PATCHINESS OF SNOW COVER AND ITS RELATION TO QUALITY ASSURANCE IN WINTER OPERATIONS

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1. Abstract

Uniform levels of service for winter operations are difficult to maintain across a large road network where snow conditions are monitored qualitatively and at infrequent intervals. The development of the variable slip approach to friction measurement provides an opportunity to measure or classify snow conditions automatically and with known reliability.

Four approaches by which friction measurements can enhance existing Quality Assurance methods were investigated; aggregate friction over a road segment, point-wise classification of surface conditions, point-wise measurement of snow covered area and, frequency and length of snow covered patches. Automatic classification of surface types was reliable under limited conditions while measurement of snow cover fraction was highly reliable. Aggregate friction and snow covered patch length were closely related to each other and both were related to elapsed time since application of road salt. Sampling spacing requirements varied with the patchiness of snow cover, with maximum number of samples required at mid-range values of friction.

2. Introduction and Background

Description of the quality of highway driving surfaces in winter is important to many aspects of highway maintenance operations. Quality assurance, monitoring of contracted operations to ensure that they meet defined levels of service, is one.

Levels of service for snow removal on highways in Ontario are specific to classes of traffic volume and to geographic location, and specify either maximum time allowed before bare pavement is restored after the end of a winter storm or on lower volume roads where bare pavement is not required, that a tractive surface be maintained free of loose snow, ruts and potholes (MTO, 1998). Plowing, salting or sanding operations are to be carried out as required until the specified conditions are met.

Surface conditions are observed and reported several times per day using a standard lexicon of qualitative descriptors to plan daily winter maintenance operations, and are checked at random intervals by Contract Administrators to ensure that Contractors meet standards. When standards are not met, the Contractor may be subject to sanctions. The random checks provide desirable flexibility in dealing with individual Contractors but can result in non-uniform application of standards across the province. A system of repeatable, objective measurements such as those obtained from friction measuring devices can help in applying standards uniformly.

General correspondence has long been observed between snow cover characteristics and conventional fixed slip or locked wheel surface friction measurements. However, the repeatability of measurements between samples and measuring devices may be insufficient to provide statistical confidence for quality assurance purposes.

The information content of friction measurements can be increased by variable slip devices which measure friction over a range of slip ratios or slip speeds at each sample location. Experience on bare pavement has shown that variable slip measurements define a relationship between friction and slip speed which is unique to a given tire, contact pressure and surface type, and can be used to measure surface texture (PIARC, 1992).

The shape of the curve can be represented by three parameters (Rado, 1994): peak resistance (F_p), slip speed at which the peak resistance occurs (V_{crit}), and locked wheel resistance (F_{60}) (Figure 1). F_p is the peak friction value of the slip-friction relationship and is the threshold about which ABS breaking systems cycle on wet pavement. Vcrit typically occurs at slip ratio in the range 10 to 20% on wet asphalt. F60 is the friction at a slip speed of 60 km/h and corresponds approximately to the slip speed at which locked wheel friction occurs on a wet asphalt surface under standard test conditions.

The increased information content of a variable slip measurement allows estimation of the peak friction and selection of a comparison point on the friction-slip curve which maximises the sensitivity to test conditions (Figure 1) compared with devices which measure at a fixed slip ratio.

Andresen and Rado (1995), Fleege and Wambold (1998), and Perchanok (1998), presented case studies suggesting that curve shapes may discriminate between different types of snow cover on a road surface (Figure 1). If the case study results can be applied under all winter conditions then variable slip friction measurements can be used to enhance Quality Assurance monitoring for winter operations.

The purpose of this paper is to investigate the correspondence between surface friction and descriptors of snow cover during winter storms, and to demonstrate the capabilities and limitations of its use to monitor the end result of maintenance operations.

