Development of New Performance Measure for Winter Maintenance by Using Vehicle Speed Data

Chanyoung Lee, Wei-Yin Loh, Xiao Qin, and Mike Sproul

The study investigated vehicle speed changes during winter weather events. A total of 954 winter maintenance logs in 24 counties over three winter seasons were analyzed. Several variables of interest were developed, such as storm duration, maintenance operation hour, crew delayed, maximum speed reduction, and the storm start and end times. Also, *t*1, which represents the start of vehicle speed reduction, and *t*3, the time at which vehicle speeds recover to normal winter driving speeds, were measured from automatic traffic recorder data. The study confirms that vehicle speed seems to be a good measure of representing driving conditions during winter weather events and winter maintenance performance alike. Speed recovery duration was found to be a dependent variable, defined as a possible evaluation of winter maintenance operations using vehicle speed data.

According to a recent study, traffic volumes are not significantly affected by adverse weather conditions as much as by vehicle speed (*1*). Most drivers are not willing to cancel their trips or change their plans just because of inclement weather. As a result, it becomes important for transportation professionals who are responsible for maintaining the traveling quality of public roads to meet the expectation of motorists. Considering that roadway conditions are severely affected by winter weather events and that the United States spends $1.5 billion a year to manage snow and ice on roadways which incur $5 billion in indirect costs, it is essential to perform winter maintenance operations effectively and efficiently.

Lee and Ran stated that "winter maintenance in the area of transportation encompasses those activities that attempt to keep roadways in proper condition to travel during winter weather events" (*1*). To improve winter maintenance operations, well-defined performance measures, which can be easily understood by both practitioners and public, should be developed. Doing so would enhance the effectiveness and the efficiency of winter maintenance activities.

C. Lee, Center of Urban Transportation Research, University of South Florida, 4202 East Fowler Avenue, CUT100, Tampa, FL 33620-5375. W.-Y. Loh, Department of Statistics, Medical Science Center, Room 1165, 1300 University Avenue, and X. Qin, Traffic Operations and Safety Laboratory, University of Wisconsin–Madison, 1415 Engineering Drive, Madison, WI 53706. M. Sproul, Bureau of Highway Operations, Wisconsin Department of Transportation, Hill Farms State Transportation Building, 4802 Sheboygan Avenue, P.O. Box 7910, Madison, WI 53707-7910. Corresponding author: C. Lee, cylee@cutr.usf.edu.

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An initial pilot study conducted by Lee and Ran showed the potential of using vehicle speed as a performance measure for winter maintenance (*1*). However, the study was conducted with a very limited sample size, and additional extensive research with a larger sample size to validate the findings from the initial study was recommended. This study is intended to validate and expand on the previous study, which can potentially improve winter maintenance operations.

DATA COLLECTION

The Wisconsin winter maintenance logs (winter storm reports) for 3 years (2003 to 2004, 2004 to 2005, and 2005 to 2006) were obtained and analyzed in this study. The snowstorm report is recorded by the winter maintenance crew in each county. A record represents one winter maintenance task that was conducted for one snowstorm in one county. It contains information about winter weather events and maintenance activities, including the use of labor and materials. The winter maintenance logs were acquired before analysis of the data set, and a filtering process was applied to identify and remove anomalies in the data, such as a negative storm duration or a record with multiple missing fields. Also, the logs were further refined by excluding counties that do not have relevant automatic traffic recorders (ATRs).

Twenty-four candidate ATR sites were selected for this study on all five roadway categories. These categories classify roadways according to average daily traffic (ADT). The highest ADT roadways are called Category 1 roadways, primarily consisting of six-lane highways. The lowest ADT roadways are called Category 5 roadways, which are generally two-lane highways with an ADT of fewer than 5,000 vehicles. These categories are also used to classify counties: counties with high ADT are considered Category 1 counties, and counties with low ADT are considered Category 5 counties. See Appendix A for more information on the roadway categories.

For the data gathered from the ATRs to be used, the roadway category where the ATR was located had to match the county category in which the highway was located. For example, an ATR on a Category 1 road had to be in a Category 1 county to be selected as a candidate site for this study. With use of this criterion, three Category 1 sites, six Category 2 sites, seven Category 3 sites, four Category 4 sites, and four Category 5 sites were selected for this study. Figure 1 shows the location of sampled counties for the study. A detailed list of all ATRs used with ADT and winter average daily traffic (WADT) is shown in Table 1.

