Evaluation of Performance of Automatic Vehicle Location and TowPlow for Winter Maintenance Operations in Wisconsin

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Winter maintenance operations are a major expense for state departments of transportation located within the Snow Belt of North America. Winter maintenance-related expenses for 2005 through 2010 ranged from $46 million to $87 million per year for state highways in Wisconsin. During the past two winters, the Wisconsin Department of Transportation implemented TowPlow and automatic vehicle location (AVL) technologies to optimize winter maintenance operations. A TowPlow is a plow that is attached to a regular plow truck to increase the snow removal capacity. AVL is a combination of systems capable of monitoring the location of a vehicle, material application rates, and road conditions from a central location. In this paper, qualitative and quantitative evaluations are presented for these two technologies. Findings from both evaluations showed that the implementation of these technologies would result in potential cost savings resulting from lower salt usage (AVL) and more efficient operations (TowPlow). The use of a TowPlow to perform the same task as a regular plow truck resulted in 32% to 43% operational cost savings. Implementation challenges, maintenance issues, and reduction in salt usage by counties that implemented AVL were evaluated. Implementation of AVL resulted in about 6% savings in salt usage from increased plow operator compliance with guidelines. When only the savings in salt usage and none of the intangible benefits were considered, the benefit–cost ratio values ranged from 1.05 to 1.89 depending on the cost of salt and percentage of reduction in salt usage.

Winter weather has a profound impact on the transportation system and, consequently, on every aspect of modern societies exposed to winter conditions. Snow and ice reduce pavement friction and vehicle maneuverability, which in turn leads to slower speeds, decreased roadway capacity, and adverse effects on traffic safety. Snowy or slushy pavement conditions result in a 30% to 40% reduction in arterial speeds (*1*). Speed reductions of 3% to 13% are observed on freeways as a result of light snow, while heavy snow results in 5% to 40% speed reductions (*1*). According to the Federal Highway Administration, every year in the United States 24% of weather-related crashes take place on snowy, slushy, or icy pavement and 15% occur during sleet and snowfall (*1*). Each year, crashes on snowy, slushy, or icy pavement conditions result in more than 1,300 people killed and in more than 116,800 injured (*1*). In Wisconsin, winter weather-related crashes totaled approximately 6,000 per year during the 2005–2006 through 2009–2010 winters (*2, 3*).

Safety and operational performance of roads are not the only agency concerns about winter maintenance. Cost considerations are also important because in the United States approximately 20% ($2.3 billion) of the state departments of transportation (DOTs) maintenance budgets are spent annually on winter road maintenance (i.e., snow and ice control operations) (*1*). The winter maintenance practice followed by the Wisconsin DOT is to contract with the 72 county highway departments to maintain state-owned highways. Total expenses billed by the counties to the Wisconsin DOT for the winter maintenance of state-owned highways ranged from $46 to $86 million during the 2005–2006 through the 2009–2010 winter seasons as shown in Figure 1.

The significant increase in winter maintenance costs since the 2006–2007 winter motivated the Wisconsin DOT to implement new technologies for winter maintenance operations. During the 2009–2010 winter season, the Wisconsin DOT began implementing several new technologies to make winter maintenance operations more efficient and cost-effective. Among the technologies implemented were

1. TowPlow, which is a towable plow added to existing plow trucks that can increase the total plowed area in a single pass, and
2. Automatic vehicle location (AVL) for plow trucks, which allows automatic reporting of material use, road conditions, and actions taken by the plow operator during a maintenance operation.

Evaluations presented in this paper range from qualitative evaluations, which document the findings by the authors after meeting with stakeholders involved in the implementation of the technologies, to quantitative evaluations, which document the effect of the technologies in achieving expected goals, such as reducing materials used during winter maintenance operations. Each of the technologies evaluated is presented in separate sections of this paper.

TowPlow CHARACTERISTICS

Figure 2 shows a TowPlow (commercial name of a device manufactured by Viking-Cives, Ltd.), a plowing trailer that is towed by a 350-horsepower (or more) regular plow truck that increases