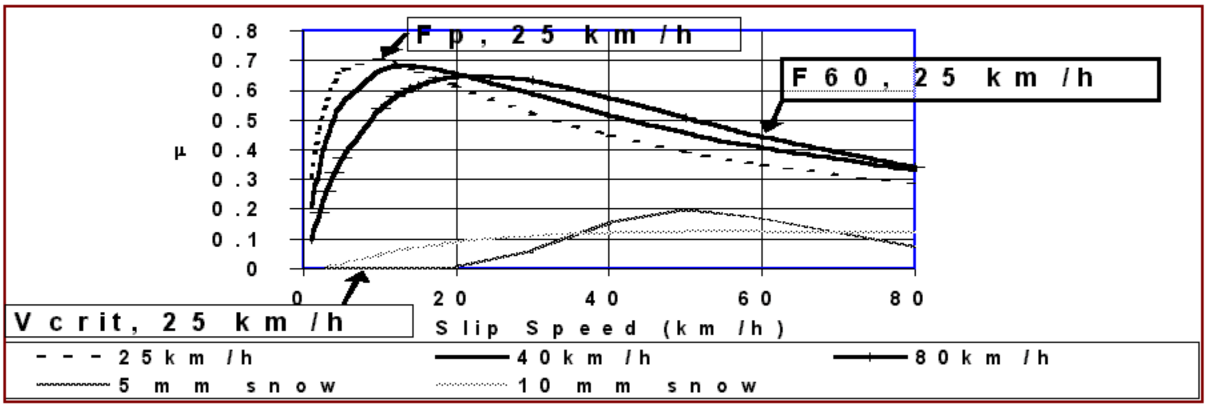


Figure 1. Friction, slip speed and tow speed on bare and snow covered pavement

3. Approach

This study examined four approaches to friction measurement for quality assurance:

Friction as an aggregated quantity

The mean and variance of F_p is described over a road segment of known length. This approach can be applied when standards specify a threshold value of mean friction. If the threshold is met as a mean value then the operation was successful and standards were met. It is an improvement over visual, qualitative description because it:

i) provides an objective, repeatable measurement
ii) can be applied over short or long road segments
iii) facilitates statistical analysis
iv) relates physically to vehicle traction, stopping distance and driving safety.

It does not provide direct information about the physical characteristics, extent or location of snow coverage on the road.

Classification of snow cover type at point

Case studies suggest that variable slip measurement can be used to automatically classify the type of material under the measuring tire. This improves upon simple measurement of friction by providing information about physical characteristics of the surface .

Measurement of snow cover fraction at a point

Friction measurements are used to predict snow cover fraction. Snow cover fraction is a companion measure to snow cover type but differs by varying continuously rather than in discrete types.

Measurement of snow cover patch length

Patches can be defined as discrete segments of a surface which have internally homogeneous characteristics. Predictive models relating friction at a measuring point to snow cover type or cover fraction can be applied to divide the measured surface into segments of known condition. This improves on simple measurement and on point-wise classification or description by providing information on the spacing and length of different surface qualities.

Different models are used in each investigation and impose different assumptions on the data. The methods and assumptions are described below.

4. Data Collection

Three data sets of variable slip friction and two data sets of snow cover conditions were acquired.

Sliding resistance was measured using a Norsemeter friction measuring device mounted on a trailer and towed by a van. Resistance was measured over a range of slip speeds by hydraulically braking a 35 cm diameter measuring wheel a blank-treaded pneumatic tire from a free-rolling to fully locked condition. Hydraulic pressure over a 1.7 second braking cycle was measured over .025 m of wheel rotation. Measurement cycles were separated by a short, operator-selectable interval normally set at 1.0 s in which the wheel recovered to free rotation. Hydraulic pressure in the brake system was converted to a friction coefficient, $\mu=f_v/f_h$ where f_v is the static load carried by the measuring tire and f_h is horizontal resistance calculated from pressure in the braking system. Data acquisition software fit a curve to the data points for each braking cycle and provided a value Fp, F_{60}, V_{crit} and a goodness-of-fit parameter (Norsemeter, 1997). The sampling distance covered by each braking cycle varied with the speed of the tow vehicle and averaged approximately 40 m for all data collected on the highway. The average tow speed was approximately 60 km/h. Each sample was annotated with distance traveled and time at the beginning of the measurement cycle.

