A success story, Eight-year pavement performance assessment for Highway 407, East Extension phase 1 in Ontario

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Abstract

The pavement performance refers to its serviceability to support the traffic and to meet the expectations of the design over time. It depends on various factors, such as traffic loading, environment, pavement structure design, material properties, and maintenance strategies. Pavement performance indicators include functional and structural characteristics, such as roughness, skid resistance, surface distress, rutting and structural capacity. These condition indicators can be measured using multifunctional data collection vehicles, skid testers and the falling weight deflectometer (FWD). Pavement condition data are one of the key components of a pavement management system. This paper aims to present the methodology used to evaluate the network level pavement for the Highway 407, East extension in Ontario based on the contract requirements since its induction in 2016. The pavement condition was evaluated between 2016 and 2023 using a specialized multifunctional data collection vehicle. These vehicles meet internationally recognized standards and methods in the fields of image capture, roughness measurement, crack and distress measurement, rutting and satellite positioning.

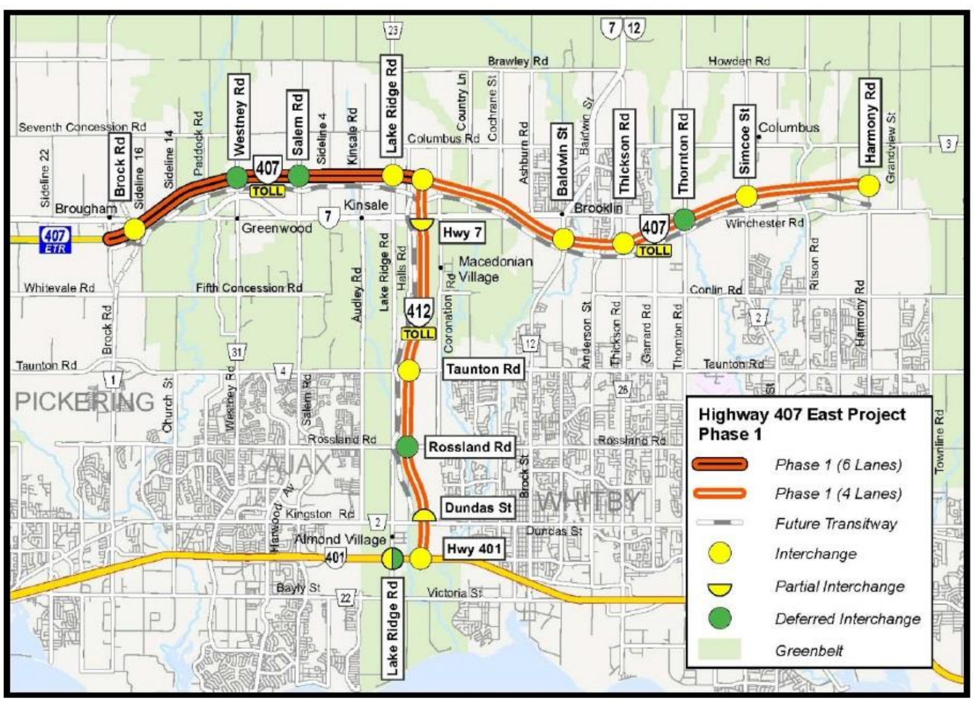
The pavement performance indicators evolution trends were predicted to reveal how the pavement deteriorates with time and to establish pavement maintenance and rehabilitation requirements. The results show slight degradation of the performance indicators compared to common evolution models. Moreover, the structural integrity of the pavement was supported by FWD tests results showing a good structural capacity of the pavement. This success story could not be possible without a good pavement design, tight QC/QA during construction and optimal maintenance since the opening of the road.

Introduction

Pavement performance evaluation is one of the most important elements in the pavement management systems by which a most effective strategy for maintenance and rehabilitation is developed. Thus, an awareness of the pavement condition is necessary in order to maintain the roadways in a good condition. This approach was adopted by the 407-East Development Group (407EDG) in Ontario to maintain the Highway 407 East Extension phase 1 since its opening to traffic in 2016.