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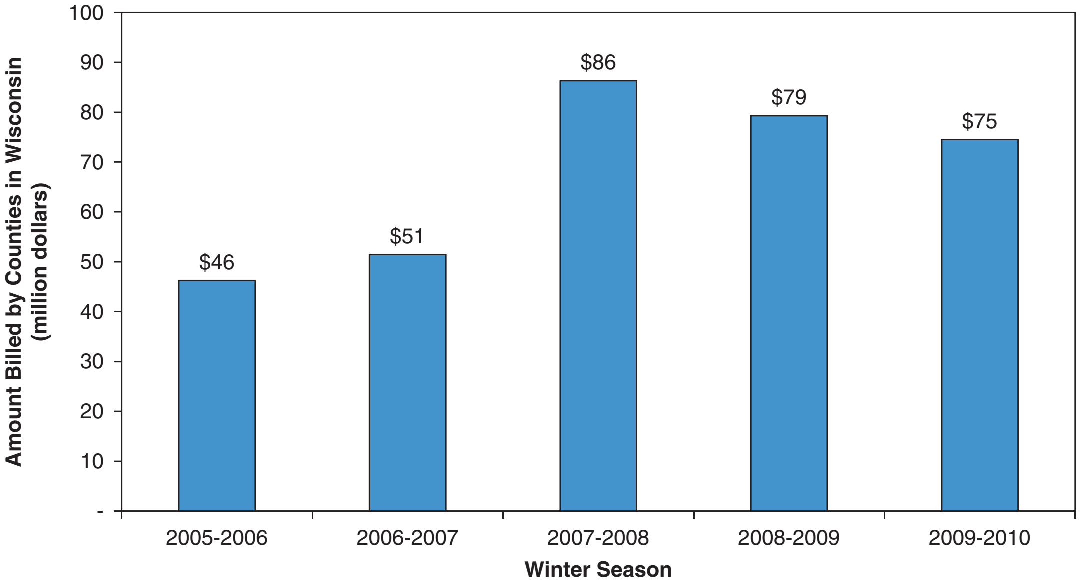


FIGURE 1 Costs billed by counties to Wisconsin DOT for maintaining state-owned highways.

the plowing width capacity. Attaching a TowPlow to the truck is achieved by the use of conventional pintle hitch and air brakes. A TowPlow is capable of carrying extra treatment material, such as granular salt or liquid brine. One of the benefits claimed by the manufacturer is the ability to clean approximately an extra lane of highway without the need for an additional plow truck. A TowPlow is connected to the plow truck's hydraulic system and can be controlled by two hydraulic controls in the truck cab. One hydraulic control is used for lifting and lowering the blade, while the other steers the rear axles and swivel torque. As a result, the tow truck operator can control the angle of operation (up to 30°) of a TowPlow from the truck cab, allowing cleaning of up to 23 ft of road. In the case of wing-equipped trucks, the extra width provided is added. TowPlows are currently being used by over a dozen states in the United States as well as in Canada (*4, 5*).

(a)

(b)

FIGURE 2 TowPlows operated by (*a*) Marquette County and (*b*) Eau Claire County.

Evaluations from state DOTs have resulted in positive feedback and concluded that having a TowPlow attached to their plowing trucks increases the value of an existing snow fighting fleet (*6*). Two TowPlows were acquired by the Wisconsin DOT and were used during the 2009–2010 winter by Marquette (Figure 2*a*) and Eau Claire (Figure 2*b*) counties. As shown, the TowPlows used by Marquette and Eau Claire counties are similar in size and operational characteristics. However, the TowPlow used by Eau Claire County is capable of carrying liquid brine whereas the one used by Marquette County is capable of carrying granular salt in a 7.8-yd^3 live-bottom hopper single-axle truck with a 435-horsepower engine. During operation, material carried by the TowPlow can be applied over the lane occupied by the device while the material carried by the truck can be applied to the lane occupied by the truck. Marquette County is also one of the few implementations in which a single-axle truck is used to pull a TowPlow. According to the manufacturer, out of approximately 200 TowPlow implementations, only two (including Marquette) use a single-axle truck.

One of the reasons why the use of a TowPlow is considered beneficial is that the device can alleviate some of the problems with "gang plowing" (i.e., having multiple plow trucks traveling next to each other to clean a highway segment in one pass). The state of Missouri reported that gang plowing was causing problems, such as shifting resources away from other routes and increasing the route maintenance cycle because of the arrival of trucks at the salt shed simultaneously, which caused delays in replenishing the trucks with material (e.g., salt) (*7*).

From a purely economics-based point of view, the acquisition of TowPlows can reduce capital costs by eliminating the need to acquire new plow trucks, if it is assumed that a plow truck with an attached TowPlow can treat the same area covered by two regular plow trucks. However, based on what has been reported in the literature, as well as an understanding that every state and county has different considerations, an evaluation of the TowPlow technology in Wisconsin was warranted before the validity of the aforementioned assumption was accepted.