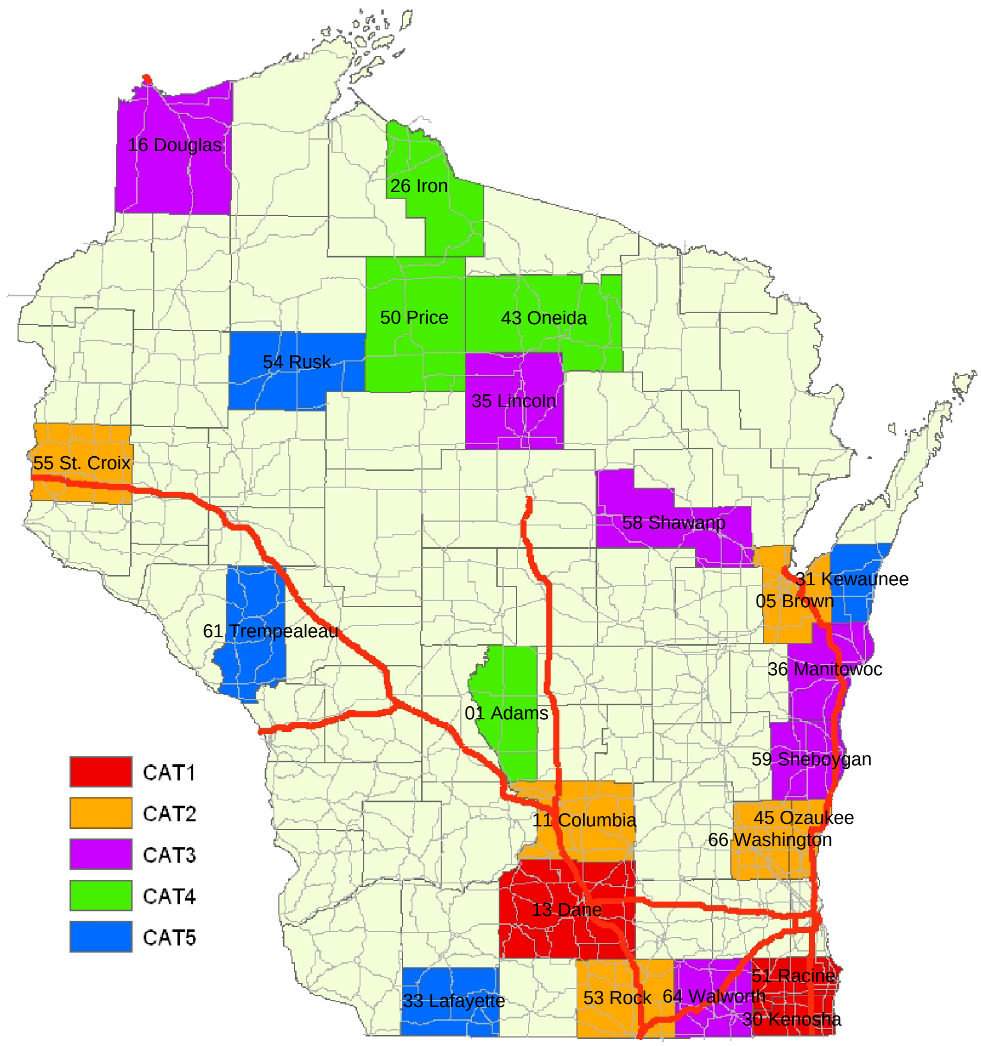


FIGURE 1 Sampled counties for study.

VARIABLES OF INTEREST

To conduct the analysis effectively and efficiently, variables of interest were identified and developed through the manipulation of the data set. The winter storm report was analyzed by using a VBA script in Microsoft Excel, and ATR data were processed using MATLAB.

Storm Duration, CrewInOut, and CrewDelayed

The winter storm report contains details of each storm event, including precipitation type and depth. It also includes regular and overtime labor hours spent by maintenance operations for each storm and county. CrewDelayed represents the time duration between StormStart, the start time of the storm, and CrewOut is the time hen maintenance crews begin working. This value can be negative if crews were deployed before the storm start time. Also, CrewInOut shows the duration of maintenance activities. Several other variables such as pavement temperature, precipitation type, and amount of precipitation were also included.

Information in the winter storm report represents all maintenance activities for each storm for each county. However, the study collected information associated with roadways in assigned categories. Therefore, the use of labor and materials that may not be relevant to a roadway's assigned category was not included in the list of potential contributing variables.

Maximum Speed Reduction, *t*1, *t*2, and *t*3

Four main terms were defined to analyze vehicle speed data: the maximum speed reduction (MSR), *t*1, *t*2, and *t*3. A computer script was written in MATLAB to determine approximate values for these terms, and then all terms were checked visually using plots created in Microsoft Excel. Much of the data were analyzed by comparing them with an average speed. The average speed was found by taking hourly speed data from six different dates: three dates from the 3 weeks preceding the storm date, and three dates from the 3 weeks following the storm date. For example, if the winter storm occurred on the first Monday in December, the data used would be from the three Mondays after the first Monday in December and the three Mondays before the first Monday in December. If a winter storm occurred on one of the three dates before or after the storm date, the data were not included in calculating the average data.

TABLE 1 Sampled ATRs

Category	ATR ID	County	ADT 2005	WADT 2005
1	130004	Dane	87,494	79,075
	510001	Racine	83,919	76,027
	300004	Kenosha	86,874	80,464
2	550002	Saint Croix	41,247	39,927
	050001	Brown	54,656	46,917
	110002	Columbia	24,825	22,060
	450239	Ozaukee	45,817	40,559
	660001	Washington	32,961	29,382
	530001	Rock	30,288	27,365
3	160002	Douglas	5,834	4,625
	350002	Lincoln	18,577	15,549
	580001	Shawano	21,019	18,265
	360001	Manitowoc	19,230	16,960
	360002	Manitowoc	8,068	6,996
	590608	Sheboygan	20,012	19,976
	640002	Walworth	12,975	11,359
4	260001	Iron	3,552	2,924
	506052	Price	2,227	1,887
	430001	Oneida	5,935	5,091
	010001	Adams	3,287	2,768
5	540001	Rusk	2,939	2,197
	310002	Kewaunee	3,474	3,246
	610001	Trempealeau	1,487	1,152
	330001	Lafayette	4,099	3,866

NOTE: WADT: average of monthly ADT (Dec.–March).

After the dates of average data were determined, the speed and volume data from each hour were averaged, giving 24 data sets. Then, all data points smaller than the first average were disregarded, and a second average was taken of the remaining points. This second average eliminates some of the impact of traffic incidents or unexpected events, and it was the average used in this project. Figure 2 illustrates the variables of interest.

MSR is defined as the greatest difference in traffic speed caused by a winter weather event. Quantitatively, it is determined by subtracting the reduced speed caused by the winter weather event from the ADT traffic speed. Important to note is that MSR must occur during a winter weather event, so the maximum speed drop after the winter weather event begins is the value determined for the MSR. Also, the percentage of reduction in speed was calculated based on the average speed for the day.

The term *t*1 is defined as the time after the snowstorm starts at which traffic begins to slow down. Qualitatively, it is the point on a speed–time graph where the traffic speed begins to decrease significantly. If there is a reduction in vehicle speed before the time the snowstorm starts, *t*1 is defined as the time that the snowstorm starts. If the reduction occurs after the snowstorm starts, *t*1 is quantitatively defined as the first point that falls below 8% of the average traffic speed for the day. This 8% threshold was obtained intuitively and programmed into MATLAB, but for greater accuracy, the *t*1 time was checked visually using plots created in Microsoft Excel. The term *t*2 is defined as the time when the MSR occurs. In the MATLAB script, it is linked to the MSR. Generally, the script showed few inaccuracies with the value of *t*2, so little manual checking was required in reporting *t*2. The term *t*3 is the time after *t*2 at which traffic speed resumes to normal. Qualitatively, *t*3 is the point on the speed–time graph where the traffic speed reaches a steady value. Quantitatively, *t*3 is the time that traffic speed comes within 8% of the average speed for the day. Like *t*1, *t*3 was verified manually after the computer processing to improve accuracy. Some snowstorms lasted for 2 or more days. For these snowstorms, *t*3 was determined manually by qualitative comparison between the average speed plot and the speed plot for the day the snowstorm ended.

