Evaluation of Semiautomated and Automated Pavement Distress Collection for Network-Level Pavement Management

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The Ministry of Transportation Ontario (MTO) and the University of Waterloo examined the feasibility of using automated pavement distress collection techniques in addition to data collected through manual surveys. Test sections including surface-treated, asphalt concrete, composite, and portland cement concrete pavement structures in 37 locations in southern Ontario, Canada, were evaluated. Distress manifestation index (DMI) values were computed for each section by MTO pavement design and evaluation officers using the manual evaluation data collected. DMI values were then computed for each section by using automated distress evaluation data. Before DMI values could be computed, the relevant data had to be extracted and verified, and the distress data had to be categorized. DMI values computed from data collected manually and by using automated systems were compared. Finally, a repeatability analysis was performed on both the manual and the automated techniques. Results indicate no significant differences among sensor-based equipment; however, there are significant differences among measurements obtained from digital image–based technology. The implications of such outcomes are discussed, including the specifics regarding methodology implementation in order to encourage practitioners to benefit from the preliminary investigation. Current available techniques can provide MTO with valuable information for pavement management purposes. The automated results are comparable with manual surveys. However, these surveys should be supplemented with manual surveys, especially for design purposes, because some of the pavement distresses were difficult to identify with the automated methods.

Pavement management systems (PMSs) rely on consistent and repeatable distress data collection. Traditionally, such data have been collected through manual surveys, which are subjective, tedious, and time consuming. Ideally, the data would be collected at travel or high speed with state-of-the-art image-capture equipment. Considerable research and development have gone into such high-speed data collection and analysis, and several units are commercially available around the world (*1*).

The Ministry of Transportation Ontario (MTO), like many provincial and state departments of transportation (DOTs), was interested in determining which of these units or systems, if any, are applicable to Ontario, Canada, needs and if so, whether they can replace or supplement the existing manual approach. This required a review of available high-speed data collection technologies, an evaluation of their capabilities, and an experiment to compare the best technologies identified with the manual approach. In addition, it was desirable to streamline the number of distress types collected in the manual approach. The term "automated" in this paper refers to both automated and semiautomated distress surveys. The work plan included a comprehensive literature review, an identification of the most promising technologies, and the design and execution of a field experiment to compare and assess the automated technologies vis-à-vis the manual method. The paper summarizes the design and results of the experiment and includes a set of recommendations for application to network-level usage of automated distress surveys for a DOT.

ANALYSIS APPROACH

The goal of this study was to determine the applicability of automated pavement distress data collection and processing for a large transportation agency by using data from the province of Ontario. As part of this research, a test circuit was designed that consisted of 37 pavement sections located in southern Ontario. All four pavement types were examined, including surface treatments, asphalt pavements, concrete pavements, and composite pavements. Three consultant service providers collected automated distress data over the 37 test sites and a team of MTO pavement evaluators manually evaluated the pavements. These data provided a basis for relating manual surveys to automated surveys.

The study involves the following main aspects:

- To assess data needs required for pavement management. This approach is expected to identify the type of information that the agency is currently collecting manually in the field, how that could be collected with automated equipment, and how the data elements might be loaded into a PMS;
- To evaluate the accuracy, repeatability, and consistency of current pavement condition data collection methods and compare them with available automated data collection technology; and
- To recommend the type of technology that should be used for data collection and processing by the MTO. This includes providing detailed procedural guidelines and specifications for both performing automated condition surveys and improving the use of the automated pavement distress data collected in the ministry's PMS.

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The study involved an extensive statistical analysis of the field experiment information and current industry practices to evaluate the following:

- Differences among devices, through comparisons among the automated systems for consistency of observation on a given segment;
- Difference between a pair of devices, through comparisons between the automated systems for consistency of observation on a given segment;
- Equipment repeatability, through comparisons among the automated systems for the repeatability of observations on the same test segments;
- Validity of custom-based performance indicators, through comparisons between performance indicators calculated by using automated systems and ground truth;
- Distresses with greatest reliability, through comparisons among pavement distresses by using the automated systems and ground truth;
- Variability of image-based technology, through the correlation of custom-based performance indicators between automated systems and ground truth; and
- Variability of sensor-based technology, through the correlation of ride quality performance indicators among automated systems.