Qualitative and quantitative evaluations of using a TowPlow were performed. Qualitative aspects of the evaluation involved an interview and ride-along with a TowPlow operator from Marquette County, as well as a meeting with the Marquette County highway commissioner. Feedback was also received from the Eau Claire County highway commissioner. For the quantitative evaluation, an evaluation of the benefits of using a TowPlow for winter maintenance operations was conducted.

County Feedback

At the time of the ride-along, the TowPlow operator had 21 years of plowing experience. During those 21 years, the operator had been involved in only one mishap, which involved a vehicle rear-ending the plow truck. In terms of maneuverability, the operator felt completely confident about handling the TowPlow, even though the day of the ride-along was the first time he was using the device. One immediate benefit perceived by the operator included an improved ability to keep the centerline of the road clear, which, according to the operator, is one the most difficult things to achieve during a typical snowstorm.

The plow operator expressed concerns about how highway users would react to a TowPlow operating on the road. Additionally, the operator felt an increased mental workload because of the need to be more vigilant than usual as a result of the increased size of the TowPlow and plow truck combination as well as the area covered. Other concerns expressed by the operator included maneuverability at median crossovers and the ability to perform ramp cleanups. On a follow-up conversation with the Marquette County highway commissioner, ramp cleanups were reported to be difficult when a TowPlow was used because maneuverability during the operation was difficult given the need to constantly move back and forth.

The operator noticed increased fuel consumption (as expected because of the TowPlow weight) during the ride-along. An analysis of fuel efficiency of a TowPlow and plow truck combination is shown in the next section of this paper. In addition to increasing fuel consumption, the TowPlow weight had an impact on the type of plow truck used with the TowPlow. The Ohio DOT reported the need to use a tandem-axle truck with a 350-horsepower engine (*8*). In Eau Claire County, the TowPlow was operated with a tandem-axle 330-horsepower truck.

Additional limitations discussed with the operator included a reduced distance that can be traveled by the vehicle when the road is treated with granular salt. The reduction in distance is a direct result of the TowPlow's having a smaller salt container compared to the regular plow truck. The 7.8-yd^3 salt capacity of the TowPlow is smaller than that of the regular plow truck (10 yd^3) and limits the distance over which a TowPlow-equipped truck can apply salt. However, the distance limitation can be offset by the extra width covered with a single TowPlow pass.

Colleagues of the operator expressed concerns that the speed that the operator maintained was slower than the speed achievable with plow trucks, approximately 5 mph slower, even though speeds achievable with the TowPlow were reported to be between 25 and 35 mph with a single-axle truck with a 435-horsepower engine. The argument made is that the lower threshold for the operational speed of the TowPlow (approximately 25 mph) is lower than the same threshold for a regular plow truck (approximately 30 mph). All these values are based on the experience of drivers and are not based on equipment design values. In Marquette County, no significant increases in speed were reported when the vehicle was not carrying any material nor did the vehicle present any balance problems under the described "empty" scenario. However, terrain in Marquette County is more level than in Eau Claire County, where lower speeds were reported in uphill sections of the highway.

Economic Evaluation

The main purpose of completing an economic evaluation of the TowPlow was to determine potential cost savings in Wisconsin given the procedures followed by counties in Wisconsin. Cost per mile and cost per hour of maintaining a highway segment with two lanes per direction using a TowPlow versus a regular plow were compared. The comparison was made for highways with two lanes per direction because the TowPlow does not provide any additional benefits compared to a single plow truck with wings for two-lane undivided highways. Table 1 shows the parameters used in comparing a TowPlow-equipped truck with a regular plow truck. Costs shown in Table 1 are based on values reported by Marquette County. No differences between the maintenance of a regular plow and a TowPlow were reported by Marquette County; therefore, no additional maintenance costs are considered for the TowPlow.

When using the TowPlow, counties reported being able to clean, in a single pass, twice the width of road normally cleaned using a regular plow truck. Table 2 shows the cost per hour incurred when a TowPlow (one pass) is used as well as a regular plow truck (two passes). When fuel and labor costs required to clean the same width with a TowPlow ($71.67) instead of a regular plow truck ($125.60) are combined, the resulting cost per hour of using a TowPlow is 43% lower than that of a regular plow.