The data set acquired for investigation of friction as an aggregated quantity was measured during 12 passes in one direction over an 8 km section of a 2-lane asphalt highway during 24 hours of a major winter snow storm on January 9, 1999. The measurement period included two cycles of snow accumulation and two cycles of snow depletion , during which the surface was plowed four times, salted four times and sanded twice.

The snow type classification data were acquired by operating the friction trailer on highways (MTO, 2001) and on icy airport runways (Boccanfuso, 1999) under a wide variety of snow conditions during three winter seasons. The measured surfaces were simultaneously videotaped from a tow vehicle or a roadside surveillance camera. Surface types were classified using pictures and sounds from the video tapes, and the classifications were matched with the approximate centre point of each 40 m long friction sample using time annotations on the video and friction data. Surface types were classified only when the surface appeared to be uniformly covered or bare.

A similar approach was used to acquire data for the snow cover fraction analysis using a subset of the January 9, 1999 data. Cover fraction was measured by dividing the driving lane into three lateral, 1.2 m square segments and estimating the cover fraction in each segment. Only the segment in the friction tire track was used in the analysis.

The data set acquired for investigation of friction as an aggregated quantity was also used for the analysis of snow cover segments.

5. Data Analysis

Friction as an aggregated quantity

Changes in F_p during a snow storm were investigated by comparing the variance structure and resulting confidence intervals with mean values for all measurement passes during the snow storm of January 9, 1999.

Confidence intervals on the mean value of a large, normally distributed data set can be estimated as: $c.i.=1.96/(\sigma/\sqrt{n})$, where $\sigma=\sqrt{n}\ (\sum x^2-(\sum x)^2/n(n-1)$. If the confidence interval is specified the number of samples required or the maximum sampling interval can be estimated as,
$n=(\sigma\ (1.96/c.i.))^2$.

In this study the required sampling interval over the 8 km road section was compared under a variety of real surface conditions during a winter storm using a 95% confidence interval about the mean of .05 friction units.

The variance structure was first investigated for each measurement pass using two statistics which summarise characteristics of the frequency distribution; variance and skewness. Variance is defined as σ^2 , and skewness is a measure of asymmetry of a distribution about the mean, where skewness=0 is symmetrical, skewness>0 indicate a right tale and skewness<0 a left tale of the distribution.

Transformations were applied in each pass to minimise skewness and normalise F_p before estimating σ and n. Trends in distribution characteristics and confidence intervals were then compared.

Classification of snow cover type at point

Discriminant analysis was used to investigate whether friction can be used to classify types of snow on a paved highway surface. Discriminant analysis identifies a linear combination of predictor variables that maximise differences between two or more pre-defined groups, and classifies each observed case into one of the groups (Klecka, 1975).

Discriminant analysis requires data with the following characteristics::

1) normal distribution within groups,
2) equality of variance across groups and variance is independent of the mean,
3) relationships among predictor variables are linear,
4) cases are equally distributed across groups.

The assumptions were not met by the raw data sets and power transformations based on a Spread-Level analysis (SPSS, 1999) were applied to normalise distributions and equalise variance across groups. Log Determinants which are an indicator of co-variance across groups, were used as a standard of acceptance for transformations such that models in which Log Determinants varied by sign or by more than 100% across groups were rejected.

Linearity of variable relationships was screened using scatterplots of the selected transformations and data.

The last assumption ensures that the discriminant functions respond to the strength of variable relationships and not to the number of repetitions of those relationships. The data sets were collected in an uncontrolled manner which did not equally represent all variable conditions or groups and therefore weight factors were calculated for each analysis to equalise repetitions in each group.

Model fit was assessed by comparing predicted with known classifications using a validation data set. Results were assessed separately for each snow type because the number of cases varied widely by snow type and because snow types may have a different frequency of occurrence in general application than they do in this data set. In the validation data set each case was classified using a model computed from all cases except the one being classified (SPSS, 1999).