The approach employed to achieve these objectives is illustrated in Figure 1. The primary basis of assessment involved the calculation of the distress manifestation index (DMI) and comparisons with both manual and automated methods.

AUTOMATED TECHNOLOGIES

The longitudinal profile of a roadway can be measured automatically by instrumented vehicles in order to evaluate the road user's ride quality (*2*). The systems evaluated in this study measured the road surface profile with noncontact sensors (laser, infrared, or ultrasonic beam) and measured the vertical displacement between the vehicle and the road. An integrated accelerometer in each sensor measured vertical acceleration. Signals from the noncontact sensors, accelerometers, and distance measuring system are fed into a computer that calculates the profile of the pavement. Profile data are recorded at evenly spaced intervals (usually 25 mm) and stored on computer hard disk for further processing. This involves the calculation of a ride quality index, which is a primary criterion to assess performance of new and rehabilitated pavements, by using mathematically standardized procedures.

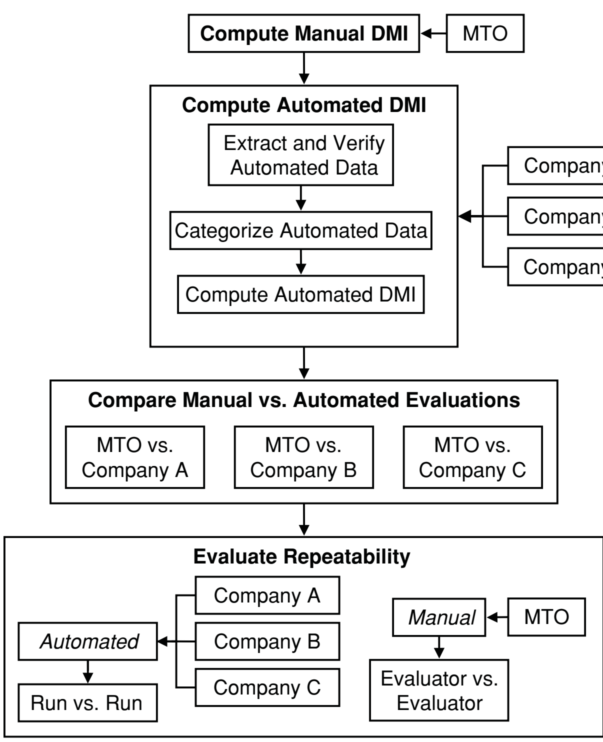

FIGURE 1 Methodology of statistical analysis.

Although roughness is somewhat related to surface distress (the more cracks, the rougher the pavement will be) as well as structural integrity (surface distress can be a sign of impending or current structural problems), pavement roughness alone does not provide detailed information about the surface pavement condition. However, information is available through image-based devices. Image-based technology involves the identification of pavement surface distresses (e.g., cracking and patching) from pavement images by the means of photographing, videotaping, and digital image capturing. Surface distress modes can be broadly classified into the following three groups (*3*):

- Fracture. This could be in the form of cracking (in flexible and rigid pavements) resulting from such things as excessive loading, fatigue, thermal changes, moisture damage, slippage, or contraction.
- Distortion. This is in the form of deformation (e.g., rutting, corrugation, and shoving), which can result from such things as excessive loading, creep, densification, consolidation, swelling, or frost action.
- Disintegration. This is in the form of stripping, ravelling, or spalling, which can result from such things as loss of bonding, chemical reactivity, traffic abrasion, aggregate degradation, poor consolidation or compaction, or binder aging.

Integrated systems are multipurpose vehicles that contain both embedded digital-imaging and laser-sensing technologies. In a single pass of a data-collection vehicle configured as an integrated system, a variety of data will be collected, depending on specific vendor and user requirements. Some of the data elements collected include pavement distress, right-of-way information, and other images such as signs, longitudinal and transverse profile measurements, and in some cases a texture-measuring system. These systems are in a state of rapid evolution, but several limitations of the equipment have been identified, as reported by Sokolic et al. (*4*).

Whether images are captured through photologging or videotaping, the control of film or tape progression and tying images to specific mile points can be an onerous task. For that reason, almost all image-collection procedures now require that the images be date-, time-, and location-stamped. The location will often be coordinates derived from global positioning system instrumentation on the survey vehicle. This means that agency roadway files (inventory) must also be tied to those coordinates. The identification of various distress types as well as their severities and extents from images requires observers or raters who have been well trained in both pavement distress evaluation and in the use of the workstation hardware and software. The rating process is extremely demanding, for raters must be able to coordinate the simultaneous use of several monitors while keeping track of the observed distresses and entering those observations into rating software.

