Evolution of Pavement Performance Specifications Integration of Risk and Pavement Asset Management Data

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ABSTRACT

Conventional quality control and quality assurance (QC/QA) specifications typically define the as-built requirements for pavement rehabilitation and construction activities but have limited direct linkage with the in-service performance of the treatments. The Ministry of Transportation of Ontario (MTO) is moving to develop and implement a category of performance specifications which provide a direct relation to in-service performance using actual field performance data. MTO defines these performance specifications as specifications that describe how the finished product should perform over time.

This paper describes the framework used to develop performance specifications for flexible pavements in Ontario. Details on modelling the performance requirements, measuring performance, and setting of acceptance criteria are presented. Recent work using the Automated Road Analyzer (ARAN) equipped with advanced laser measurement systems including crack measurement capabilities is discussed. Implementation of these specifications in innovative warranty-based alternate delivery contracts is presented.

INTRODUCTION

Considering the major investments made by Canadian transportation agencies to construct and maintain our roadway infrastructure, it is critical that not only the initial quality but the long-term performance of these expenditures be assured. Conventional QC/QA specifications that specify end product quality are used by transportation agencies as a means for assuring the initial construction quality of roadway pavements. However, these construction and rehabilitation specifications should clearly state the quality goals to ensure that the as-built pavement meets the as-designed criteria.

Most materials and construction specifications for roadway construction and maintenance offer minimal connections between selected quality assurance metrics measured and the in-service short and long term performance of the delivered product. This methodology of quality assurance has limitations to both the transportation agency and the contracted road builder including:

- Focusses the contractor's efforts on initial acceptance rather than long term performance
- Minimizes the flexibility for the contractor to initiate, innovate, and introduce new products
- Inappropriate risk/responsibilities are allocated to the agency when the contractor is best able to manage these issues
- Limits the agency's ability to account for the changes in performance due to differences in quality between the as-designed product versus the as-built product

In recent years, agencies are exploring the opportunities to incorporate performance specifications (1) in their construction contracts to specify quality as it relates to desired long-term performance. These specifications also provide a means to account for the value lost or gained by the variations in performance from the specified criteria.

Previous Studies

The development of performance specifications (PS) and performance related specifications (PRS) for flexible pavements is well documented. Initial efforts to develop PRS for new HMA pavements began under NCHRP Project 10-26 (2). NCHRP Project 09-20 developed PRS for HMA pavement based on field data (3). A comprehensive overview and guidelines for pavement warranty programs is given in NCHRP Report 699 (4).

DEVELOPMENT OF PERFORMANCE WARRANTY REQUIREMENTS

Performance Records

MTO has systematically collected pavement performance records for provincial highway pavement sections since the mid-1960's (5). Since the early 80's, subjective distress performance evaluations have been recorded by trained evaluators using standard procedures (6). Since the mid 90's, objective records of pavement roughness, wheel track rutting, and pavement cross fall have been collected by the MTO Automatic Road Analyzer (ARAN) with a 10 m reporting interval. From 2012, 2D and 3D lasers systems are employed to obtain objective pavement distress metrics that can be used directly in a performance specification. Quantitative and qualitative differences that were introduced when using manual distress rating datasets required assumed factors to transform each of the manual distress rating to represent actual quantity and extent of the distress. These limitations are mitigated in the new data collection method as these distresses are now directly quantified by the new advanced 2D and 3D systems.

An analysis of the performance records has been carried out to establish reasonable and defensible expectations of pavement performance. Subjective evaluation records for the 2005 to 2011 period (10,322 records) and objective ARAN records for the 2007 to 2010 period (5052 records) have been used for the analysis.

Statistically, the subjective records contain categorical, paired data and the objective records contain continuous data. An example of the categorical, paired data is moderate, frequent flushing. To facilitate the analysis, it was necessary to transform the paired subjective records to a single parameter. This transformation was carried out applying equal weight to the distress severity and density, with the resulting single parameter termed the Distress Index (DI).

The performance records were collected for the purpose of network level pavement management with some limitations such as:

- categorical, discrete pavement distress records describing the predominant distress only,
- limited detail on construction and any subsequent maintenance activity.

Due to these data limitations, detailed field evaluations of selected pavement sections were carried out to validate the analysis results, described later in this paper.

MTO has established a warranty evaluation segment length (or lot size) of 500 lane-metre (lane-m) for pavement warranties, with a shorter length used where necessary, such as the limits of a project. Where applicable, warranty requirements are specified relative to this length (e.g. average rut depth/500 lane-m). The 500 lane-m length has been selected to balance the contractor's increasing risk of non-conformance with shorter lengths and the owner's increasing risk of unrepaired localized areas of poor performance with longer lengths. Where possible, for analysis the performance records have been transformed to values for a 500 lane-m length.

Performance Sensitivity Evaluation

As a first step in the analysis, the performance sensitivity to key highway attributes such as geographic region, traffic volumes, road classification, and work type was evaluated. Performance sensitivities were addressed by one of three methods:

- Vary performance requirements by attribute - higher road classifications exhibit lower roughness (MRI), as is expected by the use of higher reliability and lower terminal serviceability in the AASHTO pavement design procedures.
- Exclude attribute by specification warrant - local classification highways typically exhibit markedly lower performance compared to collector, arterial, and freeway classifications.