Measurement of snow cover fraction at a point

Multiple regression analysis was used to develop a model predicting snow cover fraction from the variable slip friction parameters. Unlike snow cover type, cover fraction is a continuous quantity which may have values anywhere between 0 and approximately 1. Multiple regression is a suitable tool where the variate is determined by the value of one or more continuous or discrete variables.

Multiple regression analysis requires that input data have the following characteristics:

1) cases are independent and normally distributed,
2) relationships between variables are linear and,
3) residuals are randomly distributed.

Normality was assessed using the skewness coefficient. Transformations were applied to each variable and the one which resulted in skewness closest to zero was used to develop the regression models. Linearity between transformed variables and the random distribution of residuals was assessed using scatter plots.

Measurement of snow cover patchiness

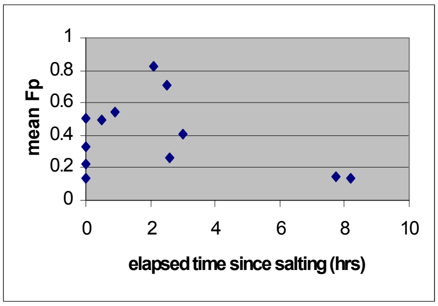
Each pass of the continuous variable slip record from January 9, 1999 was divided into segments of bare pavement and snow covered pavement using an arbitrary threshold of F_p. Segments with F_p >.30 were defined as bare pavement and those with F_p <=.30 were defined as snow covered.

Variance and skewness coefficients were estimated for each measurement pass. Data were analysed to show relationships between the distribution characteristics, similar measures of friction, and snow clearing operations during a winter storm.

6. Results

Friction as an aggregated quantity

F_p varied increased and decreased through two cycles during the period monitored, but comparison of mean values with salt application times indicates a trend of increasing F_p during the two hours after salt application and decreasing F_p with time after that (Figure 2). Three sample traces from times of low, medium and high mean F_p show that variance increased with the mean value of F_p (Figure 3).



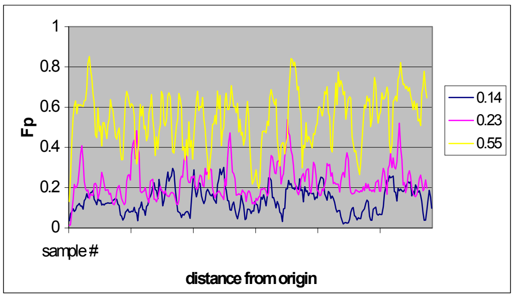
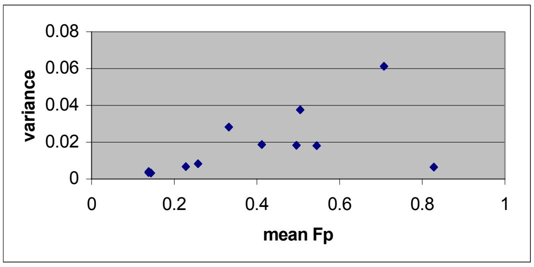


Figure 2. Effect of salt application on mean F_p. **Figure 3**. Fp on three measurement passes

Variance was not directly correlated with mean friction but peaked at mid-range values (Figure 4). The distribution of F_p values as represented by the coefficient of skewness, was Gaussian during measurement passes with minimum values of F_p, strongly right-tailed during passes with low mean F_p, and shifted gradually to a strongly left-tailed distribution with increasing F_p (Figure 5). The trends in variance and skewness at mid-range of F_p suggest that F_p does not represent a continuous variation in surface characteristics. Instead, low mean values are the aggregate of many low values and a few high values and high mean values are the aggregate of many high values and a few much lower values. At the mid range of mean Fp the numbers of high and low readings are balanced. Reference to mean values shown on Figure 2 indicates that similar trends were observed through two consecutive cycles of snow accumulation and removal.