TEST SITE SELECTION AND TESTING PROGRAM

In collaboration with MTO, the base record information for the needs sections included in the field experiment design was provided as stored in the ministry's PMS database. The test sections were selected to cover a range of pavement types found in Ontario, including asphalt concrete (AC), composite (COM) composed of a rigid base with an asphalt concrete surface, bituminous surface treatment (ST), and portland cement concrete (PCC) pavements. In addition, the sections covered a variety of pavement conditions ranging from good to poor and included most of the significant distresses rated in Ontario. Flat and hilly terrain areas were included in the test section selection, but bridges, intersection roads, sudden changes in grade, curvature, or excessive distress in the wheel paths were avoided. Various site conditions, such as different traffic volumes and number of lanes, were also incorporated in the study. The minimum length of each site was at least 500 m with enough extension so the survey equipment could safely accelerate to operating speed and decelerate securely.

The location of the test sections was also considered. In order for the service providers to be able to complete the testing within the anticipated period and within their businesses' constraints, most of the sections were located in southern Ontario. Within each section, a length of pavement was identified for evaluation and marked accordingly in the field.

DATA COLLECTION

Traditionally, subjective measurements have been the primary method for monitoring surface distresses. The most recent protocols for the various types of pavements (*5–9*) include rules for identification of distresses and quantification (i.e., severity and density levels). These also provide information on documenting pavement condition through standardized pavement condition evaluation and calculation for condition indices. Detailed training of regional pavement design and evaluation officers ensures consistency across the province. Annual training is provided to staff, and the differences noted between evaluators are very small.

The data collection approach was to provide the basis for a comparative evaluation of the techniques, equipment, and field and office procedures. The distresses of most interest for this study, in accordance with current MTO protocols, are identified in Table 1.

Each test section was rated by three MTO rating crews whenever possible. The MTO rating crews conducted pavement condition ratings on each test section according to the detailed distress survey procedures described above. The data were submitted according to MTO standard operating procedures.

Several independent pavement engineering consulting companies were screened for the technology they used and their experience, service options, and availability. Three were identified to collaborate in this research study and invited to demonstrate their technology in Ontario on the 37 test sections. These partners are identified as companies A, B, and C. These three service providers collected data on the test sections with their own automated equipment in August and September 2004. The service providers were encouraged to work according to their individual common specifications as much as possible.

GROUND TRUTH BENCHMARK MTO MANUAL SURVEYS

The motivation for establishing a "ground truth" or benchmark was to provide a basis for comparing the three automated measures with the manual MTO DMI measures. Depending on how subjectively pavement surface distresses are identified and measured, assessments of the pavement condition can vary significantly. Therefore, a ground truth was established on the basis of the ratings conducted via a visual survey by experienced MTO personnel and by using the previously mentioned protocols to identify and quantify the various distresses for all the pavement types.

Two main aspects of the MTO protocol were considered in the establishment of the ground truth. First, pavement condition information for each type of pavement on Ontario provincial highways was considered in the study. Second, DMI was calculated to reflect the overall Pavement Condition Index. The numerical reduction required to determine the DMI of each pavement section from the manually collected condition information is presented in the next section. The resulting DMI values that represent the ground truth are also presented.

It was not possible to establish a ground truth for three asphalt sections as visual ratings were not made available for these sections. Where multiple visual surveys were performed in the same section, DMI values were computed from the data collected by each evaluator and the average was taken. When sections were subdivided into segments and an evaluation was performed on each segment, as was the case in the composite pavement surveys, the severity and density values for the entire section were averaged before computing the DMI in order to remain consistent with the other sections.