The bare and wet time in the snowstorm report is defined as the time when the roadway surface is free from drifts, snow ridges, and as much ice and snow pack as is practical, and when the roadway can be traveled safely at reasonable speeds. A passable roadway should not be confused with a dry pavement or a bare pavement, which is essentially free of all ice, snow, and any moisture from shoulder to shoulder. The dry and bare pavement condition may not exist until weather conditions improve to a point where the pavement condition can be made possible. The definition of reasonable speed is considered a speed that a vehicle can travel without losing traction. Motorists can expect some inconvenience and will be expected

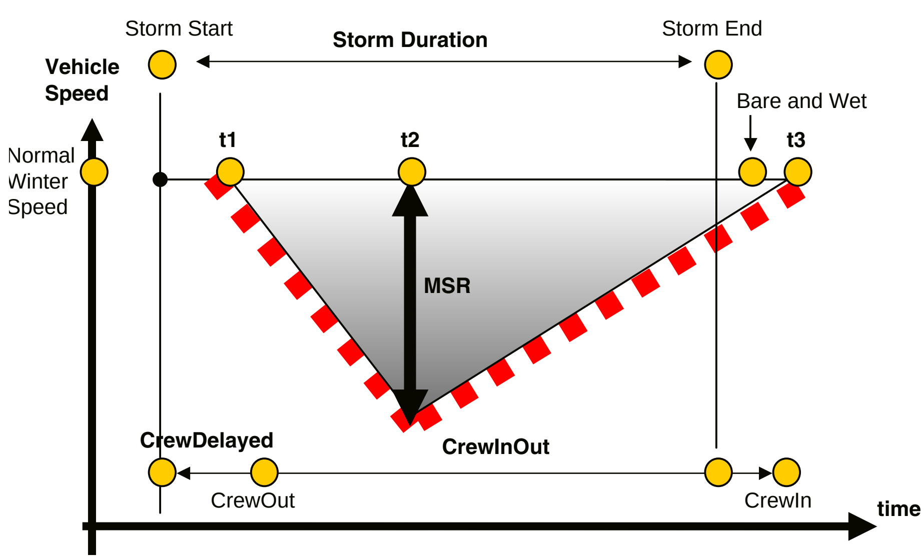


FIGURE 2 Variables of interest.

to modify their driving practices to suit road conditions (*2*). The bare and wet time can appear before the end of a snowstorm or several hours after a snowstorm ends, depending on the severity of the storm and the performance of the winter maintenance crew. In this study, the bare and wet time in the snowstorm report was compared to *t*3, which was calculated based on ATR data.

SUMMARY OF DATA

Storm duration and maintenance operation hours were calculated based on the snowstorm report. On average, storm duration in this study is around 10 to 11 h, and maintenance operations last 14 to 15 h. There is a 2- to 5-h difference between storm duration and maintenance operation hours for Category 1 and Category 2 counties. However, there is a minimal difference for the remaining counties, which have smaller traffic volumes.

As for time to dispatch winter maintenance crews, most Category 1 and Category 2 counties have less than 1 h of delay to dispatch their maintenance crews while counties of Categories 3, 4, and 5 experience a relatively longer delay time.

Also, time lag of vehicle speed reduction after the winter weather event started was calculated based on storm start information in the snowstorm report prepared by the county highway departments, and the value of *t*1 was obtained by analyzing ATR data. Vehicle speeds started to drop an average of 0.65 h (39 min) after winter weather events began, but the median value is 0, which means vehicle speeds started to drop at the onset of, or shortly after winter weather events. In addition, there are very few cases where traffic speeds started to drop more than 3 h after a winter weather event began.

According to a previous study (*1*), the MSR in a snow event and the snow event duration are the significant variables that affect duration of winter maintenance operations. As can be seen in Figure 3, MSR during winter weather events is not close to a normal distribution. The average of the MSR is located between 13.6 and 14.7 mph with a 95% confidence interval. Most county categories show a 10% to 30% speed reduction due to winter weather events. However, there are not many differences between the categories, and an average of approximately 20% MSR was observed based on the box plots.

Table 2 shows the time duration between several key points associated with winter weather events and maintenance operations. The designation *t*2–*t*1 stands for the time to get to the MSR point during a winter weather event, and *t*3–*t*1 stands for the time duration of reduced vehicle speeds due to a winter weather event. For instance, for Category 1 counties, 1 h after a storm starts, vehicle speed starts to drop and reaches the MSR point after 3.5 h, and it usually takes approximately 10 h to achieve normal winter speed after the MSR point. It is also discovered that *t*3–*t*1 shows larger variation among categories than *t*2–*t*1 does.

One assumption made at the beginning of the study and in most winter maintenance practices is that vehicle speed will recover when the pavement reaches a wet condition after the winter weather event. To confirm the assumption, *t*3 was obtained from ATR data, which represents the time vehicle speeds reach normal winter speed, and compared with the bare and wet time in the snowstorm reports. Figure 4 shows the graphical summary of *t*3 and bare and wet. A negative value means vehicle speed became close to the normal winter speed before the bare and wet time reported in the snowstorm report. The mean of the time differences ranges from 0.42 to 0.76 h with a 95% confidence interval, and the standard deviation is 2.68 h. According to observed