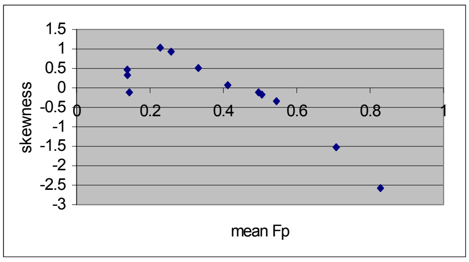
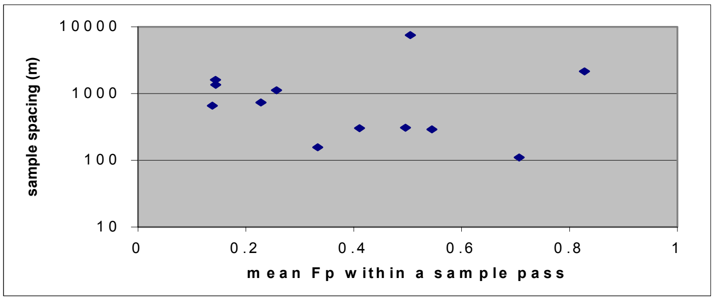


Figure 4. Change in variance with mean F_p **Figure 5**. Change in skew with mean F_p

Using normalising transformations appropriate to each distribution, the sample spacing required to define 95% confidence intervals within +/-.05 units of the mean was estimated (Figure 6). The maximum sample spacing allowed by the confidence interval was 1000 m for a sample pass with mean Fp< 0.2 and 100m for a sample pass with mean Fp of 0.7.

Figure 6. Change in sample interval with mean F_p, +/- .05 mup



Classification of snow types

Snow conditions on the road or runway surfaces were originally classified into 13 types. These thirteen types were merged into the three classifications systems shown in Tables 1, 2 and 3 including two, three and six groups respectively.

Boxplots showing the median, quartiles and outliers of F_p, F_{60} and V_{crit} for the six group classification (Figure 7) suggest that any one variable is unlikely to discriminate all groups and that discrimination may be improved using two or three variables together.

Discriminant models were developed using predictor variables F_p, F_{60} and V_{crit} individually and together for each of the snow type classifications. The best classification results for the two group classification were obtained using F_p alone as predictor. Model assumptions were met using F_p in raw form .

Table 1.
Two group classification of snow type

1-A	1-B
Bare dry, Bare wet	packed snow, bare ice, snow on ice

Table 2. Three group classification of snow type

2-A	2-B	2-C
bare dry, bare wet	packed snow, bare ice, snow on ice	slush, wet snow

Table 3. Six group classification of snow type

3-A	3-B	3-C	3-D	3-E	3-F
Bare dry, bare wet, slush	wet snow, bare ice, snow on ice	thin snow, loose snow	packed snow	sanded pack	packed snow on ice, wet snow on ice, snow on rutted ice