TABLE 1 Pavement Distresses by Pavement Type

Flexible	Rigid	Surface Treated	Composite
Raveling	Raveling	Raveling	Raveling
Flushing	Polishing	Flushing	Flushing
Rippling/shoving	Scaling	Streaking	Spalling
Wheel track rutting	Potholing	Potholing	Tenting or cupping
Distortion	Joint cracking or spalling	Rippling and shoving	Wheel track rutting
Longitudinal wheel track cracking Single or multiple Alligator cracking Meander and mid-lane	Faulting	Wheel track rutting	Joint failure
	Distortion	Distortion	Distortion and settlement
	Joint failure	Longitudinal cracking	Longitudinal meander cracking
Transverse alligator	Longitudinal meander cracking	Transverse cracking multiple	Pavement edge breaking
Centerline alligator	Transverse cracking	Transverse joint reflective cracking	Alligator cracking
Pavement edge single multiple	Sealant loss	Centerline cracking single	
Pavement edge alligator	Diagonal corner or edge cracking	Centerline cracking multiple	

TABLE 2 Surface Distresses and Weighting Factors for Manual Evaluations

AC Pavement	W	PCC Pavement	W	COM Pavement	W	ST Pavement	W
Raveling	3	Raveling	0.5	Raveling	3	Raveling	3
Flushing	1.5	Polishing	1.5	Flushing	1.5	Flushing	2
Rippling or shoving	1	Scaling	1.5	Spalling	2	Streaking	1
Rutting	3	Potholing	1	Tenting or cupping	2.5	Potholing	1
Distortion	3	Joint cracking or spalling	2	Rutting	3	Rippling and shoving	2
Multiple cracking	1.5	Faulting	2.5	Joint failure	3	Rutting	3
Alligator cracking	3	Distortion	1	Distortion and settlement	1	Distortion	3
Meander mid-lane cracking	1	Joint failure	3	Longitudinal meander cracking	2	Longitudinal cracking	1
Transverse alligator	3	Longitudinal meander cracking	2	Transverse cracking multiple	1	Pavement edge breaking	2
Centerline alligator	2	Transverse cracking	2	Transverse joint reflective cracking	2	Alligator cracking	3
Pavement edge single/multiple	0.5	Sealant loss	0.5	Centerline cracking single	0.5		
Pavement edge alligator	1.5	Diagonal corner/edge cracking	2.5	Centerline cracking multiple	1.5		

The DMI values provided an approximation of ground truth that was later used to estimate how well the output of automated evaluation systems represented the distresses that appeared in the pavement sections.

CALCULATION OF DMI FROM MANUAL MTO EVALUATIONS

In Ontario, individual surface distresses are identified by severity and density levels to reflect the pavement surface condition. Table 2 is an example showing individual distresses and their weighting factors for individual pavement types used in the ministry's PMS-2 application. The ministry uses Equation 1 to convert the assessments of all individual distresses into DMI, which is a subjective rating index for the evaluation of pavement distresses manifested on MTO's provincial highways:

$$\text{DMI} = 10 \times \frac{\text{DMI}_{\max} - \sum_{i=1}^{n} W_i \cdot (s_i + d_i)}{\text{DMI}_{\max}} \tag{1}$$

where

- i = distress type,
- n = total number of distresses related to a given pavement type,
- W_i = weighting factor (0.5–3.0) representing the relative weight or attribute to overall pavement surface condition of each evaluated pavement section (Table 3),
- s_i = severity of distress,
- d_i = density of distress occurrence, and
- $\text{DMI}_{\max}$ = maximum value theoretically assigned to an individual pavement distress.

Based on the new weighting factors, the $\text{DMI}_{\max}$ values assigned for AC, PCC, COM, and ST pavements are 208, 196, 220, and 135, respectively. Due to the variation in MTO manual evaluation forms for different pavement types, severity and density ratings scales are dependent on the type of pavement being evaluated. A 5-point rating scale, ranging from 0.5 to 4, is applied for all AC pavements; ST pavements are rated on a scale ranging from 1 to 3 (Table 3).

The automated distress data provided by each service provider were separated into the respective pavement types. Irrelevant observations, such as railway crossings, curbs, drainage, patches, location, and geometry, were removed. Segments of sections less than 50 m in length were also removed to avoid overrepresentation of a short segment in the by-segment approach to computing the DMI.

The type of distresses observed by the manual evaluators and the type of distresses observed by each automated system were considered when determining which distresses would be included in the analysis. Efforts were made to incorporate every distress available in each service provider's database, whether this involved reclassifying a distress or combining similar distresses. For example, within the company C database it was necessary to split the total longitudinal cracking observations between two longitudinal crack categories (wheel track and nonwheel track) because the ministry considers these distinct crack types.