Under the assumption that the TowPlow operator travels 5 mph slower than a regular plow truck (based on anecdotal evidence by the colleagues of the TowPlow operator), the hourly costs reported in Table 2 are not a true side-by-side comparison. Therefore, the length of the segment covered by a TowPlow in an hour is shorter than what can be covered by the regular plow truck. To conduct a fair comparison, the cost of cleaning a mile of highway with a width equal to that covered with the TowPlow (i.e., the width covered by approximately two plow trucks) was computed. As Table 2 shows, cleaning the same width of roadway with a TowPlow costs 32% to 43% less than using regular plow trucks to perform the same task.

Discussions with Marquette County indicated that the TowPlow can be used during any snowstorm, but the actual benefits are seen on storms with snow accumulations greater than 1 in. According to the Wisconsin DOT storm report database for the previous 10 years, an estimated 15 storm events per year had snow accumulations greater than 1.0 in. Also, with an average of 18 h of cleanup per storm

TABLE 1 Parameter Comparison

Equipment	Fuel Efficiency (mpg)	Labor Cost ($/h)	Operational Speed (mph)	Fuel Cost ($/gal)
TowPlow	3	40	25	3.8
Regular plow truck	5	40	30	3.8

TABLE 2 Operational Cost Comparison

Equipment	Labor	Fuel	Total
Costs per Hour ($/h)			
TowPlow	40.00	31.67	71.67
Regular plow truck	80.00	45.60	125.60
Costs per Mile ($/mi)			
TowPlow	1.60	1.27	2.87
Regular plow truck	2.67	1.52	4.19

(based on the Wisconsin DOT storm report database), estimated savings from using a TowPlow would be achieved for 270 h per year. With the data from Table 2, an estimate of $14,500 in savings per year could be achieved from the use of one TowPlow-equipped vehicle. On the basis of a cost of $75,000 per TowPlow, a reasonable assumption is that acquiring a TowPlow to supplement the existing fleet of vehicles would allow breaking even in a period of approximately 5 years. However, the biggest savings from purchasing a TowPlow materialize when the device is purchased in lieu of replacing an existing truck with a new one. Because these are average numbers, counties that experience greater snowfall during the winter season could potentially see bigger savings and vice versa.

AUTOMATIC VEHICLE LOCATION

AVL describes a group of technologies that enable tracking the position of individual vehicles and, when equipped with appropriate sensors, monitoring the actions and status of additional vehicle devices. When a plow truck is equipped with AVL technology, managers can monitor the vehicle location, material application rates, status of the plow, and other vehicle status indicators. AVL is not a new technology; Colorado, Iowa, Kansas, Maryland, Michigan, Minnesota, and Virginia in the United States, as well as Ontario, Canada, have implemented AVL technologies (*9*).

AVL has emerged as a technology capable of meeting the challenge of increasing productivity during winter maintenance operations along with quality and environmental stewardship while maintaining, and in some instances improving, the level of service of roads. Most of the literature available about the implementation of AVL technology portrays results of the implementation as favorable; furthermore, the technology appears to have matured over the years (*10*). However, there are many intangible benefits that, if not considered and quantified properly, can lead to benefit–cost evaluations inflated on the benefits or cost side of the equation. Some of the benefits that have been identified and suggested as a direct result of AVL system implementation include

- Safety improvements because of better road conditions,
- Optimization of maintenance routes,
- Better operator compliance with instructions,
- Increased accountability, and
- Faster response to incidents.

Safety-related benefits, such as expected reductions in crashes, are often the driving force behind inflated benefits. Another benefit, which has been documented in the literature, includes reduced liability costs resulting from the ability to monitor the position of vehicles in the past and ascertain whether claims by those seeking compensations for alleged damages were valid (*11*).

There are limited publications that present a benefit–cost evaluation of AVL implementation. Kansas has completed the most comprehensive benefit–cost evaluation, which predicts benefit–cost ratio values ranging from 2.6 to 24, depending on the aggressiveness of the implementation. The Kansas evaluation included benefits of the implementation related to safety as well as administrative impact of the technology. The assumed safety-related benefit was a reduction of 5% in all winter storm-related crashes. Administrative benefits included a 25% reduction in total administrative costs (*12*). Evaluations by other states and countries have been limited, but nevertheless the findings are reported and briefly discussed. Colorado reported experiencing a reduction of 15% in treatment costs along with a productivity increase of 12%. Michigan reported reductions in salt consumption, reduced removal costs, quicker response time, and reduced operator fatigue, along with a reduction of approximately 3% to 4% in the miles of road on which no maintenance action was being performed, even though the plow trucks were traveling (*10*).

