5 | 4,837.50 | 4,905.00 | 6,004.61 | 5.58 | 0.0 |
| 1/16-1/17/2014 | 1.0 | 83.0 | 3,735.00 | 5,445.00 | 4,259.58 | 5.00 | 0.0 |
| 2/17 -2/18/2014 | 2.7 | 51.0 | 2,295.00 | 4,410.00 | 2,626.05 | 4.56 | 0.0 |
| 3/12/2014 | 6.3 | 108.5 | 4,882.50 | 5,355.00 | 5,942.56 | 5.00 | 0.0 |
| 11/19-11/21/2014 | 4.2 | 96.5 | 4,342.50 | 5,490.00 | 4,612.19 | 5.00 | 0.0 |
| 1/8-1/9 2015 | 2.4 | 122.0 | 5,490.00 | 4,545.00 | 8,000.18 | 6.00 | 0.0 |
| 1/21/2015 | 2.2 | 50.0 | 2,250.00 | 3,735.00 | 3,331.50 | 4.00 | 0.0 |
| 2/1-2/2 2015 | 9.7 | 117.5 | 5,287.50 | 6,120.00 | 7,700.35 | 5.48 | 0.0 |
| 3/3/2015 | 1.5 | 56.0 | 2,520.00 | 3,465.00 | 3,473.92 | 6.00 | 0.0 |
| 11/21/2015 | 8.2 | 48.5 | 2,182.50 | 3,375.00 | 3,798.54 | 1.06 | 18.0 |
| 12/28/2015 | 1.4 | 86.0 | 3,870.00 | 8,775.00 | 5,799.80 | 5.00 | 6.3 |
| 1/10- 1/12/2016 | 4.3 | 46.0 | 2,070.00 | 5,572.67 | 3,629.80 | 3.00 | 6.0 |
| 2/24-2/25/2016 | 10.4 | 124.0 | 5,580.00 | 8,405.00 | 9,744.76 | 2.83 | 32.0 |
| 3/1-3/2/2016 | 7.2 | 62.0 | 2,800.00 | 6,626.00 | 4,516.54 | 4.00 | 14.8 |

**APPENDIX E**

**WINTER TRAVEL SPEED DATA ANALYSIS**

# APPENDIX E

## WINTER TRAVEL SPEED DATA ANALYSIS

### E.1 Travel Time and Delay Analysis

As discussed in Section 5.4.2, RITIS data were used to evaluate travel time and delay performance measures. Vehicle speed, a component of the performance measures, is monitored during a winter storm event. During the event, average vehicle speeds typically decrease. Once the storm ends, average vehicle speeds recover. This recovery, or regain time, is defined as the average speed within 5 mph of the historical average speed for a least 1 hour after the end of the event (Figure E.1).