Similar to manual pavement evaluations, the products of automated evaluations are severity and density levels for each distress found to be present on the pavement surface. The conversion of severity levels to the appropriate severity range on the basis of the pavement type

TABLE 3 Pavement Rating Scales

Distress Severity	Distress Extent	Rating
AC, PCC, and COM Pavements		
Very slight	Few	0.5
Slight	Intermittent	1.0
Moderate	Frequent	2.0
Severe	Extensive	3.0
Very severe	Throughout	4.0
ST Pavements		
Slight	Intermittent	1
Moderate	Frequent	2
Severe	Extensive	3

TABLE 4 Pavement Ratings for Distress Severities and Extents

Distress Severity	Distress Extent	Rating
AC, PCC, and COM Pavements		
Low	<10%	0.5
	10%–20%	1.0
Moderate	20%–50%	2.0
	50%–80%	3.0
High	>80%	4.0
ST Pavement		
Low	<20%	1
Moderate	20%–50%	2
High	>50%	3

TABLE 5 Summary Results for Hypothesis Testing of Paired Comparison Analysis

Evaluator	Pavement Type	$F_{observed}$	Significant Difference?
Company A	AC	11.56	Yes
	PCC	3.11	No
	COM	3.78	No
	ST	808.91	Yes
Company B	AC	0.11	No
	PCC	0.13	No
	COM	1.62	No
	ST	46.45	Yes
Company C	AC	63.89	Yes
	PCC	19.59	Yes
	COM	167.32	Yes
	ST	2.63	No

can be seen in Table 4. In instances where no severity levels were provided, a moderate severity level was assumed.

To account for the variations in units, all distresses not provided as areas were converted to areas through a series of assumptions. The assumptions made are as follows:

- 1 m of cracking is equivalent to a 1-m^2 area distress,
- A single pothole affects a 1-m^2 area,
- Transverse distresses (e.g., transverse cracking or joint sealant loss) span the entire lane width, a distance of 3.5 m, and
- Distresses presented as counts in PCC and COM pavements, excluding transverse distresses and potholes, affect 25% of the slab, an area of 6 m^2.

Once all the values were computed, they were checked by both the research team and the MTO.

STATISTICAL TEST RESULTS

The randomized block design (RBD) approach was chosen in this study because it provided the best outcome in initial investigations. In an experiment involving the RBD, testing the equality of measured means is equivalent to conducting testing in terms of treatment effects. In these analyses, the *F*-test and the Student's *t*-test were used. The confidence level was always selected to be 95%. The analyses were performed on the distress data collected by manual evaluators and by automated equipment. The results of the blocking design show that while there seems to be no significant difference among companies in roughness testing, there are significant differences for both cracking and pothole measurements. For the image-based measurements, significant differences were found for all types of distress and severities, except for two instances of severities in the pothole type of distress. Further investigation on these two instances revealed that for the "low" severity occurrence, 98 out of 111 measurements were zeros. This might have also contaminated the results when "all" severities were considered together, which explains the different results from the rest of the image-based technology data (*10*).

SUMMARY OF FINDINGS

Hypothesis testing for RBD was performed to determine if the differences in the DMI values established on the basis of the automated evaluations and ground truth were statistically significant. Sections were segregated by pavement type for analysis purposes in order to identify service provider strengths and weaknesses in terms of pavement types; initial findings were encouraging (Table 5).

Company C's DMI values were found to be statistically significant in all but the ST pavement sections. Inversely, company B's DMI values were statistically significant in ST pavement sections only. Company A's DMI values were found to be statistically significant in the AC and ST pavement sections. Examination of the individual DMI values revealed that while some service providers' DMI values were not statistically significant in particular pavement types, the DMI values differed greatly in magnitude when compared with the ground truth DMI values, particularly in the PCC pavement type. Thus the root mean square (RMS) of the difference in DMI values between ground truth and the automated evaluations was computed for each service provider in each pavement type (Table 6). While the difference between Company A and Company B DMI values for PCC pavement and ground truth were not found to be statistically significant, the RMS values are quite large. Thus, the hypothesis testing results are misleading for the PCC pavement sections.