- Apply the worst case performance - the performance requirement is being established based on wheel track rutting depths on Superpave^{TM} traffic category D&E pavements, based on the observed ~2 mm average increase in observed wheel track rutting depths from category A to category E pavements (142 Contracts, 2807 500 lane-m segments), shown in Figure 1.

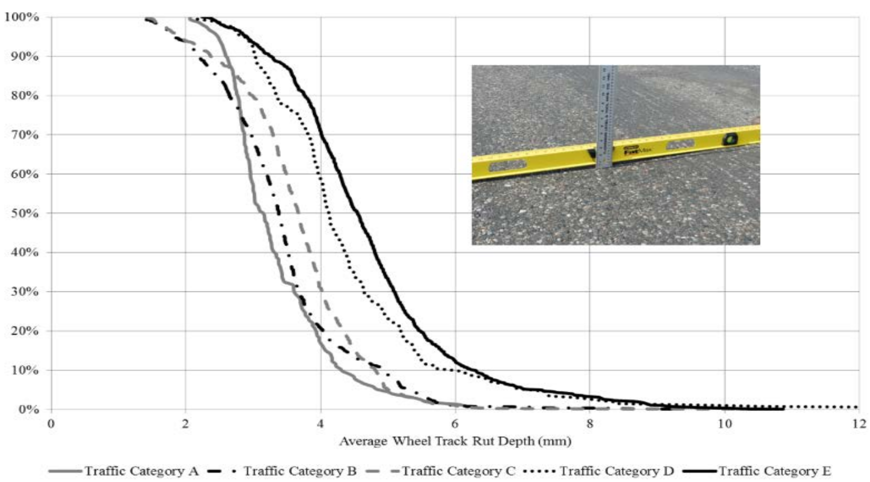

FIGURE 1 Sensitivity of wheel track rutting to Superpave^{TM} traffic category after seven years of service, based on 147 contracts, 2807 segments (500 lane-m/segment).

Figure 2 shows the sensitivity of pavement edge cracking to highway classification, and the evidence of significantly higher amounts of edge cracking for local classification highways. The reason for this sensitivity is simple, local highways in Ontario are typically very low volume with less HMA thickness and do not warrant partially paved shoulders. Evaluating the sensitivity of performance to key highway attributes is necessary prior to further analysis, since application of one of the 3 methods above may require selective extraction of the historical data, along with removal of outliers.

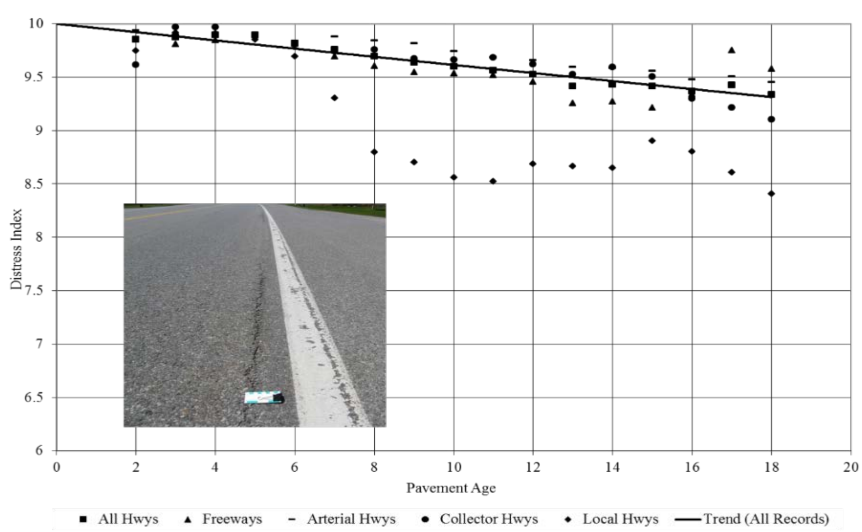

FIGURE 2 Sensitivity of edge cracking to highway classification, based on 445 contracts.

Performance Distribution

In the second step, the performance records for each distress type for the performance year of interest were extracted and best fit statistical curves plotted through the performance distribution. The performance year of interest is 7 years, selected by MTO as the performance warranty period for new, reconstructed, and rehabilitated flexible pavement structures, which is ~40% of the typical 18 year design life of these structures (Ontario experience).

Figure 3 shows the distribution of flushing performance for 445 pavement sections that were 7 years old at the time of evaluation. It can be noted from this distribution that ~65% of the pavements were evaluated as having no flushing distress. A power function best fit curve has been plotted through the lower portion of the distribution with probability density function y = 5E-15 (Distress Index)$^{13.785}$.