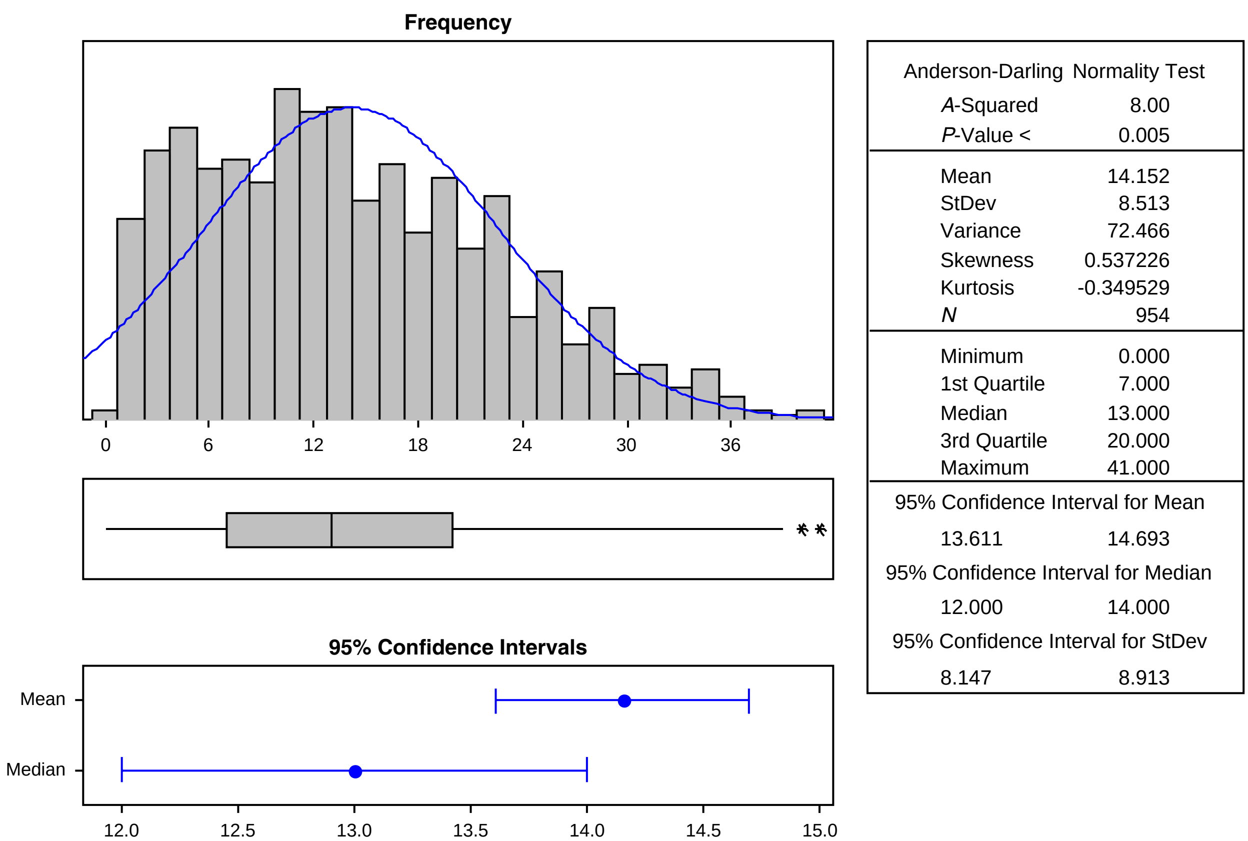


FIGURE 3 Summary of MSR.

TABLE 2 Speed Reduction Time ($t1$, $t2$, $t3$)

		Storm Start, Speed Starts to Drop (h)				$t2$–$t1$ (h)				$t3$–$t1$ (h)			
Category	County	03–04	04–05	05–06	Average	03–04	04–05	05–06	Average	03–04	04–05	05–06	Average
1	13	0.2	1.7	1.7	1.3	3.3	6.6	4.2	4.7	12.8	13.5	11.5	12.5
	30	2.5	0.9	2.4	2.0	1.5	2.7	2.6	2.5	23.0	15.4	7.3	11.8
	51	1.2	0.5	0.8	0.8	3.3	3.1	1.7	2.7	16.5	16.6	14.0	15.7
	Avg.	0.9	1.0	1.5	1.2	3.1	4.4	2.9	3.5	15.4	15.2	11.6	13.8
2	5	1.1	1.4	1.8	1.5	3.0	3.1	2.9	3.0	7.3	7.7	11.1	8.8
	11	1.1	1.3	0.5	0.9	5.0	1.9	3.1	2.6		10.0	9.8	9.9
	45	1.5	0.7	0.8	1.0	3.4	2.9	3.9	3.3	13.5	9.8	11.2	11.3
	53	1.5	1.5	1.2	1.3	3.0	0.8	3.3	2.9	10.6	5.2	12.7	11.2
	55	0.8	0.8	0.9	0.8	2.4	2.9	2.1	2.5	12.1	7.7	7.9	8.4
	66	1.0	0.8	0.3	0.6	3.9	2.3	3.8	3.3	9.2	8.2	9.8	9.1
	Avg.	1.2	0.9	0.9	1.0	3.2	2.6	3.1	2.9	10.6	8.4	10.1	9.5
3	16	0.8	1.4	1.0	1.1	2.6	1.9	3.2	2.5	17.5	15.9	12.2	14.9
	35	1.0	0.7	0.5	0.7	3.5	3.1	3.1	3.2	13.3	14.1	13.2	13.6
	36	2.3	0.7	1.0	1.2	1.9	2.5	3.1	2.6	11.4	9.9	13.4	11.8
	58	2.3	1.2	0.8	1.3	3.2	6.0	2.9	3.7	18.0	14.8	12.1	14.2
	59	1.1	0.3	0.4	0.6	3.5	2.4	3.3	3.1	14.8	12.9	13.8	13.9
	64	0.0	0.0	0.5	0.3	3.4	3.2	2.2	2.7	11.4	9.2	8.6	9.3
	Avg.	1.4	0.8	0.7	0.9	2.8	2.7	3.0	2.9	14.1	12.9	12.5	13.0
4	1	0.4	1.3	2.5	1.5	3.0	2.8	2.5	2.7	19.0	13.2	11.8	14.3
	26	0.0	0.1	1.6	1.1	5.0	1.3	2.3	2.1	12.0	12.2	17.8	15.8
	43	1.4	1.7	0.6	1.3	2.8	3.6	4.8	3.8	19.3	21.9	19.0	20.4
	50	1.4	2.0	1.2	1.3	5.1	9.0	6.0	5.7	20.9	27.0	24.0	22.9
	Avg.	1.1	1.4	1.4	1.3	3.7	3.2	4.2	3.7	19.6	18.3	18.6	18.8
5	31	0.0	1.3	0.6	0.7	1.0	2.2	1.6	1.7	6.0	5.2	10.2	8.6
	33	2.1	1.2	2.3	1.7	2.0	3.1	5.0	3.5	14.5	13.1	19.0	15.3
	54	0.8	0.4	0.8	0.6	4.4	2.4	3.6	3.4	19.2	16.2	13.9	16.3
	61	0.0	0.7	0.5	0.6	0.0	3.1	3.9	3.4		9.9	11.4	10.4
	Avg.	1.1	0.7	0.9	0.8	3.7	2.8	3.4	3.2	17.4	12.3	13.1	13.4