Consideration was then given to the magnitude of the DMI values computed from the three service providers' data in relation to ground truth. Company C's DMI values were found to be too high, indicating that distresses were being missed, distresses were being improperly recorded (in terms of severity or extent), or the reduction

TABLE 6 RMS of Difference Between Ground Truth and Automated DMI

Evaluator	Pavement Type	RMS
Company A	AC	0.51
	PCC	0.99
	COM	0.38
	ST	1.98
Company B	AC	0.56
	PCC	0.80
	COM	0.31
	ST	0.93
Company C	AC	0.87
	PCC	1.65
	COM	1.09
	ST	0.71

method applied to arrive at DMI values was not sensitive enough. Examination of the individual distress severity and extents revealed that Company C's equipment picked up very few distresses that were not cracking or rutting despite these distresses being present in the pavement sections, thus causing the DMI values to be much higher than they should have been.

With an understanding of why Company C's DMI values were for the most part statistically significant, Company A and Company B results were then examined. Scaling factors were included in the extent computations to determine what impact raising or lowering the sensitivity of the extent computation method would have on the DMI values, particularly the statistical significance. Including a scale factor of 1.5 and 0.5, which has the same effect as increasing the section areas by 50% and reducing the section areas by 50%, respectively, was explored. The former scale factor decreases the distress sensitivity, thus increasing the DMI values, while the latter has the opposite effect. Results are presented in Table 7.

Considerable improvement was observed in the company A DMI values for both the AC and COM pavement types when a 1.5 scale factor was included. Thus, although the original procedure applied to compute the DMI from automated evaluations suited the company B observations, a scaling modification was required for the company A observations as the lengths and areas of distresses measured were more voluminous.

Little to no improvement was observed in the RMS values for the rescaled PCC and ST pavement extents. Examination of the individual distresses showed that both the company A and company B automated equipment incorrectly identified the distresses, picking up raveling and polishing in the PCC and alligator and transverse cracking in the ST when the manual observers did not observe these distresses. This caused the DMI values for the ST pavements to be too low, providing a good relative relationship between the sections but a poor absolute relationship with ground truth. In addition, the measurements made in the PCC did not allow for differentiation between the extent levels as the magnitude of the areas and lengths of distresses were very similar when in actuality they should not have been. Extents were predominantly in the lowest category counteracting the erroneously included distresses.

TABLE 7 Results of Hypothesis Testing of DMI Values (rescaled)

Evaluator	Pavement Type	$F_{observed}$	Significant Difference?
Company A (rescaled by 1.5)	AC	0.41	No
	PCC	4.05	No
	COM	0.14	No
	ST	580.56	Yes
Company B (rescaled by 1.5)	AC	0.19	No
	PCC	0.15	No
	COM	0.94	No
	ST	34.10	Yes
Company A (rescaled by 0.5)	AC	35.66	Yes
	PCC	1.69	No
	COM	11.84	Yes
	ST	175.20	Yes
Company B (rescaled by 0.5)	AC	1.06	No
	PCC	0.03	No
	COM	15.73	Yes
	ST	143.60	Yes

REPEATABILITY ANALYSIS

When determining the potential of automated pavement distress surveys to replace manual evaluation methods it is important to consider not only the accuracy of the distress evaluation but also the repeatability of the results. For this reason, multiple runs were executed by the automated systems over a selection of sections and a comparison between the runs was performed for each pavement type. COM pavements were excluded from this comparison as multiple runs were not executed by the service providers in this pavement type. The company C system produced the most repeatable results. PCC pavements appear to have presented the greatest challenge in terms of repeatability for all three service providers.

The repeatability of manual ground truth evaluations was also evaluated by comparing the DMI values for sections where multiple raters performed evaluations. Multiple ratings were available for all pavement types. Manual evaluators appear to produce the most consistent evaluations in COM pavement sections. This consistency may relate to the section being segmented by the evaluators, causing inconsistencies to average out when DMI values were computed for entire sections. Automated system results appear to be more repeatable than manual evaluation results in AC and ST pavements. Due to the deficiency in repeated PCC and COM pavement sections it was not possible to compare the repeatability of the manual and automated evaluations. However, overall, the output of automated systems appears to have a greater level of repeatability when compared with manual evaluations.

Although the discrepancies in units were resolved during the computation of DMI values from the automated evaluations, it is possible that the assumptions required to do so may have hampered the results. The most success was achieved by using the company B data, while the company A data were a close second when the scale factor was included to reduce the extent sensitivity. Company C as a whole was insensitive to many distresses, which created problems. However, Company C's results were found to be the most repeatable. All three companies showed greater repeatability in the AC and ST pavement types when compared with the manually performed evaluations. Thus, although there appears to be a disconnect between the automated evaluation systems and ground truth, the repeatability of the results is equivalent, if not better.