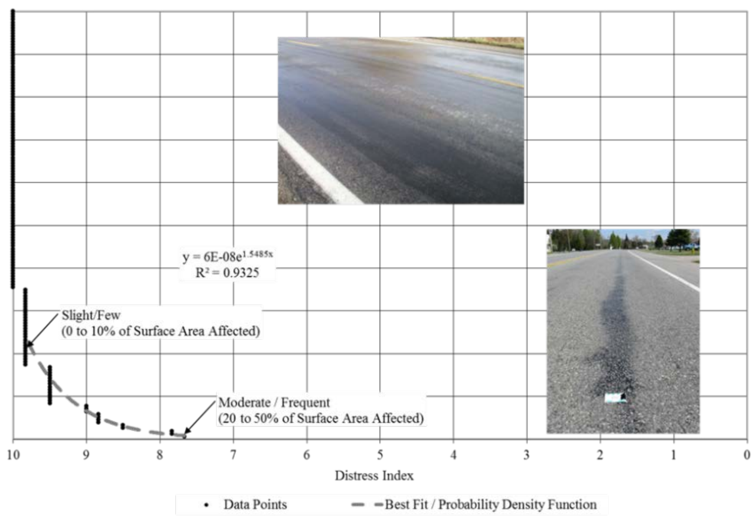

FIGURE 3 Flushing performance distributions after 7 years of service, based on 445 contracts.

Performance Acceptance Limits

The 3rd step in the process is to use the performance distribution to statistically set the acceptance limits. NCHRP Report 699 states '….the DOT may set the threshold at 2σ…. with additional experience or improved consistency, the DOT may decide to tighten the threshold (to between 1σ and 2σ) or extend the warranty' (4). The use of reasonable performance thresholds that balance road builder risk (and project cost) and agency expectations is critical. For pavement performance specifications, MTO has selected a threshold of 1.5σ for most distress types and combined with payment adjustment based on performance.

Some performance distributions are too skewed to permit normalization. Where normalization is not possible (based on generally accepted limits for skew and kurtosis), the threshold is based on the best fit probability distribution or density function with a probability of exceedance of 6.7% (equivalent to 1.5σ).

Figure 4 shows the measured (by ARAN) average wheel track rut depths on 500 lane-m pavement segments. The measured data is normalized by a power (Box-Cox) transformation (7) with transformation results shown in Figure 5. Back-transformation yields mean + 1.5σ and + 2σ values of 6.7 mm and 7.8 mm, respectively, as shown in Figure 4.

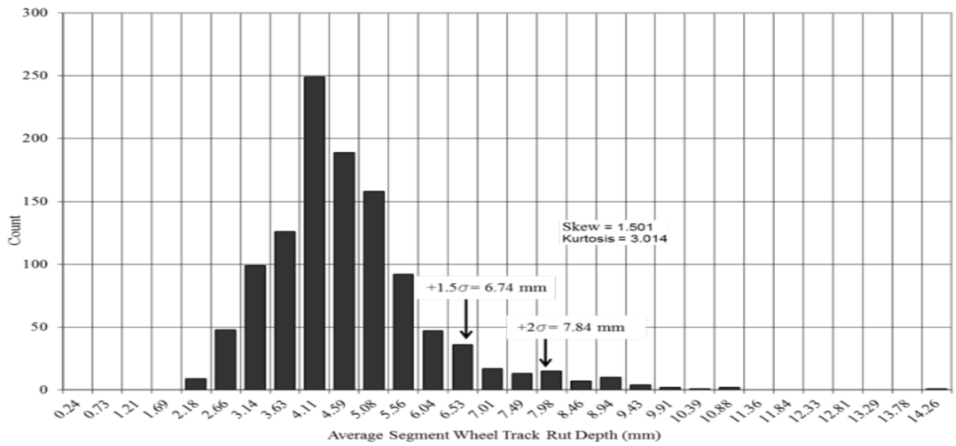

FIGURE 4 Average wheel track rut depth after 7 years of service based on 64 SuperpaveTM traffic category D & E contracts, 1125 segments (500 lane-m/segment).

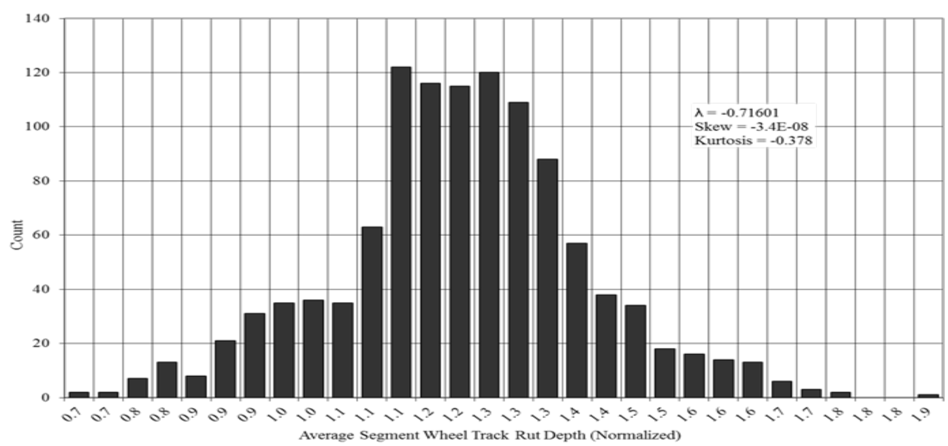

FIGURE 5 Normalized wheel track rut depth

Performance Categories and Requirements

For flexible pavement structures, performance requirements have been established for the following eight categories; Flushing, Coarse Aggregate Loss, Wheel Track Rutting, Roughness (MRI – Mean Roughness Index), Alligator Cracking (or Crack Density), Single and Multiple Cracking, Joint Separation, and Differential Frost Heaving.