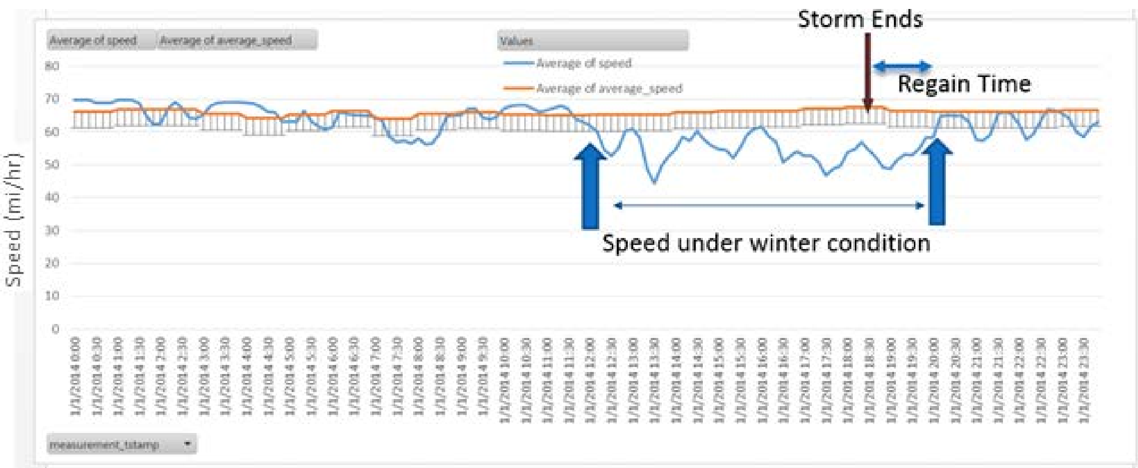


**Figure E.1: Analysis Process of Vehicle Speed Data**

#### E.1.1 Summary of Data

At the time of this study, RITIS data are only available for freeways. Therefore, I-96 and US-23 in Livingston County, Michigan, were selected for speed data collection. Supplemental information about the selected routes is shown below:

- I-96 is a major east-west route connecting Toledo, Ohio; Detroit; Lansing; and Grand Rapids. The portion of I-96 in Livingston County consists of 3 lanes in each direction.

- US-23 is a major north-south freeway connecting Toledo, Ohio, to parts of northern Michigan, and travels through Ann Arbor, Flint, and Saginaw. The portion of US-23 in Livingston County consists of 2 lanes in each direction.

Figure E.2 shows the selected routes for which speed data were obtained. Speed probe data for 22 winter storms from the 2012-2015 winter season were analyzed along these two routes.