The East extension of Highway 407 phase 1 extends over from the Brock Road Interchange Eastern Limit in Pickering to the Harmony Road Interchange Eastern limit in Whitby/Oshawa and it also includes Highway 412 between Highways 407 and 401. The extension includes highway mainline, crossing roads and ramps with a total length of approximately of 348 lane km.
Both Highways 407 and 412 were built by 407EDG to improve the transportation network in Durham region by allowing residents more efficient access to other areas of the Greater Toronto Area. It also creates opportunities for businesses, accommodate population and employment growth and provide detour routes for emergency purposes. The project has been executed in Public-Private Partnership (PPP) mode.
This paper presents the methodology used to assess the pavement performance and to maintain the performance level for the East extension of Highway 407 phase 1. First, the various performance indicators used are described, followed by the pavement evaluation tools and the specified target values during the term of the initial life cycle. Then, the prediction of the pavement performance indicators trends was presented based on the pavement performance surveys. Finally, an overview of the pavement condition evolution used to schedule the maintenance/rehabilitation plan was presented.

Figure 1 Location of the east extension phase 1 of Highway 407



Pavement design and construction

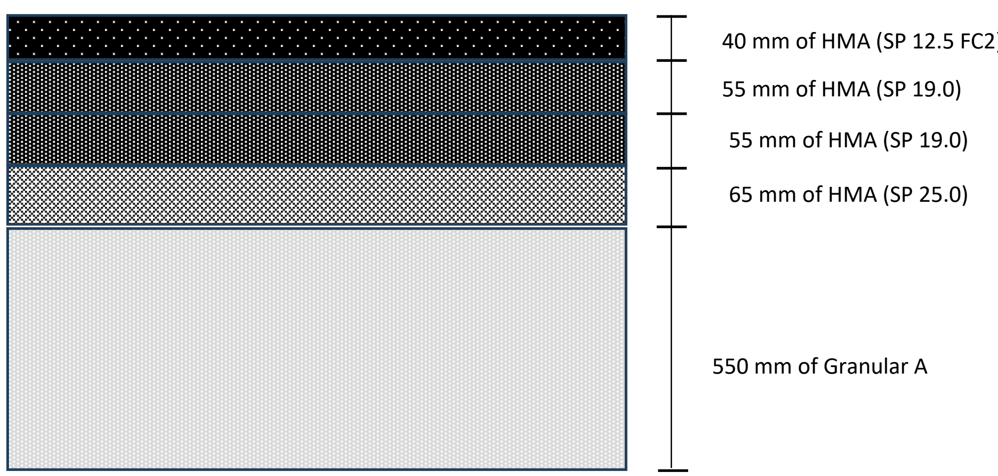
The extension of Highway 407 was designed as a flexible pavement using 1993 AASHTO Guide for Design of Pavement Structures. Pavement design of a new highway requires many parameters, where some of them are fixed by contractual constraints and others have to be established by testing or correlation with other parameters. Various AASHTO Pavement design parameters have been selected according to the MTO Materials information Report MI-183 Adaptation and Verification of AASHTO Pavement Design parameters for Ontario Conditions.

The traffic load calculations were carried out as described in the Ontario Ministry of Transportation (MTO) Report Procedures for Estimating Traffic Loads for Pavement Design (Jerry Hajek, January 1995). Some input numbers, such as the Average Annual Daily Traffic (AADT), the percentage of heavy vehicles and the growth rate were provided by 407EDG. Truck factors and lane distributions were selected according to typical values presented in the MTO report.

The subgrade soil characteristics is a critical factor in developing a viable pavement design. In the extension of Highway 407, the subgrade soil has been investigated with nearly 700 test pits and boreholes, evenly spaced along the route. The subgrade soil resilient modulus was measured using a light weight deflectometer (LWD) in some test pits. The mechanical characteristics of the subgrade soil, mainly ranged from silty sand to sandy silt in the northern section and from silty clay to clayey silt in the southern section, were determined by using CBR and resilient modulus testing in the laboratory. The thermal characteristics of the subgrade soil were determined using soil segregation potential tests and usual geotechnical tests. Frost protection considerations have been done in accordance with Cold Regions Pavement Engineering manual.[1]

The pavement design was completed to determine minimum thicknesses of hot asphalt mix (HMA) and granular layers. The total thickness of the pavement ranges from 680 mm to 765 mm in the mainline of Highway 407, from 690 mm to 890 mm in Highway 412 and equal to 875 mm in the realignment of Highway 401. As an example, Figure 2 presents the design of pavement structure for a section in Highway 407.

Figure 2 Highway 407 pavement design



[1] D'AMOURS, L., CONTANT, A., & Ng, J. (2016). Assessment of Subgrade Soils for Pavement Design for Highway 407, East Extension Pickering to Oshawa, Ontario. *Conference and Exhibition of the Transportation Association of Canada*

The construction of the Highway 407 extension was completed in 2016. It included the constructing of Highway 407 between Brock Road to Harmony Road (4 to 6-lanes), the connecting Highway 407 to Highway 401 with Highway 412 (4-lane divided highway in Whitby) and 5-kilometre realignment of Highway 401 to accommodate the connection to Highway 412. The extension was opened to the public in June 2016 as a toll highway. The Hwy 412 toll became ineffective on April 5, 2022, while the tolls for the rest of the project remains.