For each category, there will be requirements that apply throughout the warranty period, and requirements that apply in the final 12 months of the warranty period only, as shown in Table 1. The requirements listed in Table 1 will be implemented in 7 year pavement with performance warranty on selective contracts tendered after 2015. Prior to 2015, all 7 year pavement with performance contracts contained performance requirements that were set based on conservative estimate of pavement performance to facilitate trial projects while determination of performance requirements for various contracting period length were developed per Table 1.

Table 1 Performance Requirements for Warranty Contracts

Performance Category	Measurement	Entire Warranty Period		Final 12 Months of Warranty Period	
		Performance Requirement	Repair	Performance Requirement	Repair
Coarse Aggregate Loss	SP-024 Evaluation	No severe or very severe	Remove HMA surface course uniform depth and replace	Moderate coarse aggregate loss shall be < 10% of segment length	Remove HMA surface course uniform depth and replace
Flushing	SP-024 Evaluation	No severe or very severe	Remove HMA surface course uniform depth and replace	Moderate flushing shall be < 10% of segment length	Remove HMA surface course uniform depth and replace
Alligator Cracking	SP-024 Evaluation	No moderate, severe or very severe	Reconstruction	Slight alligator cracking shall be < 10% of segment length	Reconstruction
Cracking	ARAN	N/A		The length of cracking up to 20 mm in width shall be < 160% of segment length	Remove / replace HMA full depth
				No cracks > 20 mm	Full depth crack repair
Wheel Track Rutting	ARAN	No wheelpath locations ≥ 30 m with average rut depth > 14 mm	Reconstruction	Average depth of wheel track rutting / segment < 8.0 mm	Remove HMA variable depth and replace
Roughness	ARAN / ASTM E 950-09 Profilometer	No lane segments ≥ 30 m with MRI > 2.6 m/km	Remove HMA variable depth and replace	Average MRI / segment < 1.6 m/km (freeway), < 1.75 m/km (arterial), < 1.90 m/km (collector)	Remove HMA variable depth and replace
Joint Separation	Direct measure	N/A		Separation shall be < 5 mm	Joint Sealing
				Separation shall be < 20 mm	500 mm wide strip repair
Differential Frost Heaving	ASTM E 950-09 Profilometer	No lane segments ≥ 30 m with MRI > 6.0 m/km	Reconstruction	N/A	

The requirements that will apply throughout the warranty period, termed limits, are intended to address conditions where the safety and/or serviceability of the pavement may be impacted. These requirements by their nature have a low probability of being exceeded.

The requirements that will apply in the final 12 months of the warranty period, termed levels, are the expected reasonable level of pavement performance, as determined by the statistical analysis of historical performance.

The performance requirements in the final 12 months of the warranty period are based on a +1.5σ threshold, except those categories with a payment adjustment for performance are based on a +2σ threshold. Payment adjustment for performance is only being applied to categories measured objectively by the ARAN; cracking, wheel track rutting, and roughness and these are the three key performance categories for flexible pavement. A protocol for field calibration of the ARAN or equivalent systems for measurement of warranty contract will be implemented.

Due to the limitations with the analysis, described earlier, detailed field evaluations were carried out on seven year old pavement sections in 2012 and 2013, to corroborate and validate the results of the statistical analysis. The detailed field evaluations generally validated the expected statistical non-conformance rates of 6.7% (1.5σ) and 2.3% (2σ).

The analysis of historical PMS performance data described in this paper has been used to refine and further develop the specifications used for the initial trial contracts. It is expected that the analysis, shared with Ontario's road building industry, will increase bidder understanding of performance risks, and improve the outcome of future projects using pavement performance specifications.

Advanced Automated Distress Detection and Rating System

Advances in automated detection of pavement distresses, Table 2, and the capability to process, categorize and report automated pavement condition data is enabling MTO to shift from manual to automated assessment of pavement performance.

Table 2 Automated Pavement Distress Detection Systems

<table>
<tr><th>Type</th><th colspan="2">Pavement Distress</th><th>Automated Collection</th></tr>
<tr><td rowspan="2">SURFACE DEFECTS</td><td colspan="2">Coarse Aggregates Loss, Raveling & Segregation</td><td>Raveling Index</td></tr>
<tr><td colspan="2">Flushing</td><td>Macrotexture</td></tr>
<tr><td>SURFACE DEFORMATION</td><td colspan="2">Wheel Path Rutting</td><td>LCMS</td></tr>
<tr><td rowspan="9">CRACKING</td><td rowspan="2">Longitudinal Wheel Path</td><td>Single and Multiple</td><td>LCMS</td></tr>
<tr><td>Pattern</td><td>LCMS</td></tr>
<tr><td rowspan="2">Centre Line</td><td>Single and Multiple</td><td>LCMS</td></tr>
<tr><td>Pattern</td><td>LCMS</td></tr>
<tr><td rowspan="2">Pavement Edge</td><td>Single and Multiple</td><td>LCMS</td></tr>
<tr><td>Pattern</td><td>LCMS</td></tr>
<tr><td rowspan="2">Mid-Lane</td><td>Single and Multiple</td><td>LCMS</td></tr>
<tr><td>Pattern</td><td>LCMS</td></tr>
<tr><td>Transverse</td><td>Single and Multiple</td><td>LCMS</td></tr>
</table>