CONCLUSIONS

Several conclusions can be drawn from this study:

- Automated systems can produce pavement evaluations comparable with those produced by manual evaluators; however, success is dependent upon the service provider's system and the pavement type considered. Two of the three systems considered in this study achieved a reasonable level of success, while the third struggled to encompass the wide variety of distresses present in the pavement sections. Asphalt and composite pavements were reasonably compatible with the automated technology, while concrete and surface-treated pavements presented problems.
- Although some automated system evaluations are comparable with manual evaluations, automated systems lack the ability to consistently identify the type of distress being observed. It was difficult in this project to clearly identify which distresses were collected with automated versus semiautomated techniques. However, best practices were employed. Thus, not withstanding the technology, there were several discrepancies.

• While the accuracy of the results by the automated systems was not always of the same caliber as manual evaluations, the repeatability demonstrated by all three service providers was comparable or superior to that demonstrated by the manual evaluators.

• Careful use of specifications and proper guidelines supplemented with the use of benchmarking and calibration quality assurance techniques can overcome many of the variations found in the study. The fact that a scaling procedure could be used to improve the results indicates that consistency can be achieved with these systems.

• Current available techniques as demonstrated through the three service provider evaluations in this study can provide MTO with valuable information for pavement management purposes. The automated results are comparable with manual surveys on some levels. However, these surveys should be supplemented with manual surveys, especially for design purposes, because some of the pavement distresses were difficult to identify with the automated methods.

RECOMMENDATIONS

• Since there is a discrepancy in the definition for the term "extent of distress," it is recommended that MTO and DOTs reconcile the issue with the suppliers before attempting to use automated technologies. This problem can be addressed by proper specifications. A clear definition would make the calculation of DMI more consistent and would remove the subjectivity introduced by the assumptions required to make the computation.

• Since allowing service providers to apply their own best practice creates discrepancies in which distresses are considered, service providers should be encouraged to model the set of distresses considered in each pavement type after those considered by the manual evaluators or as deemed appropriate by the agency.

• The results indicate that automated pavement evaluation systems show promise for supplementing or replacing manual pavement evaluations in the future. It is recommended that MTO remain abreast of advancements and prepare to usher in the new technology once automated systems fully meet MTO's needs.

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REFERENCES

1. Tighe, S. L., R. Capuruço, and A. Jeffray. Evaluation of Semi-Automated/Automated Pavement Condition Surveys: An Ontario Field Study. Ministry of Transportation Ontario, Highway Infrastructure Innovation Funding Program, Toronto, Canada, 2006.
2. American Society for Testing and Materials. Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements. Designation E 1926-98, March 1999.
3. *Special Report 113: Standard Nomenclature and Definitions for Pavement Components and Deficiencies*. HRB, National Research Council, Washington, D.C., 1970.
4. Gunaratne, M., and I. F. Sokolic. Evaluation of Pavement Distress Imaging Systems. Presented at 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.
5. Ministry of Transportation Ontario. *Manual for Condition Rating of Surface-Treated Pavements.* SP-021, Distress Manifestations, Research and Development Branch, MTO, Toronto, Canada, Aug. 1989.
6. *Flexible Pavement Condition Rating—Guidelines for Municipalities.* SP-022. Research and Development Branch, Ministry of Transportation Ontario, Toronto, Canada, Aug. 1989.
7. *Manual for Condition Rating of Flexible Pavements.* SP-024. Distress Manifestations, Research and Development Branch, Ministry of Transportation Ontario, Toronto, Canada, Aug. 1989.
8. *Manual for Condition Rating of Gravel Surface Roads.* SP-025. Distress Manifestations, Research, and Development Branch, Ministry of Transportation Ontario, Toronto, Canada, Aug. 1989.
9. *Manual for Condition Rating of Rigid Pavements.* SP-026, Concrete Surfaces and Composite Distress Manifestations, Research and Development Branch, Ministry of Transportation Ontario, Toronto, Canada, Sept. 1995.
10. Capuruço, R. A. C., S. L. Tighe, L. Ningyuan, and T. Kazmierowski. Performance Evaluation of Sensor-Based and Image-Based Technologies for Automated Pavement Condition Surveys. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1968,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 47–52.

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