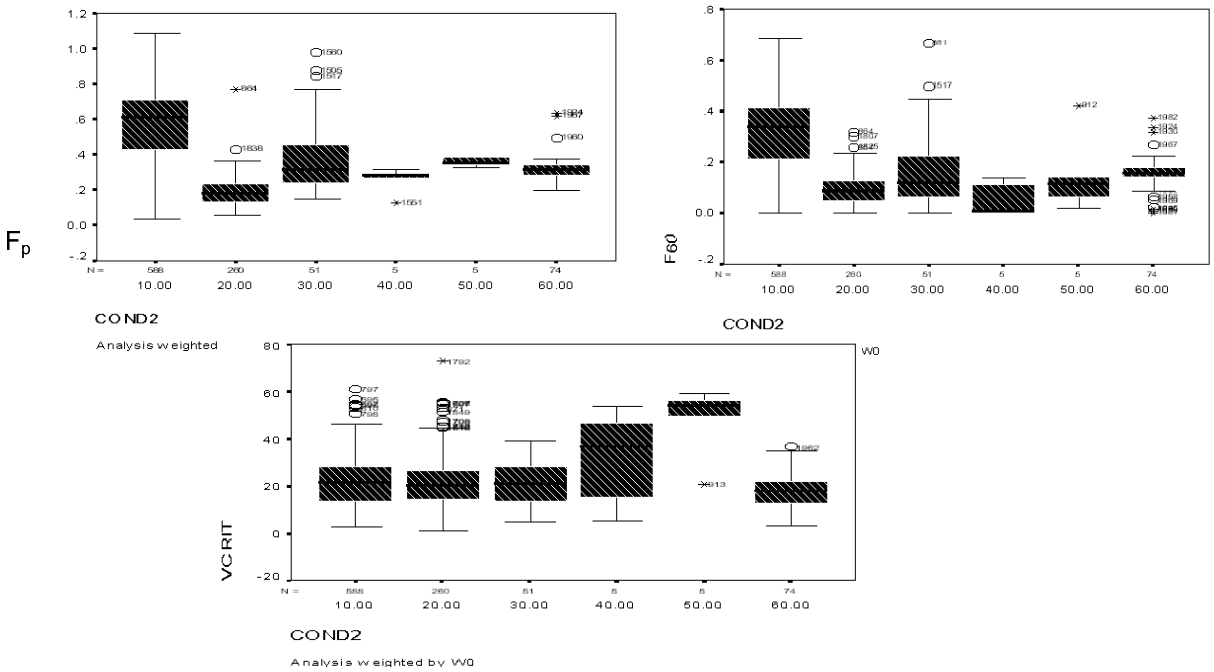


Figure 7. Boxplots of F_p, F_{60}, V_{crit} from classification data set
(Cond2 defined in Table 4)

The two group analysis correctly classified a total of 96% of the cross-validated cases with 92.5% of bare pavement cases and 99.6% of snow covered cases correctly classified.

The best classification results for the three group classification were obtained using predictor variables F_p, F_{60} and V_{crit} together. Model assumptions were met using F_p and V_{crit} in raw form, and F_{60} transformed as square root.

The analysis resulted in two Canonical Discriminant Functions and three Classification Functions which correctly discriminated at total of 66% of the cross-validated cases with 70.1% of bare pavement, 99.6% of snow covered and 31.6% of slush or wet snow cases correctly classified. This indicates that classification was not reliable in slush and wet snow conditions with partial contact with the pavement. The pattern of misclassification between groups indicates that friction on slushy and wet surfaces was more similar to bare pavement than to fully snow covered pavement.

The best classification results for the six group classification were obtained using predictor variables F_p and F_{60} together. Model assumptions were met using F_p and F_{60} transformed as square root.

The analysis for Snow Class Group 3 resulted in two Canonical Discriminant Functions and six Classification Functions which correctly discriminated at total of 50.6% of the cross-validated cases broken down as shown in Table 4. The % intersection of a row with a column indicates the proportion of cases of a snow group which were classified into itself and into each other group. 100% intersection of a group with itself indicates perfect classification of that snow group.

Classifications of snow types into two, three and six groups indicate were successful in discriminating between surface types with full snow cover or ice cover, or bare pavement. Discrimination was less effective between packed snow and ice vs. snow on ice, and between packed snow and sanded pack. The least successful classification was loose or thin snow where partial contact with the pavement may have occurred.

This discriminant analysis suggests that the variable slip approach can discriminate between bare or snow covered surface types when the surface is homogeneous but cannot discriminate types under conditions of partial contact with pavement.

Table 4. Discriminant Analysis Results, Six Group Classification
classification results from cross-validated sample

Group	% classified in group					
	10	20	30	40	50	60
10. bare pavement, slush	74.5	6	2.4	5.4	8.5	3.2
20. wet snow, bare ice, loose snow on ice	.4	71.5	.8	13.8	3.1	10.4
30. loose snow, thin snow	29.4	15.7	3.9	23.5	17.6	9.8
40. packed snow	0	20	0	60	0	20
50. sanded pack	20	0	20	20	40	0
60. packed, wet snow on ice, snow on rutted ice	5.4	2.7	17.6	13.5	13.5	47.3

Measurement of snow cover fraction

Snow cover fraction was measured for 34 samples from the friction data set of January 9, 1999. Model assumptions were met using Log F_p, raw values of F_{60} and raw values of (V_{crit}/tow speed). The latter variable is interpreted as the slip ratio at F_{60}.