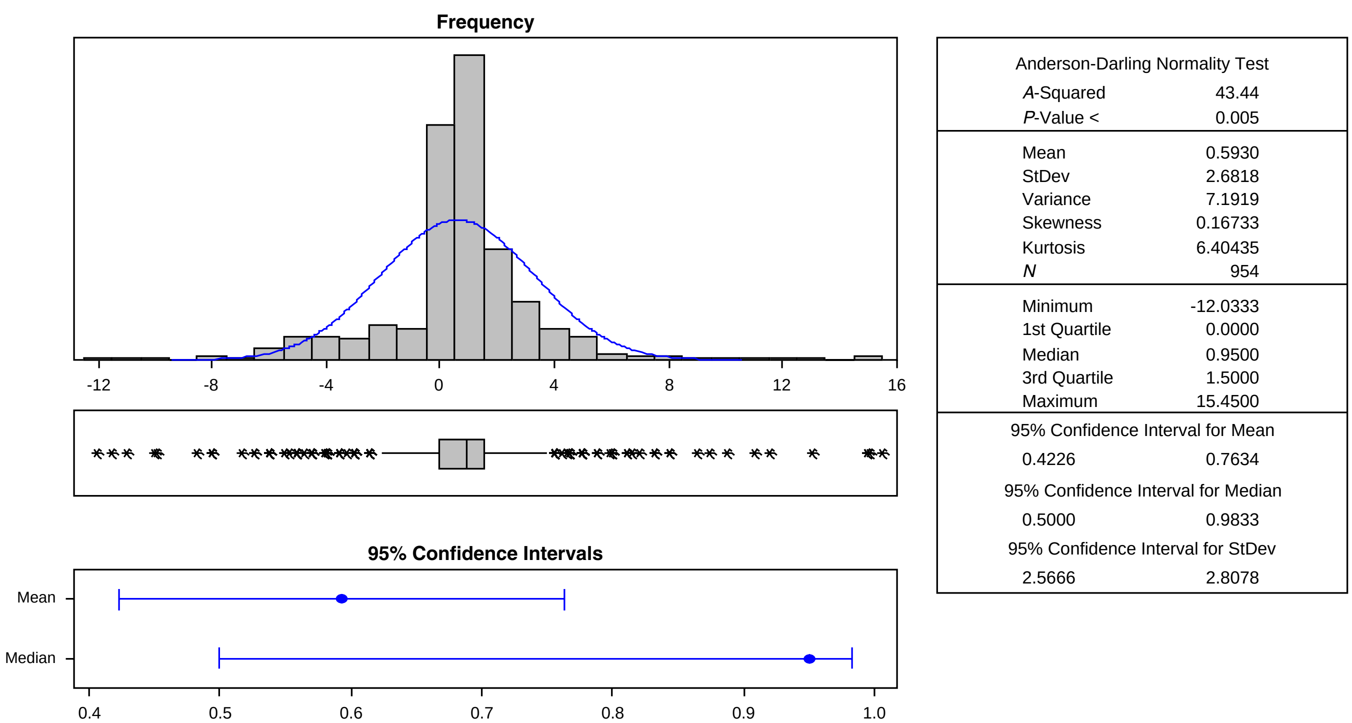


FIGURE 4 Summary of $t3$–bare and wet.