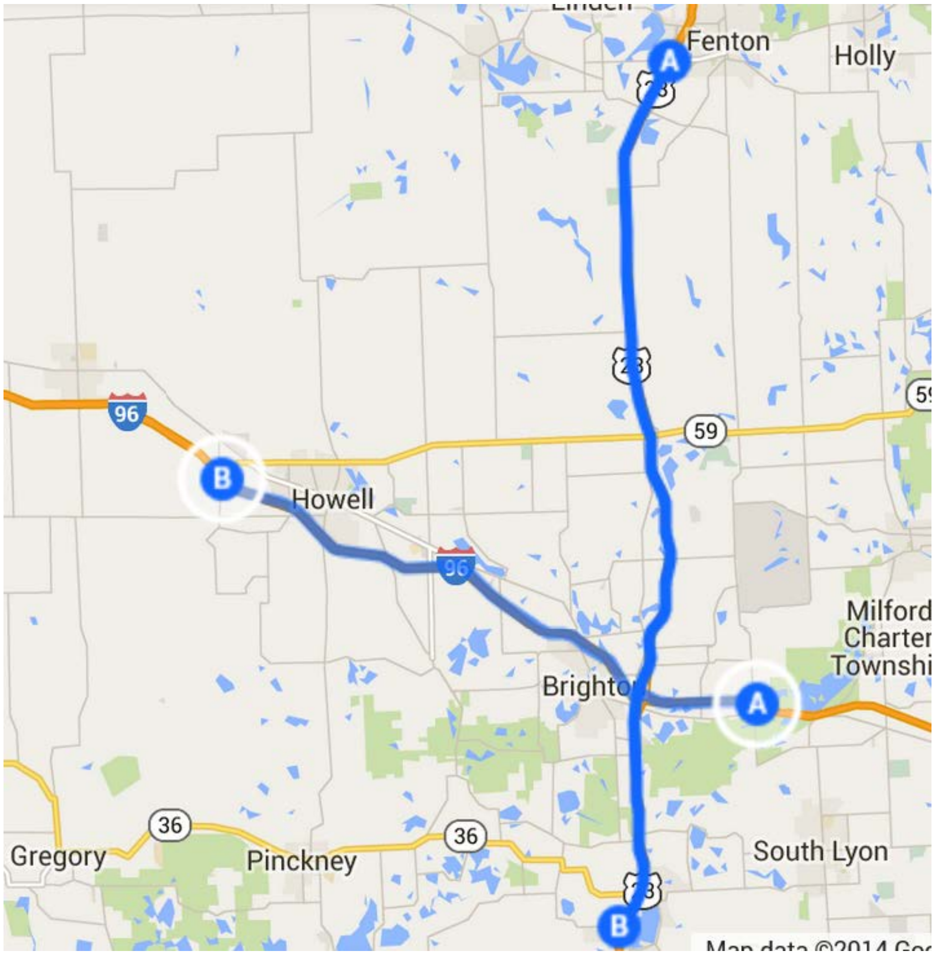


**Figure E.2: Selected *Speed Data* Routes**

Details of the speed data obtained during a winter storm on 12/21/2012 are given below in Figure E.3. Along eastbound I-96 (EB I-96), the storm started at 1:54 AM and lasted until 11:14 AM. The storm duration was 9 hours and 20 minutes and snow accumulation was estimated at approximately 1 inch. The average traffic speed fluctuated around 67 mph until 7:00 AM and then significantly dropped to 48.5 mph at 10:40 AM. The average speed, within 5 mph, finally recovered at 2:20 PM. Based on the speed data, the average normal speed (or average historical speed) was 65.44 mph and the average speed during the storm was 58.7 mph, a 9.9% reduction in speed. The lowest recorded average speed was 48.47 mph, a 25.94% reduction from the average normal speed. The speed recovery time was estimated at 3 hours and 6 minutes.

## E.2 Winter Travel Speed-Based Performance Measures for Winter Operations

A new performance measure was developed to quantify the effect of speed reduction during a winter storm. The new measure, *AREA*, is the area between the 5-mph buffer zone from the pre-winter event average historical speed and the average speed during the winter event between the times $t_1$ and $t_4$. The time $t_1$ represents the time when the speed drops below the buffer zone from the average historical speed and $t_4$ represents the time when speed has regained back to the buffer zone as shown in the figure below.