On the basis of previous research and considering the needs of the Wisconsin DOT, the researchers paid attention to three areas during the evaluation. First, the counties' experience with the technology was evaluated. Second, the effect on the granular salt in use was studied. Third, a benefit–cost evaluation solely based on salt savings as a result of better operator compliance with maintenance guidelines was completed. Consideration of only salt savings in the cost–benefit evaluation allows an analysis of the impact of the technology on one of the expensive aspects of winter maintenance. As part of the evaluation, meetings were scheduled with counties that had AVL technology operational during the 2010–2011 winter season. During the meetings, a focus group-like survey was conducted in which many of the stakeholders at the county level provided feedback regarding the experience of implementing AVL as well as recommendations for other counties planning to implement the technology.

Installation Findings

On the basis of feedback received from the county highway department meetings, the researchers determined that retrofitting existing vehicles with AVL equipment did not overwhelm shop personnel. Most counties reported installation times of less than 1 day per truck, with values ranging from 6 h to 2 days. No actual data on installation time were available; the numbers were anecdotal. Higher installation times were reported for the first truck retrofitted as well as for older trucks. Installing the required sensors, cables, and controller upgrades in older vehicles was a common difficult task expressed by counties. On newer vehicles, installation was more straightforward. One of the issues that seems to have contributed to a smooth installation process was vendor support in the form of on-site visits as well as over the telephone. However, concerning vendor support, a complaint by several counties was the lack of a standard practice or guidelines for retrofitting trucks with the new equipment. For future deployment, better documentation and training before receiving the AVL equipment can speed up the installation process as well as create a more positive attitude toward the system.

Maintenance Findings

Because this is a brand new technology for most of Wisconsin, conclusions about the performance of the equipment in terms of maintenance are premature. Most counties suggested that reliability of the technology should be assessed over upcoming winters. Several counties expressed concerns that the plow position sensor (i.e., plow down or plow up indication) failed on a significant number of trucks. According to county feedback, the vendor acknowledged the problem and in addition to replacing the sensor was in the process of changing the design to increase the reliability.

Effects on Salt Usage

To determine whether or not implementing AVL technology had an impact on salt usage by counties for winter maintenance, a methodology was developed to quantify possible salt savings (if any) from the implementation. The methodology is based on a comparison of salt usage by two groups of counties (test and control groups) before and after the implementation of AVL. Although all the counties in Wisconsin had a maintenance decision support system software tool available during the 2010–2011 winter season, none of the counties reported following the recommendations. Therefore, changes in salt usage were attributed to the implementation of the AVL system. Salt savings are expected because of better plow operator compliance with maintenance guidelines, because the truck operator application rates are logged and can be compared with the guidelines.

The test group was composed of 13 counties (Figure 3*a*) that used the AVL technology during the 2010–2011 winter. The control group was composed of 38 counties (Figure 3*b*) that did not have AVL during the 2011 winter. The remaining 21 counties (except Dane County) implemented the technology partially and were not considered part of the evaluation. Dane County had equipped its fleet with AVL in 2009 and hence was not included in either group. For both groups, the before period corresponds to average salt usage during the 2006 through 2010 winters and the after period corresponds to the salt usage during the 2010–2011 winter season. Salt usage by the counties is primarily influenced by severity of the storm and the number of miles managed by the county. To account for these two factors, salt usage by counties was normalized by the Wisconsin DOT winter severity index (Equation 2) for each county and number of lane miles managed by the county with Equation 1. Other winter severity indices, such as SHRP (*13*), were considered; however, the data available only allowed for the computation of the Wisconsin DOT winter severity index.