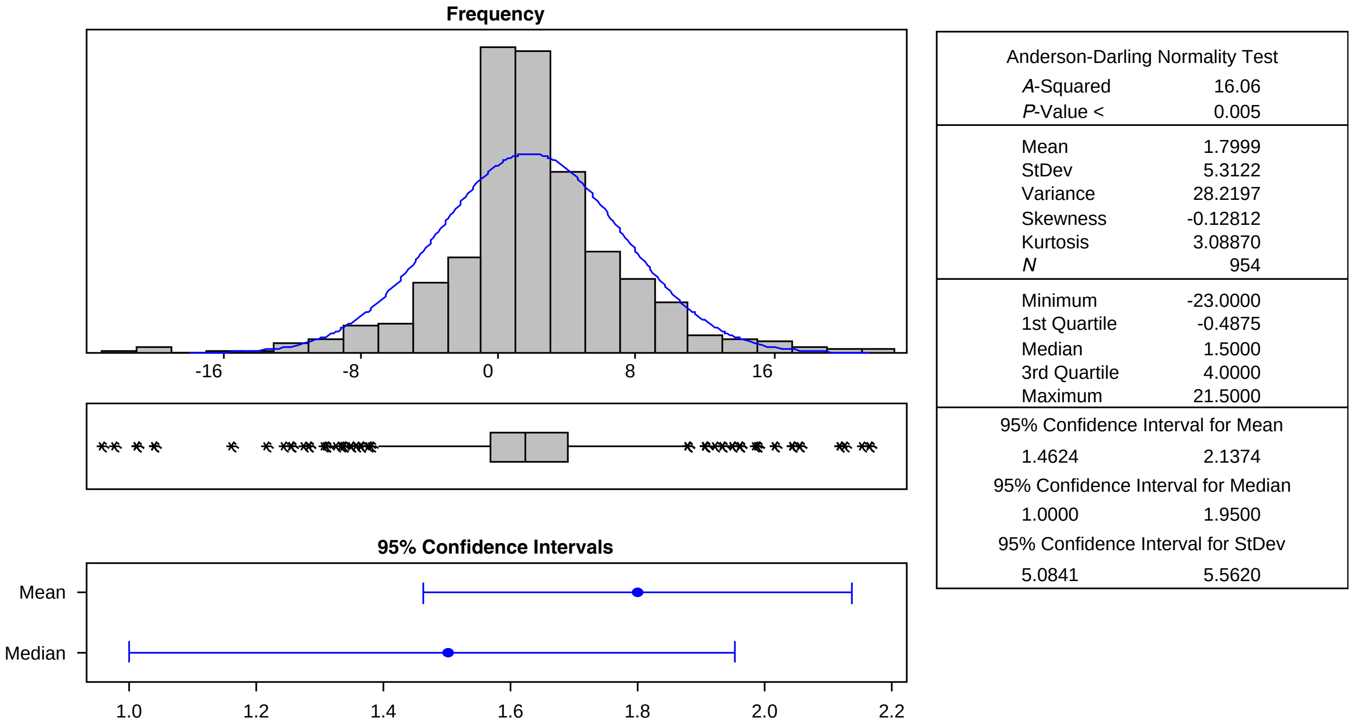


FIGURE 5 Summary of *t*3–storm end.

data, vehicle speeds usually recovered to normal winter speeds within 1 to 2 h of the pavement reaching the bare and wet condition.

Figure 5 presents the summary of the time difference between storm end and *t*3. The calculation was completed by subtracting storm end from *t*3. Negative values indicate speed recovered before the storm end time reported in the winter storm report. The mean of time difference ranges from 1.46 and 2.13 h with a 95% confidence interval, and standard deviation is 5.3 h.

Generally, vehicle speed reduction started less than 1 h after winter weather events started and took 3 to 5 h to reach the point of maximum speed reduction. Measurements indicate a 10- to 13-h recovery time frame to normal winter speed. The bare and wet pavement condition usually was reported less than 1 h in advance of *t*3, and the storm end time was reported before the bare and wet pavement condition. Figure 6 illustrates findings of the study related to vehicle speed drop and recovery during winter weather events.

DATA ANALYSIS WITH REGRESSION TREE METHOD

Methodology

The statistical analysis of a large sample like the snowstorm reports for several seasons with minimal bias is a challenging and demanding process. Generally, a regression model is a useful tool to find relationships between independent and dependent variables. However, the model becomes difficult to interpret when collinearity, nonlinearity, or interactions are present in the large data set.

To overcome statistical analysis limitations, the study adopted a regression tree algorithm, GUIDE (Generalized, Unbiased, Interaction, Detection, and Estimation) (*3*). This is a method that uses a traditional statistical approach together with machine learning algorithms. The approach can be very effective in discovering unknown useful dependencies in the data usually neglected in traditional statistical approaches. It recursively partitions the data and fits a piecewise regression model for each partition of the data. Thus, it allows nonlinear attributes of the data to be effectively modeled. The binary tree constructed by the partitioning process is pruned to minimize a cross-validation estimate of the predicted deviance.

Selected Variables

After several iterations, a total of 15 variables were selected as a final input to the regression tree analysis. The initial number of variables was 30, and half of the variables were excluded through iterations of the regression tree analysis with GUIDE. Table 3 summarizes the

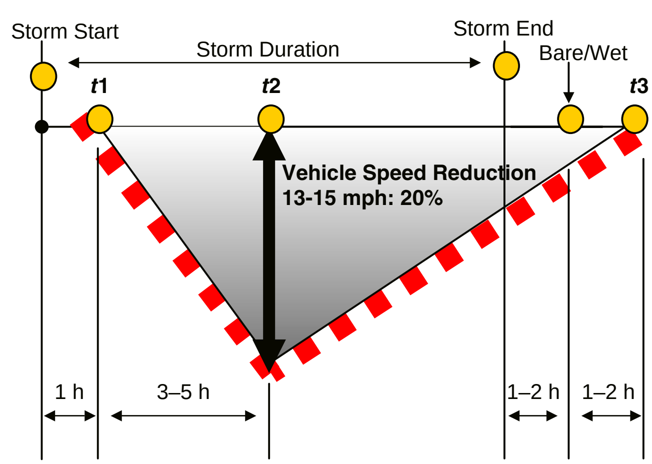


FIGURE 6 Vehicle speed reduction and recovery during winter weather event.

TABLE 3 Variables for Regression Tree Analysis

Variable	Variable Name	Data Source
County	County	Storm report
Category	CAT	Storm report
Pavement temperature	PTMP	Storm report
Maximum speed reduction	MSR	ATR
MSR (%)	MSRPCENT	ATR
Time lag to speed drop after snowstorm starts	StoS2SD	Storm report + ATR
Time to MSR after snowstorm starts	StoS2MSR	Storm report + ATR
Storm duration	StoDura	Storm report
Winter maintenance operation duration	CrewWork	Storm report
Time lag to deploy maintenance crew after snowstorm starts	CrewDelayed	Storm report
Snow type	SnowType	Storm report
Snow precipitation	SnowDepth	Storm report
Reduction of speed per time	Sdslope	ATR
ADT during winter months (2005)	WADT2005	ATR
2005 ADT	ADT2005	ATR

final set of variables. This analysis attempts to find potential affecting variables to speed recovery duration (SRD), which is the time duration from the MSR point ($t2$) to the moment vehicle speeds recover to normal winter speeds during a winter weather event ($t3$).

Regression Tree Results

Figure 7 illustrates the piecewise simple linear least-squares model constructed for the project. At each intermediate node, the case goes to the left child node if the condition is satisfied. Each terminal node presents the sample mean of the speed recovery duration (MSR2NOR) and the sign and name of the regressor. This model fits only one significant variable at each terminal node, which helps identify variables with the highest impact. The developed tree model shows the time lag to deploy a maintenance crew after a snowstorm starts, the percentage of MSR, and the slope of the vehicle speed reduction graph affecting SRD, while snow precipitation or type, pavement temperature, and winter maintenance operation hours show less statistical association. Also, it is noted that the impact by the variables is different based on snowstorm duration and average winter traffic volume. For example, if the storm duration is smaller than 11.12 h and the WADT volume is smaller than 21,000, SRD is highly associated with time lag for crew deployment.