The current ARAN 9000 provides the capability for calibrated, reliable and repeatable measurement of several pavement distress parameters such as roughness, rutting, and crack measurement. Measurement tools were developed and being refined on a continual basis and the ARAN's adaptive platform will allow the MTO to introduce additional automated pavement condition parameters over time. The equipment sub systems specifications and capabilities are listed on Table 3.

Table 3: Automated Distress Components Specification

Item	Requirement
DMI (Chainage)	775 – 900 pulse/meter
Laser SDP Static Test IRI	Average < 0.1 IRI
Laser SDP Bounced Test IRI	Average < 0.15 IRI
Geometric Crossfall/Roll	± 0.4 of Average Crossfall Slope
Geometric Grade/Pitch	± 0.2 of Average Grade Slope
Geometric Validation	± 0.4 Crossfall/Grade difference for reverse direction
Static GPS	< 1 meter position
Texture RMS	2.11 – 2.85 mm
Texture MPD	2.46 – 2.72 mm

Pavement distress data collected by the MTO ARAN is recorded and processed using Pave3D software. The system is comprised of subsystems configured to measure, record and provide continuous output for multiple data streams. Subsystems include a high speed inertial profiler that measures pavement roughness and a Laser Crack Measurement System (LCMS) to capture rutting, crack, raveling and macrotexture data. Table 3 lists the pavement distresses captured using automated data collected by the MTO ARAN.

Results of re-assessment of some of the performance criteria using the new ARAN distress metrics are shown on Table 4. These metrics will require input from internal and external stakeholders prior to consideration use in warranty implementation.

Table 4 Revised Results of Performance Requirements Based on ARAN LCMS Algorithms

Performance Category	Measurement	Entire Warranty Period		Final 12 Months of Warranty Period
		Performance Requirement	Repair	Reassessed Performance Requirement
Coarse Aggregate Loss/Ravelling	ARAN Ravelling Index (RI)	No severe or very severe	Remove HMA surface course uniform depth and replace	Moderate coarse aggregate loss shall be < 10% of segment length with RI<15
Flushing	SP-024	No severe or very severe	Remove HMA surface course uniform depth and replace	Moderate flushing shall be < 10% of segment length
Alligator Cracking	ARAN area	No moderate, severe or very severe	Reconstruction	Slight alligator cracking shall be < 4% of segment length
Cracking	ARAN	N/A		The length of cracking up to 20 mm in width shall be < 135% of segment length
				No cracks > 20 mm
Wheel Track Rutting	ARAN	No wheelpath locations ≥ 1 m with average rut depth > 20 mm	Rehabilitation	Average depth of wheel track rutting / segment < 6.5 mm
Roughness	ARAN / ASTM E 950-09 Profilometer	No lane segments ≥ 30 m with MRI > 2.6 m/km	Remove HMA variable depth and replace	Average MRI / segment < 1.6 m/km (freeway), < 1.75 m/km (arterial), < 1.90 m/km (collector)
Joint Separation	ARAN	N/A		Separation shall be < 5 mm
				Separation shall be < 20 mm
Differential Frost Heaving	ASTM E 950-09 Profilometer	No lane segments ≥ 30 m with MRI > 6.0 m/km	Reconstruction	N/A

Warranty Limitations
The performance requirements have been established using data from pavements across Ontario, and reflect typical in-service conditions. The requirements are not valid for extreme or unexpected in-service conditions and events that cannot be accounted for by pavement design. To minimize contractual dispute, the conditions that will void the pavement warranty, in whole or part, will be specified where appropriate.

INITIAL TRIAL CONTRACTS AND THEIR PERFORMANCES

Since 2007, MTO has tendered over 15 contracts using various versions of 7 year pavement warranty specifications. In these 7 year pavement warranty projects, the contractors are responsible for all aspects of the pavement design, materials and construction. MTO does not approve the contractor designed pavement structure but relies on the performance requirements during the warranty period to motivate contractors to provide a cost effective pavement solution that addresses all the performance requirements in the contract. In most cases, the contractor pavement designs were similar to, or more substantial than, what the Ministry would have designed.

Table 5 provides information on twelve of the contracts. Contracts after 2014 are not included as insufficient data were collected at the time of this analysis. Ten projects used in-place processing with or without expanded asphalt stabilization, also known as full depth reclamation (FDR) or expanded asphalt stabilization (EAS). Two projects were rehabilitated using cold in-place recycling with emulsion (CIR) or cold in-place recycling with expanded asphalt mix (CIREAM).