$$N_U = \frac{T_S}{\mathrm{SI} \times L_M} \tag{1}$$

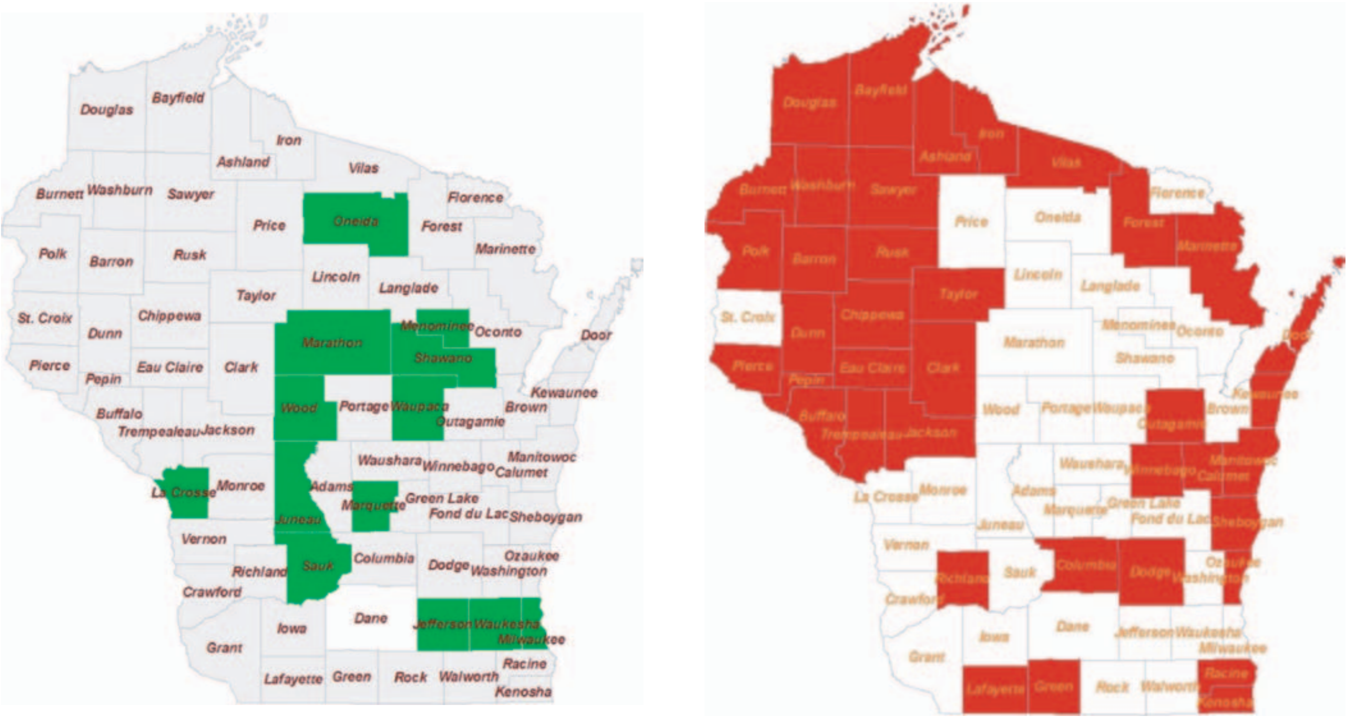
where

N_U = normalized salt usage,
T_S = total salt used (tons),
SI = winter severity index (no units), and
L_M = lane miles (mi).

$$\mathrm{SI} = 10\frac{E}{63} + 5.9\frac{F}{21} + 8.5\frac{A}{314} + 9.4\frac{D}{1125} + 9.2\frac{I}{50} \tag{2}$$

where

E = number of snow events,
F = number of freezing rain events,
A = total amount of snow (in.),
D = total hours of storms, and
I = total number of maintenance incidents.



(a)

(b)

FIGURE 3 Groups of counties: (*a*) test group and (*b*) control group.