As a next step, a GUIDE piecewise linear least-squares model with stepwise variable selection was developed. Stepwise variable selection helps to find the best set of variables to construct a regression model. As can be seen in Figure 8, storm duration is the first split variable, and if storm duration is briefer than 12.5 h, the tree splits again at WADT equal to 24,700. If storm duration is longer than 12.5 h, a split occurs at WADT equal to 6,043. This tree represents the six different regression models obtained through the stepwise variable selection process.

Table 4 shows the coefficients of the six developed regression models. The percentage of MSR appears in most regression models, which indicates the variable is highly associated with SRD in most cases. Also, CrewDelayed and StoS2MSR show statistically significant association with the SRD. In other words, as vehicle speeds reach MSR quickly and the percentage of speed reduction increases, generally more time will be required to recover vehicle speed to normal winter speed. Also, when storm duration is smaller than 8.6 h,

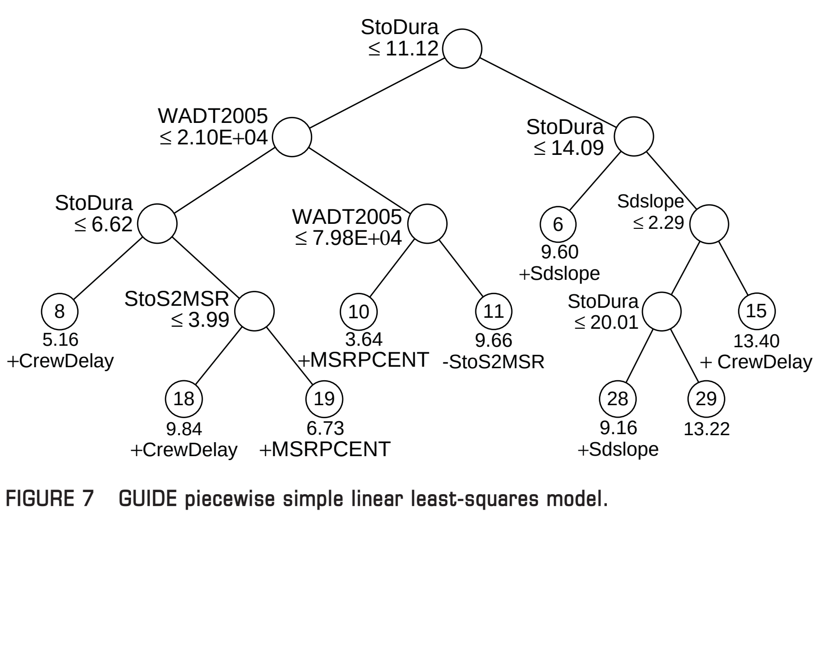


FIGURE 7 GUIDE piecewise simple linear least-squares model.

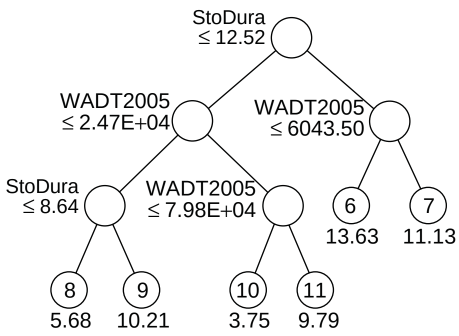


FIGURE 8 GUIDE piecewise simple linear least-squares model (stepwise variable selection).

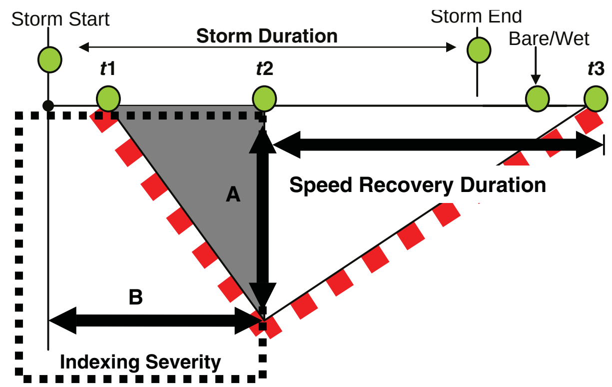
a 1-h delay in the maintenance crews dispatch results in an additional half hour in speed recovery time during winter weather events, if other conditions remain constant.

VEHICLE SPEED AS PERFORMANCE MEASURE

Vehicle speed during winter weather events is closely related to pavement condition, which is a critical component of winter driving. Also, vehicle speed data are relatively easy to collect and have high reliability compared to meteorological information. Therefore, vehicle speed seems to be an attractive measure for quality of winter maintenance operations.

TABLE 4 Coefficients of Least-Squares Regression Function

Regressor	Coefficient	*t*-Stat.	Min.	Mean	Max.
Node 8					
Constant	3.84	9.21			
MSRPCENT	11.16	6.10	0.00	0.17	0.52
StoS2MSR	–0.45	–5.29	0.00	2.67	15.50
CrewDelayed	0.61	7.44	–7.00	1.91	12.50
Node 9					
Constant	9.68	12.86			
MSRPCENT	9.93	4.54	0.01	0.24	0.53
StoS2MSR	–0.89	–8.34	0.00	3.58	10.98
CrewDelayed	0.49	6.91	–4.50	3.82	14.00
SnowDepth	–0.22	–2.05	0.12	2.42	12.00
Node 10					
Constant	2.65	7.22			
MSRPCENT	6.49	3.75	0.01	0.17	0.56
Node 11					
Constant	10.63	6.92			
MSRPCENT	22.78	2.34	0.03	0.13	0.38
StoS2MSR	–1.58	–3.51	0.00	2.36	8.48
Node 6					
Constant	13.63	32.28			
Node 7					
Constant	12.97	7.64			
PTMP	–0.13	–2.43	4.00	25.40	38.00
MSRPCENT	19.25	5.88	0.04	0.26	0.56
StoS2MSR	–0.47	–4.55	0.00	6.02	21.48
Sdslope	–0.15	–2.16	0.60	5.77	43.00



NOTE: A = maximum vehicle speed reduction in percent; B = time to maximum speed reduction from storm start time.

FIGURE 9 Speed recovery duration as performance measure.