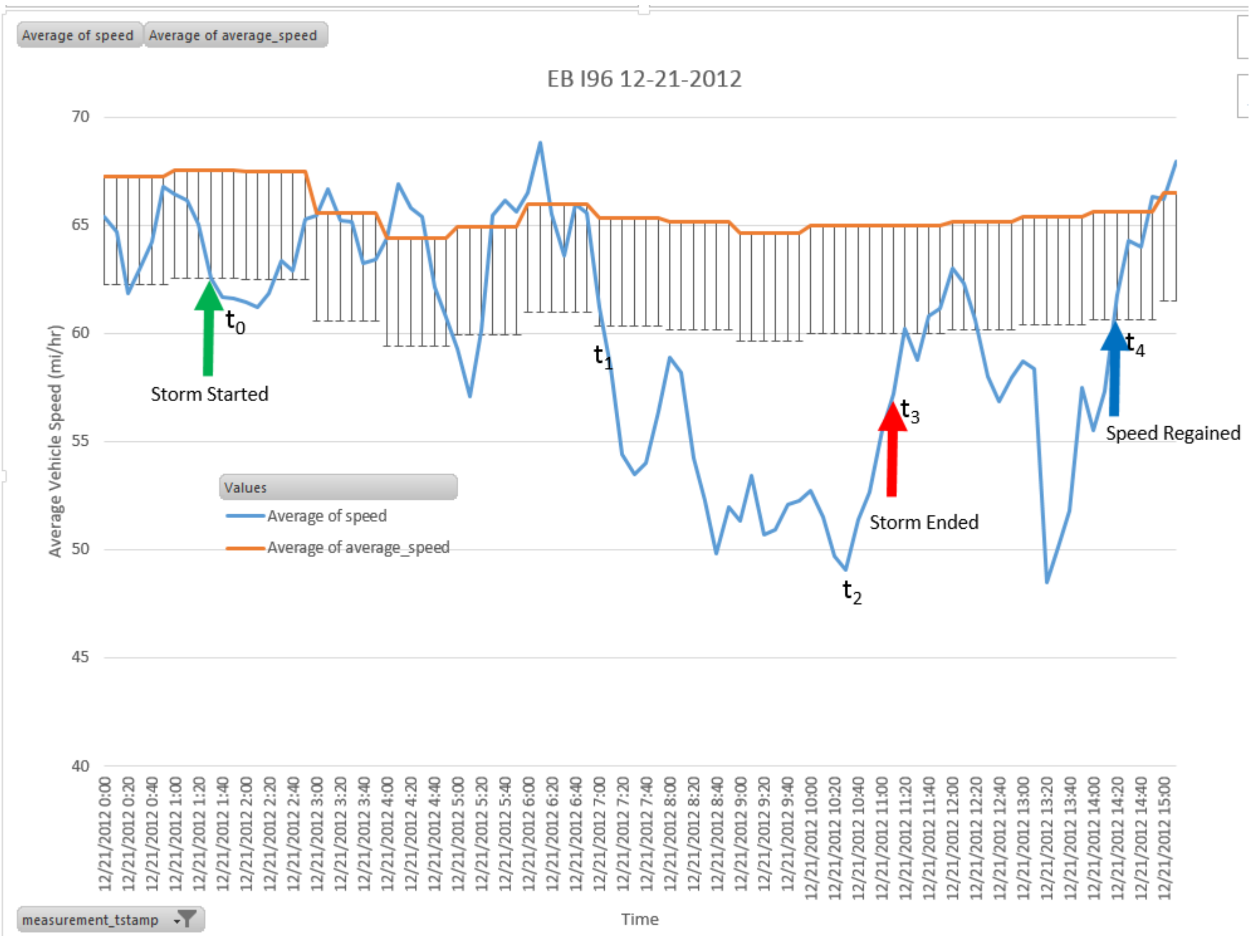


**Figure E.3: Speed Data for EB I-96 on December 21, 2012**

AREA was calculated using numerical integration of speed data during t1 and t4 for every storm from 2012 to 2015 for each direction of I-96 and US-23. The AREA parameter provides a measure of both speed reduction as well as speed recovery time. The following parameters were calculated from the plots developed from the speed data for each winter storm.

- Average Normal Speed (ANS) – The average historical speed (denoted as the orange line in Figure E.3) from $t_0$ and $t_4$ (or $t_0$ and $t_3$ if the speed is regained prior to the storm end).

- Average Winter Speed (AWS) – The average winter speed (denoted as the blue line in Figure E.3) from $t_0$ and $t_4$ (or $t_0$ and $t_3$ if the speed regained prior to storm end time).

- Minimum Winter Speed (MWS) – The minimum speed during the winter storm (speed at time $t_2$).

- AREA – The total area of the winter speed data plot between the buffer zone and the winter speed between times $t_1$ and $t_4$.

- +AREA – The positive area of the winter speed data plot between the buffer zone and winter speed between times $t_1$ and $t_4$.

AREA can be positive or negative during a winter event. If the winter speed exceeds the buffer zone before the end of the winter storm, AREA becomes negative. The total AREA between times $t_1$ and $t_4$ represents the numerical sum of all negative and positive areas. It should be noted that negative AREA represents good speed performance during the winter event (motorists are traveling at higher speeds) due to good winter maintenance activities or other reasons. Lower AREA values represent good winter performance and higher AREA values represents undesirable winter performance based on motorist traveling speed.

Figures E.4 to E.7 show the calculated AWS, MWS, AREA, and +AREA values plotted against total snow amounts of each winter storm for years 2012 - 2015. Although the snow amount was selected as the independent variable in these relationships, other variables such as snow rate, winter severity index, etc. can also be used to represent different snow events. The relationships were developed for EB I-96, WB I-96, NB US-23, and SB US-23 separately to investigate whether there were any differences in different types of roads.

The variation of AWS relative to snow amount for each route is shown below.