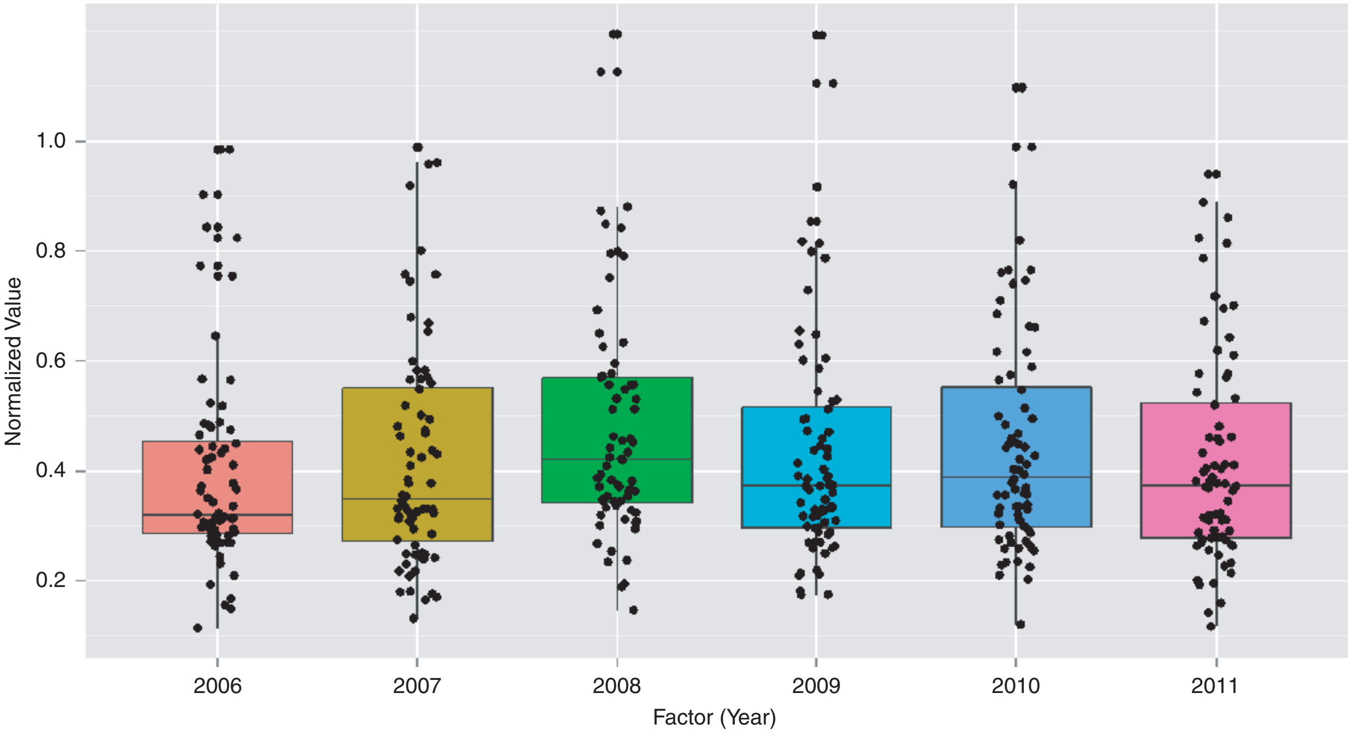


FIGURE 4 **Normalized salt usage value for the entire state.**

Normalized salt usage values were obtained using Equation 1 for all the counties by querying the storm report database, which included information such as winter severity index, lane miles managed by a county, and salt used during each maintenance activity reported by a county. A graphical representation of the values obtained with the normalization procedure is shown in Figure 4. The average normalized salt usage value (N_U) for the before period was computed for both the control group ($\overline{N_U^C}$) and the test group ($\overline{N_U^T}$). For the control and test groups, the values reported by counties in 2011 were compared with the corresponding average values with a paired *t*-test and the results are shown in Table 3. One of the goals of using a *t*-test to perform the comparison was to determine if the difference in normalized salt usage between the 2011 numbers and the before period was significant for counties that implemented AVL as well as those that did not implement AVL. For test purposes, 90% confidence level (alpha value lower than or equal to 0.10) was considered significant.

As Table 3 shows, the test group experienced a significant reduction of 9.4% ($p = .07$) in the N_U value, while the comparison group experienced a nonsignificant reduction of 2.7% ($p = .45$). In other words, it can be concluded with 93% (1 to 0.07) confidence that the test group of counties experienced a 9.4% reduction in normalized salt usage. For the control group, however, it can be concluded with 55% (1 to 0.45) confidence that normalized salt usage was reduced by 2.7%. A conservative interpretation of the results indicates that the implementation of the AVL could have contributed to at least a 6.0% reduction in normalized salt usage by counties. The approximate 6% reduction is obtained by subtracting the 2.7% reduction experienced by the control group from the 9.4% reduction experienced by the test group.

TABLE 3 **Before-and-After Comparison**

Comparison Group	Mean Difference (After – Before)	*p*-Value	Finding
Without AVL	–2.7%	.45	No significant reduction
With AVL	–9.4%	.07	Significant reduction

The salt savings that a county could experience as a result of a change in the N_U value can be computed with Equation 3. As shown in the equation, 0% reduction in the N_U value returns no salt savings (S_S) possible and 100% salt savings (i.e., $\Delta N_U = 1.0$) returns salt savings equal to the total average salt usage by a county.

$$S_S = \Delta N_U \times \overline{\mathrm{SI}_B} \times L_M \times \overline{N_U^B} \quad (3)$$

where

ΔN_U = change in normalized salt usage value,
$\overline{\mathrm{SI}_B}$ = average severity index during before period, and
$\overline{N_U^B}$ = average N_U value during before period.