The model equation, cover fraction=.419+.688 F_p -.775 F_{60} -.245 V_{crit}, had regression coefficients significant at $\alpha<.01$ and explained 94% of the variance in snow cover fraction. 88% of the variance was explained by F_p, an additional 3% by F_{60} and an additional 3% by V_{crit}. Both the standard error of the estimate and the mean residual of snow cover fraction were <0.005.

This indicates that snow cover fraction under the measuring wheel was reliably predicted using the variable slip approach and suggests that variable slip friction measurements can be used to estimate snow cover fraction for Quality Assurance purposes.

Snow cover patchiness

The mean length of snow cover patches in each measurement pass was estimated using a simple threshold value of F_p. The mean length of snow patches had an inverse logarithmic relationship with mean F_p, indicating that a small increase in friction was associated with a large decrease in the average length of snow patches at low friction values during the storm of January 9, 1999 (Figure 9). The highest frequency of snow patches was associated with mid-range of F_p. This is in agreement with trends observed in the variance of F_p with mean values of F_p for each measurement pass (Figure 4).

Total snow covered length on each measurement pass was calculated (Figure 10), showing a linear trend with F_p and providing a measure for the effectiveness of maintenance operations.

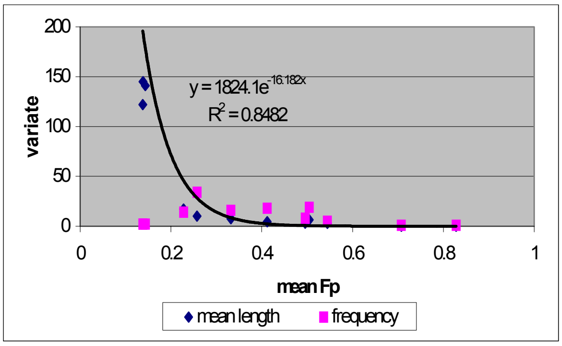


Figure 9. Mean length and total number of snow patches

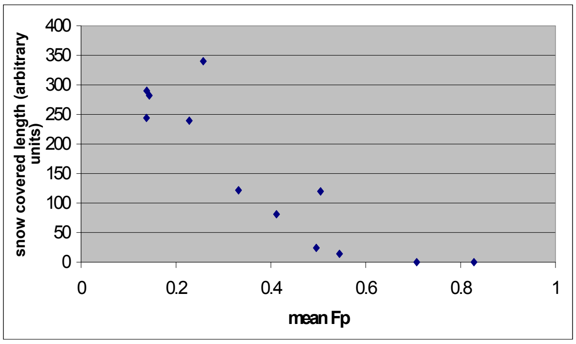


Figure 10. Snow covered length and mean F_p

Figure 11 indicates that total snow covered length decreased up to three hours after salt application and increased for longer time periods in keeping with the trend in F_p (Figure 2).

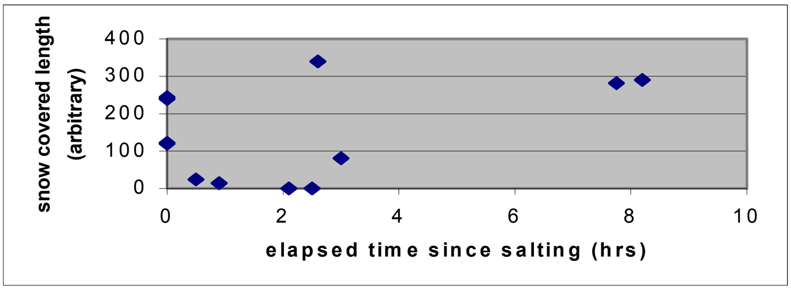


Figure 11. Snow covered length and maintenance operations

The analysis of snow patch length supports conclusions from the analysis of F_p, that changes in mean friction result from changes discrete patches of high and low friction which are patches of bare and snow covered pavement, and not from a continuous, gradual shift in friction at all points in the measurement area.