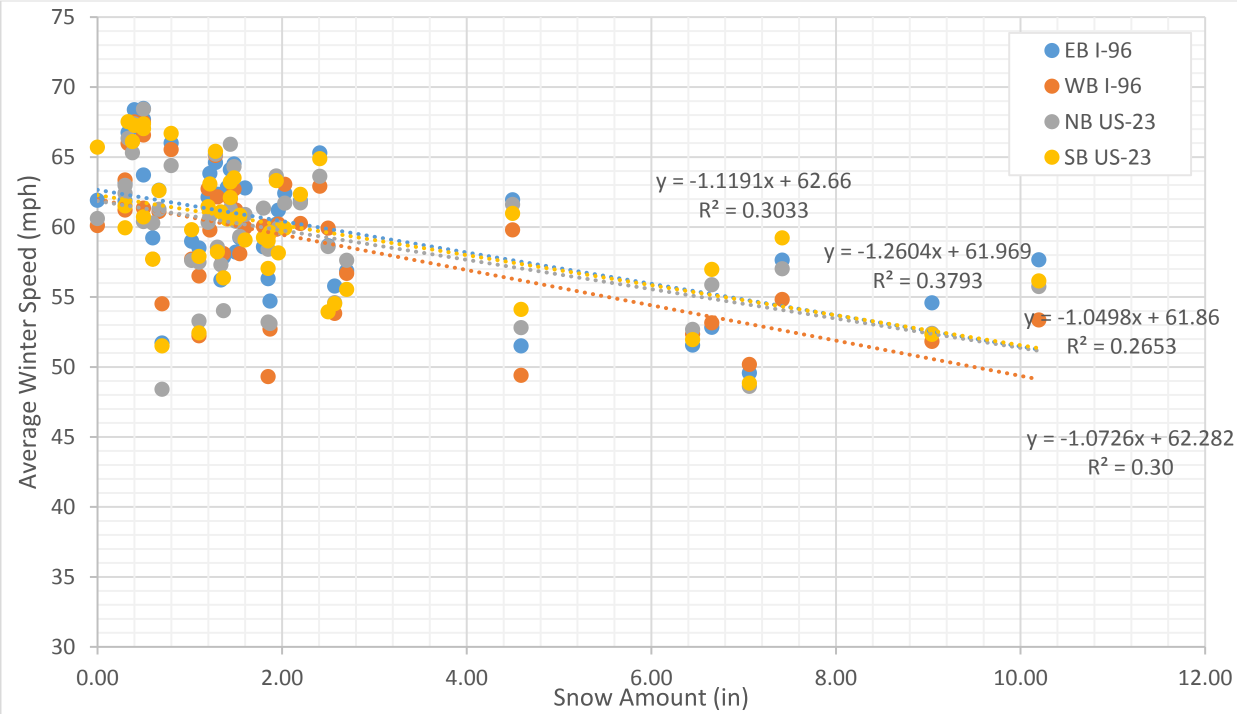


**Figure E.4: Average Winter Speed (AWS) Variation with Snow Amounts**

Marginally good relationships ($R^2$ values ranging from 0.27 to 0.38) were obtained between AWS and snow amount for both directions of I-96 and US-23.

**Table E.1: Relationships for AWS and Snow Amount**

| Direction/Roadway | Relationship | Goodness of Fit ($R^2$) |
|---|---|---|
| EB I-96 | $AWS = 62.66 - 1.12 \times (Snow\ Amount)$ | 0.30 |
| WB I-96 | $AWS = 61.97 - 1.26 \times (Snow\ Amount)$ | 0.38 |
| NB US-23 | $AWS = 61.86 - 1.05 \times (Snow\ Amount)$ | 0.27 |
| SB US-23 | $AWS = 62.28 - 1.07 \times (Snow\ Amount)$ | 0.30 |

The variation of MWS relative to snow amount for each route is shown below.