Pavement performance assessment

Pavement performance indicators

Pavement surface distress is an unavoidable situation due to various factors such as age, traffic loads and climate variations (temperature changes, wet-dry cycles, etc.). The frequent distress in flexible pavements are cracking, rutting and loss of surface friction. The evaluation of pavement surface distress is a combination of type and severity level of damage.
The MTO manual for the condition rating of flexible pavement uses the riding quality and distress manifestation measures as surface condition rating. The riding quality of the pavement surface presents the indicator for functional condition and evaluates the ride comfort. The rating of pavement surface distress manifestations presents an indicator of structural condition, it includes evaluation of surface defects, permanent deformation, and cracking.[2]
The pavement condition assessment of the East extension of Highway 407 is performed annually and includes the following measurements:

- Surface distress (Distress Manifestation Index **DMI**)
- Riding quality (International roughness Index **IRI**)
- Rutting (rut depth)
- Skid resistance (Friction number **FN**)

Surface distress (DMI)

The identification of surface distress type can orient the diagnosis toward structural problems or quality of materials. For example, wheel path cracking or alligator cracking is usually related to the action of traffic loading. The pavement surface condition assessment characterizes the distress by type, extent in terms of length, areas or numbers and qualifies distress by degrees of severity.
The Hwy 407 uses the DMI to evaluate the surface condition of roadways. This index is computed based on the severity, length or area and weighting factors of the different types of cracks and surface defects observed on the pavement. The DMI scale ranges from 1 to 10, where 10 is assigned to a new pavement and 1 to a severely deteriorated pavement.

Ride quality (IRI)

Ride quality assessment is associated with the functional performance of the roadway and is a characteristic directly perceived by road users. Smoother pavement provides safe and comfortable riding and could also reduce vehicle operating costs. Thus, it is important to control the pavement roughness and maintain it under specific limits. The ride quality is assessed using the longitudinal profile measurement to identify the deformations that affect roadway users. The performance indicator

[2] Ministry of Transportation Ontario, Manual for Condition Rating of Flexible Pavements – Distress Manifestations, SP-024, 1989.

generally used for ride quality is the IRI. The IRI is calculated for each of the wheel tracks and is generally presented as the mean value for the two-wheel paths and expressed in m/km.

Rutting (rut depth)

A rut is a longitudinal surface depression that occurs in the wheel paths after repeated load applications. Wheel track rutting results from densification and permanent deformation under the loading, combined with a displacement of pavement materials. The presence of ruts makes driving uncomfortable and affects the user safety, especially during raining conditions.
Rutting is calculated as the maximum depth measured from the deepest point in the deformed wheel path to the top of the surface beside the wheel path, using a reference length of 3.0 m. This depth is expressed in millimeters.

Skid resistance (Friction number FN)

The Skid resistance of a pavement is an important characteristic in road safety. It provides the frictional properties that contribute to overall traffic safety through risk of skidding or hydroplaning. The frictional properties depend on the pavement surface's microtexture and macrotexture. The microtexture contributes to skid resistance at low traffic speed, while macrotexture governs skid resistance at high speed. The skid resistance is generally quantified using friction number.

Highway 407 pavement data collection

Traditionally, manual surveys based on visual observation are used for inspecting and evaluation pavement degradation. This method is subjective and time-consuming, and it creates potential safety hazards. Thus, the automated pavement distress data collection is becoming common for highway agencies to overcome the challenges of the manual survey. Automated data collection uses equipment and technologies to assess the surface distress at any level of severity with a wide range of collection speeds and under different weather conditions[3].
The pavement condition assessment of the East extension of Highway 407 was performed between 2016 and 2023 using a specialized multifunctional data collection vehicle (Figure 3). This vehicle meets internationally recognized standards and methods in the fields of image capture, roughness measurement, crack and distress measurement, rutting and satellite positioning. The data collection was conducted continuously, at the legal speed limit, without being a road hazard or impacting normal traffic flow. The data included the extent of degradation and pavement cracking, the roughness, and the rut depth.
The multifunctional vehicle is equipped with a high-performance inertial navigator system and GPS with a high level of accuracy. Moreover, a high-definition camera mounted to the front and rear of the multifunctional data collection vehicle allows to capture and record images of the pavement. Cracking and distress on the pavement surface are then readily identifiable.