Equation 3 shows the salt savings that a county experiences given a reduction in the N_U value. To compute the total salt savings per year (T_S) for the entire state, Equation 4 was used, where *i* is the county number. Equation 4 was applied under two ΔN_U values as shown in Table 4.

$$T_S = \sum_{i=1}^{72} \Delta N_U \times \overline{\mathrm{SI}_B} \times L_M \times \overline{N_U^B} \quad (4)$$

TABLE 4 Projected Salt Savings from AVL Implementation

ΔN_U Savings	−6%	−9%
T_S (tons)	16,742	25,113
\$60 per ton	\$1,004,521	\$1,506,778
\$65 per ton	\$1,088,224	\$1,632,336
\$70 per ton	\$1,171,934	\$1,757,901

As Table 4 shows, expected savings in salt converted to dollar figures range from approximately \$1.0 million, with a 6% reduction in the normalized salt (N_U) value and a cost of salt of \$60 per ton, to approximately \$1.8 million, with a 9% reduction in the normalized salt (N_U) value and a cost of salt of \$70 per ton.

Benefits and Costs

A benefit–cost evaluation looks at the cost of implementing a system, the ongoing (annual) costs associated with the system, and the annual benefits obtained from the implementation through the life cycle of the system. Benefits and costs are considered for the life cycle of the project and if the total benefits are greater than the total costs incurred, when properly adjusted for inflation, the benefit–cost ratio should be greater than 1. From a decision-making point of view, any value greater than 1 is justifiable, with values larger than 1.0 being desirable.

As previously mentioned, the main objective was to perform an evaluation that considered only tangible benefits, so the decision was to include only expected salt savings as the benefits. The conservative approach does not account for all the benefits of AVL implementation previously identified as possible in the literature (*14*). Annual costs considered as part of the evaluation were maintenance and communication costs associated with the technology, which are \$720,000 given that a total of 1,200 units are expected to be operational by the end of 2011 and assuming maintenance and communication costs of \$600 per year per unit. Implementation costs, which are expenses considered to take place at year zero, total \$1,620,000 considering an installation cost of \$1,350 per unit. Installation costs used for the analyses are actual costs reported in Wisconsin and are consistent with what other states have reported (*15*).

On the basis of the cost and benefits discussed previously and using a 2.5% discount rate (a typical value used by the Wisconsin DOT) and 8 years for the life cycle, the research team computed the benefit–cost ratio for a range of scenarios, which are shown in the following table:

ΔN_U *Savings*	*−6%*	*−9%*
\$60 per ton	1.05	1.57
\$65 per ton	1.15	1.73
\$70 per ton	1.26	1.89

Benefit–cost ratios range from 1.05 to 1.89, depending on the cost of salt and assumption for normalized salt usage reduction. Therefore, projected salt savings from the implementation of the AVL technology alone can pay for the cost and produce additional annual savings. Computed benefit–cost ratios are conservative because the only benefit included is savings in salt costs. If all intangible benefits reported by Wisconsin counties as well as in the literature are included, the benefit–cost ratio will certainly increase further.

CONCLUSIONS

TowPlow and AVL are among the technologies implemented by the Wisconsin DOT as a means to improve the efficiency and cost of winter maintenance operations. Findings suggest that a TowPlow can reduce the cost of winter maintenance operations during a snow event. When compared with a regular plow truck, the operational cost (fuel and labor) of a TowPlow is between 32% and 43% lower depending on whether cost per hour or cost per mile is used for analysis. Furthermore, depending on the use, savings are estimated to be \$14,500 per year with acquisition costs being recovered in 5 years. However, attention must be paid to maneuverability of TowPlows for cleanup tasks performed on tight spaces such as ramps and median turnarounds.

A before and after comparison of salt usage shows a statistically significant reduction in normalized (for weather severity and lane miles) salt usage of approximately 9% for counties with AVL versus a nonstatistically significant reduction of approximately 3% for counties without AVL. Salt savings reported are expected because of better plow operator compliance with maintenance guidelines. A conservative estimate of 6% reduction in normalized salt usage can be attributed to AVL. Benefit–cost ratios computed for AVL range from 1.05 (6% salt usage reduction, \$60/ton of salt) to 1.89 (9% salt usage reduction, \$70/ton of salt), demonstrating the benefit of implementing AVL. The benefit–cost ratios reported are conservative because only savings in salt costs were considered as benefits. To make the evaluation objective, intangible benefits were not included. Some of the intangible benefits that will certainly translate into additional savings include reduced paperwork, improved fleet management capabilities, improved traffic safety, and better accountability. Accounting for intangible benefits will increase the benefit–cost ratios further.

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