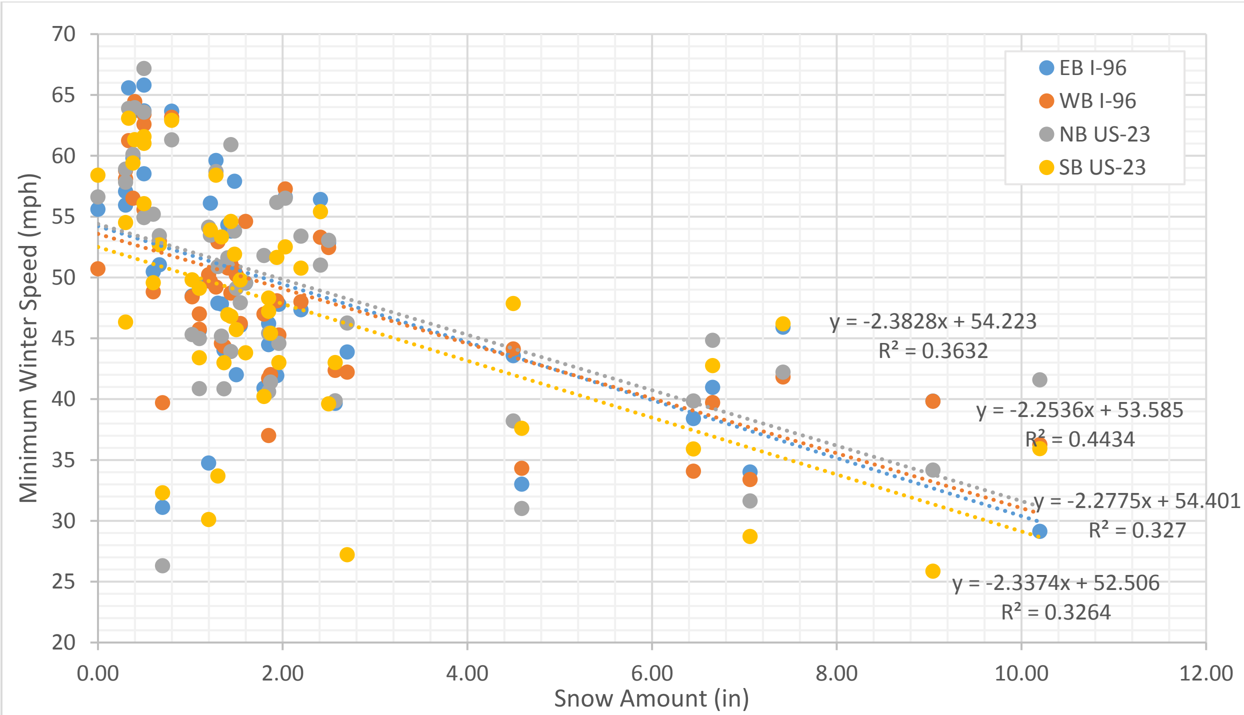


**Figure E.5: Minimum Winter Speed (MWS) Variation with Snow Amount**

Again, marginally good relationships ($R^2$ values ranging from 0.33 to 0.44) were obtained between MWS and snow amount for both directions of I-96 and US-23.

**Table E.2: Relationships for MWS and Snow Amount**

| Direction/Roadway | Relationship | Goodness of Fit ($R^2$) |
|---|---|---|
| EB I-96 | $MWS = 54.22 - 2.38 \times (Snow\ Amount)$ | 0.36 |
| WB I-96 | $MWS = 53.59 - 2.25 \times (Snow\ Amount)$ | 0.44 |
| NB US-23 | $MWS = 54.40 - 2.28 \times (Snow\ Amount)$ | 0.33 |
| SB US-23 | $MWS = 52.51 - 2.34 \times (Snow\ Amount)$ | 0.33 |

The variation of the AREA parameter relative to snow amount for each route is shown below.