7. Discussion and Conclusions

Analysis of peak friction estimated from variable slip friction measurements during snow storm conditions showed that the variance followed predictable trends with the mean value and with the distribution of snow cover. Changes in the variance structure resulted in sampling interval requirements which varied with the mean value during a storm event, ranging from about 100 metres at mid values of mean F_p to more than 1000 metres at extreme high and low values of mean F_p, for 95% confidence intervals of +/-.05 units. Patterns of variance were consistent through two cycles of snow accumulation and snow depletion over 24 hours.

Two surface types, bare and fully snow or ice covered, were successfully discriminated using F_p alone. Discrimination of many surface types when grouped into three or six different groups was less successful. Non-rigid surfaces where the measuring tire may come in partial contact with the pavement were badly mis-classified using one or more of F_p, F_{60} and V_{crit} as classifiers.

The fraction of the pavement surface covered with snow in the friction wheel track was reliably predicted using a multiple regression with F_p, F_{60} and V_{crit}. This indicates that snow cover fraction can be reliably measured using a variable slip friction device.

When a threshold of F_p was used to discriminate bare from snow covered road segments, the average length of snow patches on a given pass had an inverse exponential relationship with mean F_p, while the number of patches was highest on measurement passes with mean F_p in mid-range.

Correspondence of maximum variance of F_p and maximum number of snow patches at mid-range F_p indicates that the mean value of F_p over a measurement pass are the aggregate of discrete patches of low friction snow and high friction bare pavement rather than from a continuous, gradual shift in friction at all points in the measurement area.

F_p increased and total length of snow cover decreased during the first two hours after salt application, and then increased with elapsed time. This suggests that either F_p or snow covered length can be used to measure the level of service attained, based on elapsed time to achieve bare pavement or some other measure of surface quality.

This study demonstrates that variable-slip friction measurements can enhance or substitute for qualitative observations to objectively and repeatably measure compliance with level of service standards based on the extent of snow cover on the road surface. Additional work is required to extend its use to classifying snow types.

8. Acknowledgements

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9. References

Andresen, H, and Z. Rado, 1995. Tire Friction on Winter Surfaces. Summer-Winter Integrated Field Technologies (SWIFT) Symposium, Transport Canada, Winnipeg.

Boccanfuso, A., 1990. Management of the Joint Winter Runway Friction Measurement Program (JWRFMP), in, Proceedings, 2nd International Meeting on Aircraft Performance on Contaminated Runways, Montreal, Transportation Development Centre, Transport Canada TP 13579. November 1999.

Fleege, E.J. and J.C. Wambold, 1998. Variable Slip Friction Measurement Techniques for Snow and Ice Operations. Xth PIARC International Winter Road Congress, PIARC-World Road Association, published by Swedish National Road and Transport Research Institute, Linkoping.

Klecka, W.R., 1975. Discriminant Analysis, in Statistical Package for the Social Sciences, N.H. Nie et al, editors, McGraw-Hill, New York, 1975.

MTO, 1998. Maintenance Policy 98-01, Operations Division, Ontario Ministry of Transportation, St. Catharines, Ontario.

MTO, 1999. Maintenance 2001 Project Web Site.

Norsemeter, 1997. ROAR Owner's Manual. Norsemeter AS, Norway.

Perchanok, M., 1998. Friction Based Measures for Snow Clearing Operations. Xth PIARC International Winter Road Congress, PIARC-World Road Association, published by Swedish National Road and Transport Research Institute, Linkoping.

PIARC, 1992. International Experiment to Compare and Harmonize Skid Resistance and Texture Measurements, Publication 01.04.T, 1992.

Rado, Z., 1994. A study of road surface texture and its relationship to friction. PhD Thesis Dissertation, Department of Mechanical Engineering, The Pennsylvania State University, 169 pp.

SPSS, 1999. Statistical Package for the Social Sciences, Base 9.0 Applications Guide, SPSS Inc., Chicago, 1999.