Table 5: Description of the 7-Year Pavement with warranty contracts

Hwy	Type	Const. Yr.	Years to date	Length (km)
23	CIR	2007	8	9.1
94	FDR	2007	8	9.3
132	FDR	2007	8	4.2
118	FDR	2008	7	11.6
11	CIREAM	2009	6	9.6
144	FDR	2009	6	20.5
28	FDR	2010	5	8.6
655	FDR	2010	5	10.1
661	FDR	2012	3	4.5
28E	FDR	2012	3	18.7
518	FDR	2013	2	4.3
592	FDR	2013	2	2.0
560	FDR	2014	1	4.25

During the warranty period, the ministry has carried out pavement distress surveys at year 1, 3, 5, and 7 to ensure the contractor has fulfilled the warranty requirements.

The pavement performance data presented in this report was extracted from the MTO pavement management system and MTO Vision (2014 data). Performance data presented includes International Roughness Index (IRI), rut measurement, Distress Manifestation Index (DMI) and overall Pavement Condition Index (PCI). Reported indices include changes in performance arising from repair or rehabilitation that were carried out on these contracts. FDR, CIR and CIREAM rehabilitation processes are generally selected for their crack mitigation capabilities. Figure 8 highlights the cracking performance of these projects using the DMI metric and the overall pavement performance in Figure 9 using the PCI metric.