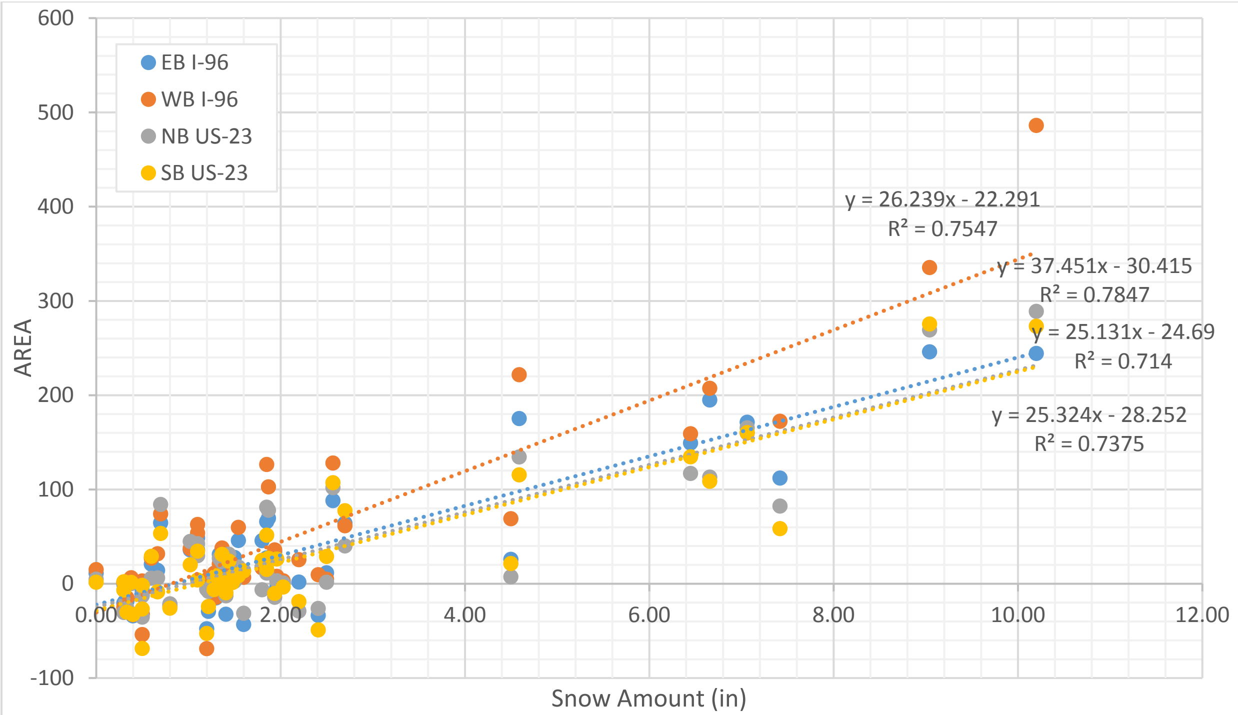


**Figure E.6: AREA Parameter Variation with Snow Amount**

Fairly good relationships ($R^2$ values ranging from 0.71 to 0.78) between the AREA parameter and snow amount were obtained for both directions of I-96 and US-23.

**Table E.3: Relationships for AREA Parameter and Snow Amount**

| Direction/Roadway | Relationship | Goodness of Fit ($R^2$) |
|---|---|---|
| EB I-96 | $AREA = 26.24 \times (Snow\ Amount) - 22.29$ | 0.75 |
| WB I-96 | $AREA = 37.45 \times (Snow\ Amount) - 30.42$ | 0.78 |
| NB US-23 | $AREA = 25.13 \times (Snow\ Amount) - 24.69$ | 0.71 |
| SB US-23 | $AREA = 25.32 \times (Snow\ Amount) - 28.25$ | 0.74 |

The variation of the +AREA parameter relative to snow amount for each route is shown below.