As part of the study, SRD was developed as a performance measure of winter maintenance operations. Through a regression tree analysis, six different regression models were developed corresponding to storm duration and WADT. The six models adopted the SRD as a dependent variable and found independent variables that showed statistically significant association with the SRD. Figure 9 illustrates how MSR in percent and time to MSR from the storm start time can be used to index severity of winter weather events in general. Also, appropriate regression models can be used to estimate the time to recover vehicle speeds to normal driving speeds during the winter.

Figure 10 shows that if there is a roadway carrying 20,000 WADT and a winter weather event lasts 10 h, the regression model at node 9 (Table 4) can be adopted:

$$\begin{aligned}\text{speed recovery duration} = {} & 9.68 + 9.926 * \text{MSRPCENT} \\ & - 0.866 * \text{StoS2MSR} \\ & + 0.493 \text{ crewdelayed} \\ & - 0.222 \text{ snowdepth}\end{aligned}$$

If the winter weather event causes a 17% maximum speed reduction with 3 in. of snow and it takes 3 h to reach the MSR point with a 3-h delay in crew dispatch, the anticipated SRD from the model is 9.58 h. Therefore, if the observed SRD is smaller than 9.58 h, it is

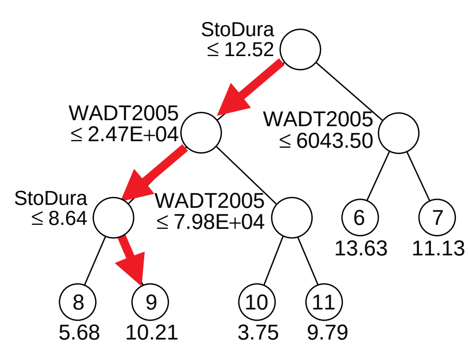


FIGURE 10 Selecting regression models.

concluded that maintenance operations in that particular roadway during the winter weather event is better than the previous 3-year average. This method does not require extensive meteorological data through the roadway weather information service (RWIS), and it avoids a geographical distance issue between RWIS locations and ATR locations. Certainly, the models and methods can be further refined and expanded to a better rating system such as a level-of-service rating used in traffic engineering.

CONCLUSIONS AND RECOMMENDATIONS

The study investigated vehicle speed changes during winter weather events. A total of 954 winter maintenance logs in 24 counties over three seasons were analyzed. Several variables of interest were developed, such as storm duration, maintenance operation hour, crew delayed, MSR, and the storm start and end times. Also, $t1$, which represents the start of vehicle speed reduction, and $t3$, the time when vehicle speeds recover to normal winter driving speeds, were measured from ATR data.

In general, the storm duration has been around 10 to 11 h for the last 3 years, and maintenance operations last 14 to 15 h. Usually, maintenance operations started a few hours after winter weather events started and continued until roadway pavement reached the bare and wet condition. Vehicle speed started to drop less than 1 h after the storm started, and the MSR was usually attained within 3 to 5 h. The amount of maximum speed reduction was 13 to 15 mph, which accounted for a 20% speed reduction compared to normal winter driving speeds. Vehicle speeds recovered within 1 h or less after roadway pavement reached the bare/wet condition. There was no major difference in vehicle speed reduction and recovery between counties in different categories.

The study confirms that vehicle speed seems to be a good measure of representing driving conditions during winter weather events and winter maintenance performance alike. SRD was found to be a dependent variable, defined as a possible evaluation of winter maintenance operations using vehicle speed data. It represents the time from MSR to $t3$ and assumes that the performance of winter maintenance operations will affect this duration.

With regression tree analysis, six different regression models were developed, corresponding to storm duration and winter average daily traffic. Delay time for crew dispatch, MSR percent and time to the MSR point after the storm start are major independent variables that affect SRD in general. According to the developed models, a longer SRD is expected if the MSR point is reached quickly and if the percentage of MSR is larger. Also, the delay time of crew dispatch may result in additional hours in SRD, depending on the situation.

A method is introduced for using a developed regression model to index the severity of winter weather event. The proposed method requires minimal meteorological data collection, and it mainly uses ATR data that will minimize potential errors by adopting two different data sources to measure performance of the system.

Overall, vehicle speed is a good measure for winter maintenance operations, and speed data are easy to collect with existing ATR locations. In addition, vehicle speed is easily understood by the public. Therefore, using vehicle speed as a performance measure has great potential to improve all winter maintenance operations by providing a fair assessment of performance.

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APPENDIX A

ROADWAY CATEGORY FOR WINTER MAINTENANCE

This appendix contains information related to winter maintenance operations on the five different roadway categories. The information is taken from the Wisconsin DOT website, in regard to passable roadways (www.dot.wisconsin.gov/travel/road/passableroadways.htm; accessed June 12, 2007).

Category 1

Major urban freeways and most highways with six lanes and greater.

These highways are considered high volume and receive 24-h coverage during the winter storm event.

Category 2

High-volume four-lane highways (AADT ≥ 25,000), some four-lane highways (AADT < 25,000), and some 6-lane highways.

These highways are considered high volume and receive 24-h coverage during the winter storm event.

Category 3

All other four-lane highways (AADT < 25,000).

These highways may be considered either high volume or all other, and they should receive either 18- or 24-h coverage during the winter storm event.

Category 4

Most high-volume two-lane highways (AADT ≥ 5,000) and some two-lane highways (AADT < 5,000).

These highways are considered high volume and receive 24-h coverage during the winter storm event.

Category 5

All other two-lane highways.

These highways are considered all other, and they receive 18-h coverage during the winter storm event.

EXCEPTIONS

Exceptions to this guideline will occur when subsequent winter storm events happen at a frequency at which it is not possible to obtain passable roadway conditions and subsequently bare pavement between the events. The severity of a winter storm event, roadway temperatures, and availability of resources, along with other factors, will dictate how soon passable roadway conditions and subsequently bare pavement can be obtained. Also, it may be deemed appropriate to use extraordinary means when impending weather or an influx of traffic, such as traffic before a holiday, is anticipated. Another exception can occur when the department of transportation, because of budget restrictions or unavailability of de-icing chemicals, has requested that counties reduce the level of effort or passable roadway condition expectations during the winter storm event. In such a case, the department, after notifying and in cooperation with the counties, may reduce level of effort expectations on one, several, or all five categories as described.

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