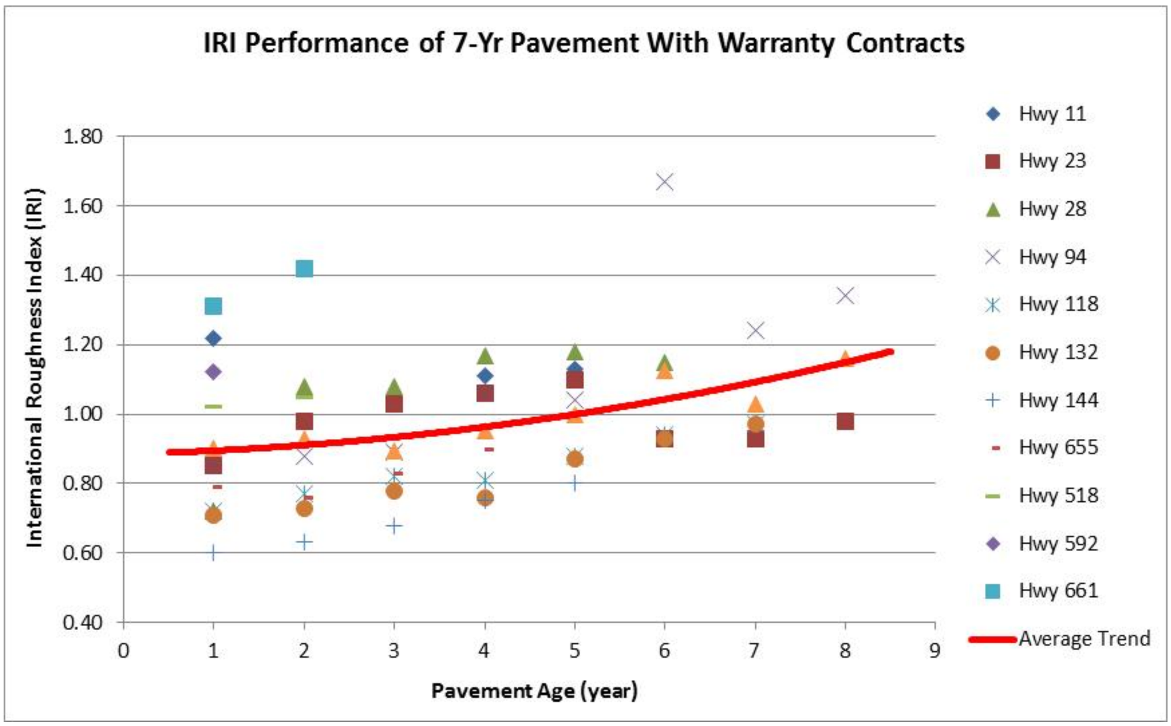

Figure 6 Average IRI Performances of 7-Year Warranty Contracts

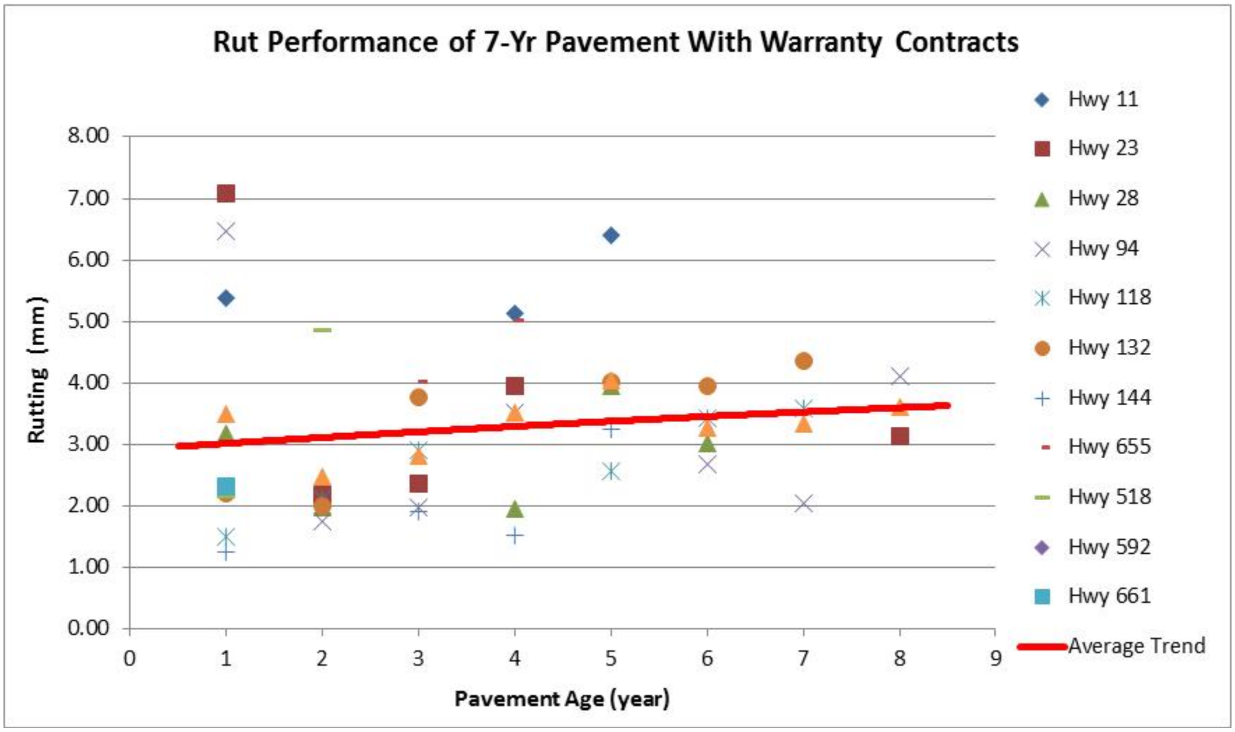

Figure 7 Average Rut Performances of 7-Year Warranty Contracts

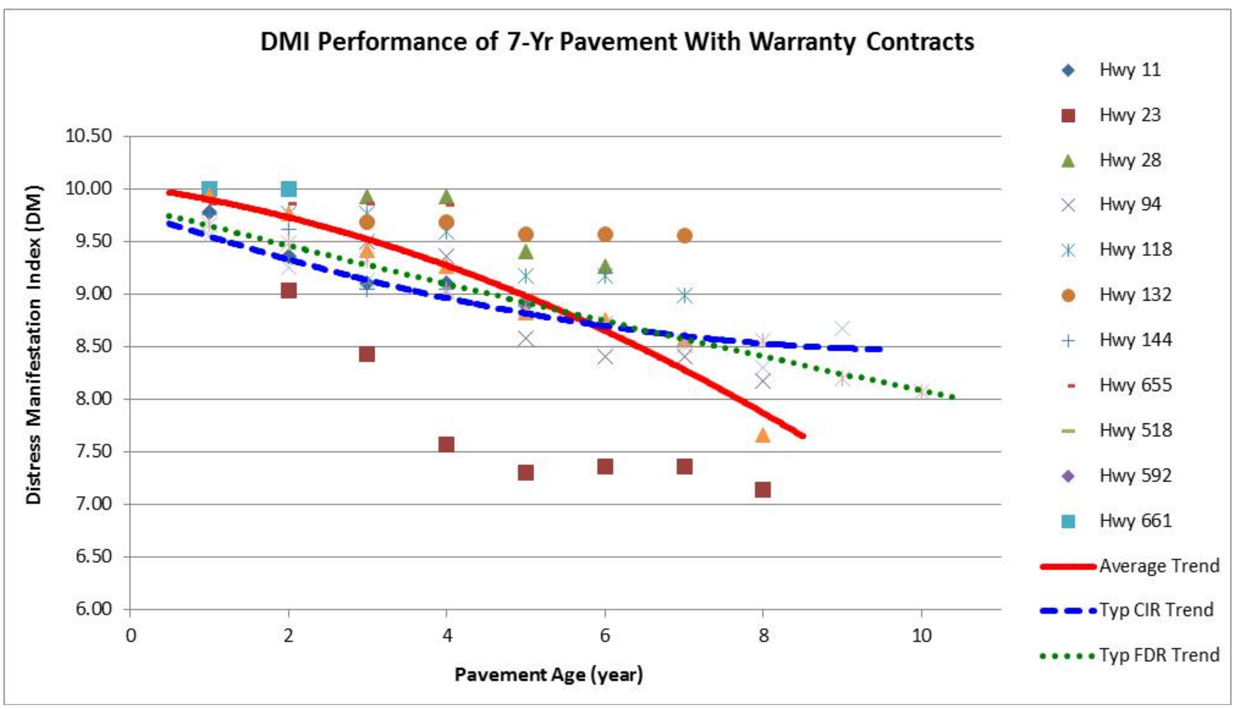

Figure 8 Average DMI Performances of 7-Year Warranty Contracts

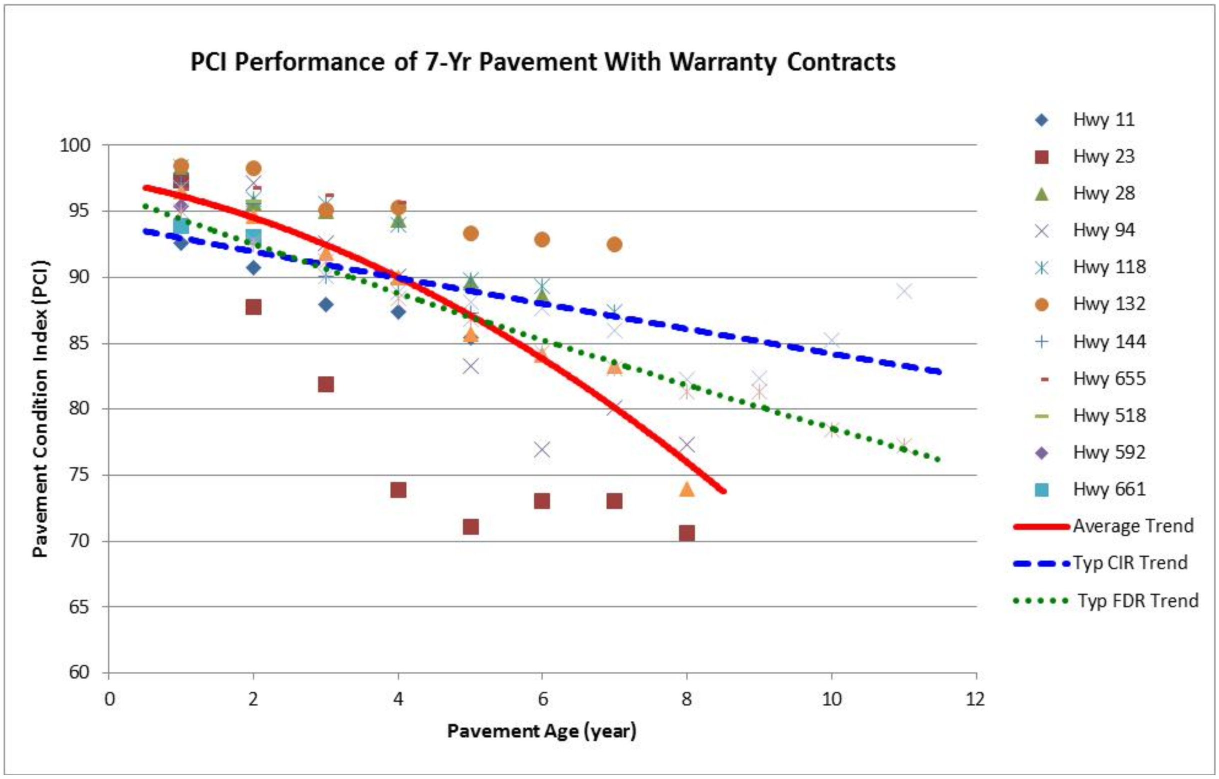

Figure 9 Average PCI Performances of 7-Year Warranty Contracts

From Figure 9, a trend line shows the pavement condition of 7 year pavement warranty projects decreasing over time. Most contracts follow the average trend line with the exception of Highway 23 that performed poorly soon after construction.

The graph includes PCI performance curves of CIR and FDR projects constructed using the conventional Design Bid Build (DBB) model. Figure 9 trend line shows a lower overall (PCI) performance with time compared to conventional DBB FDR and DBB CIR projects, although the overall warranty contract performance is comparable when the Highway 23 results are removed.

Cost Premium

For the earlier 7 year with warranty trial contracts reported in this study that included transfer of additional risks above and beyond DBB contract, a cost premium was expected. As the ministry and the contracting industry get more experience with this mode of contract delivery and with the ongoing enhancements to the performance requirements the cost premium associated with this mode of contract delivery will decrease.

SUMMARY

This paper details how data from the ministry's pavement management system was used to develop distributions for several categories of flexible pavement performance. Using these distributions, practical and measureable performance acceptance limits are established to meet the performance specification objective of describing how the pavement should perform over time. Detailed field evaluations were used to validate the acceptance limits. Analysis of data from the new, more advanced ARAN acquired by MTO in 2012 was used to assess previously developed performance limits and potential refinements for future considerations.

The analysis described in this paper has been incorporated into an updated 7 year pavement warranty specification, along with associated project selection, design, estimating, contract oversight, and performance evaluation guidelines.

Initial trials using a 7 year pavement warranty have shown that pavement performance specifications can be incorporated into innovative alternate delivery contracts. MTO will continue to pursue the use of alternate contract delivery models to expand the available program delivery options in the face of increasing resource constraints, allocate appropriate risk to those who can best manage these responsibilities, and promote partnering and collaboration between stakeholders.

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