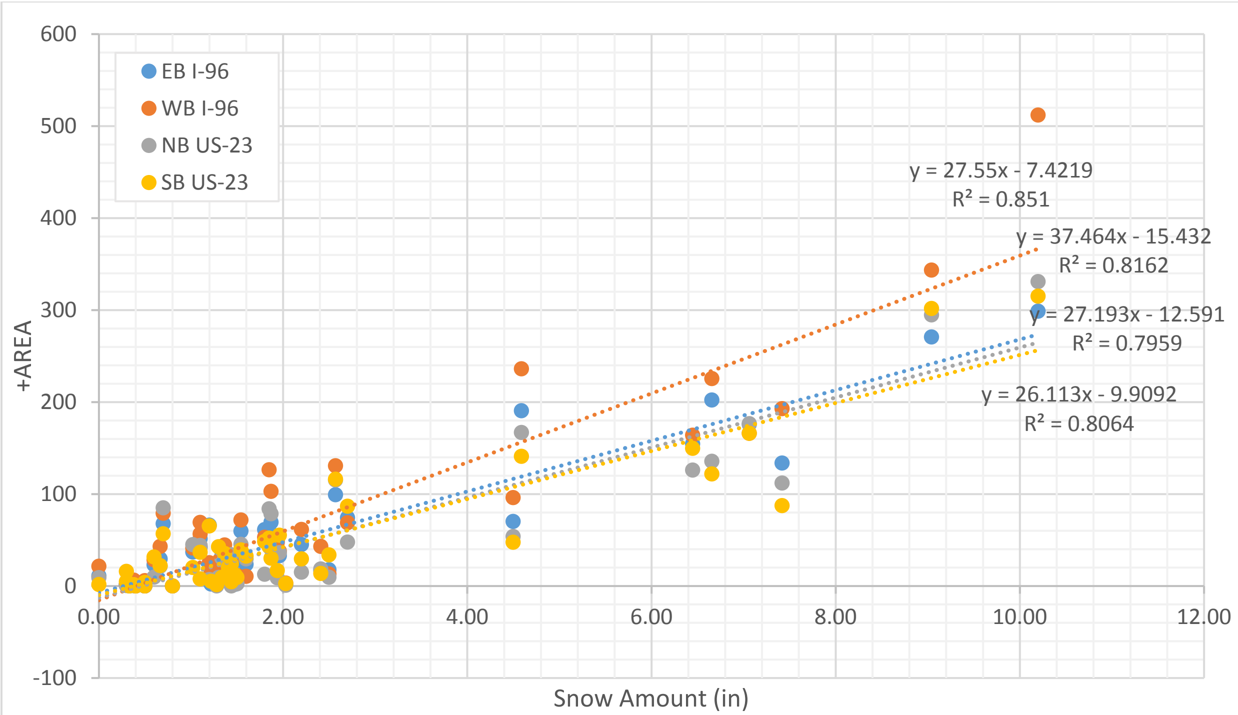


**Figure E.7: +AREA Parameter Variation with Snow Amount**

Very good relationships ($R^2$ values ranging from 0.80 to 0.85) between the +AREA parameter and snow amount were obtained for both directions of I-96 and US-23.

**Table E.4: Relationships for +AREA Parameter and Snow Amount**

| Direction/Roadway | Relationship | Goodness of Fit ($R^2$) |
|---|---|---|
| EB I-96 | $+AREA = 27.55 \times (Snow\ Amount) - 7.42$ | 0.85 |
| WB I-96 | $+AREA = 37.46 \times (Snow\ Amount) - 15.43$ | 0.82 |
| NB US-23 | $+AREA = 27.19 \times (Snow\ Amount) - 12.59$ | 0.80 |
| SB US-23 | $+AREA = 26.11 \times (Snow\ Amount) - 9.91$ | 0.81 |

As shown in Figures E.4 to E.7 and Tables E.1 to E.4, the +AREA parameter provides the best relationship between the snow amount than the other selected performance parameters: average winter speed (AWS), minimum winter speed (MWS) and AREA.

These developed relationships can be considered byproducts of this research study. These winter weather travel speed-related performance measures will provide easily understandable indicators for the traveling public as well as agency personnel.