[3] Luo, X., Gong, H., Tao, J., Wang, F., Minifie, J., & Qiu, X. (2022). Improving data quality of automated pavement condition data collection: Summary of state of the practices of transportation agencies and views of professionals. Journal of Transportation Engineering, Part B: Pavements, 148(3), 04022042.

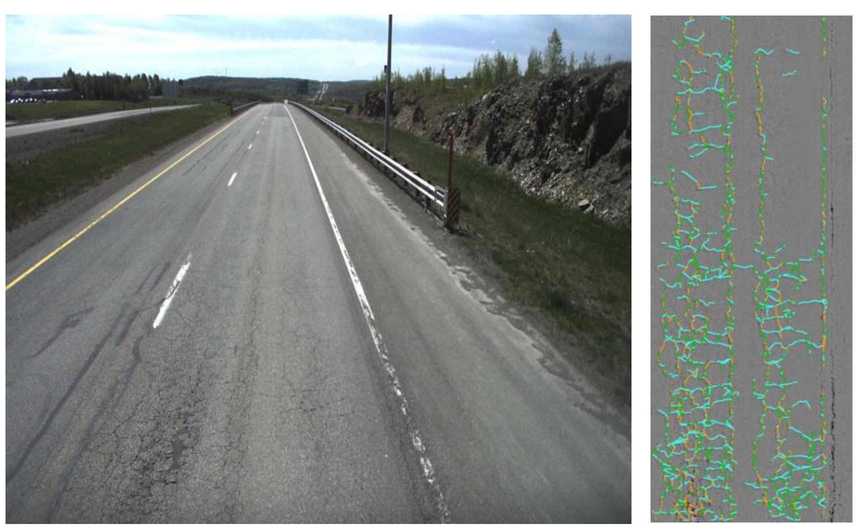
Figure 3 Multifunctional data collection vehicle (MFV)

Pavement Surface Condition Survey

Surface distress survey aims to identify the cause, extent, and severity of distress. This survey was conducted on the East extension of Highway 407 using the multifunctional data collection vehicle equipped with the latest pavement measurement technology, the Laser Crack Measurement System (LCMS).

The LCMS, mounted to the rear of the multifunctional vehicle, is a high-speed and high-resolution transverse profiling system. Capable of acquiring full 4-meter width 3D profiles of a highway lane at normal traffic speed, the system uses two laser profilers that acquire the shape of the pavement. Both the resolutions and acquisition rate of the LCMS are high enough to enable the detection of cracks at highway speeds. Custom optics and high-power pulsed laser line projectors allow the system to operate in full daylight or in nighttime conditions. The collected data were analyzed using a data processing library that has the capability of detecting and analyzing cracks and other defects, based on AASHTO R85 standard.

Figure 4 Automatic crack detection (3D image)

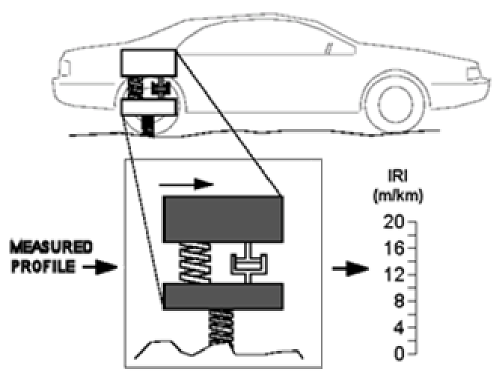


The distress data obtained from the post-processing was compiled for 50 m segments in order to produce the DMI. This index was computed based on the severity of length or area and weighting factors of the different types of cracks and surface defects observed on the pavement.

Pavement roughness measurement (IRI)

The surface roughness was assessed annually on the Highway 407 roadways using the multifunctional vehicle. The MFV assesses pavement ride quality by measuring the pavement longitudinal profile using an inertial profilometer meeting the Class 1 (higher quality) requirements of ASTM E950M-09 (2018)[4]. The longitudinal profile obtained is analyzed using a mathematical model that simulates the movement of a car's suspension (Figure 5). The model used can transpose roughness into IRI that is calculated as specified in ASTM E 1926 and averaged for the two-wheel paths for each 50 m segment[5].

Figure 5 The quarter-car model[6]



Rutting measurement

The multifunctional data collection vehicle was used to measure rut depth on Highway 407 infrastructure using a laser rut depth measuring system that captures the transverse profile of the entire traffic lane. At a frequency of 5.600 Hz, the device projects a laser beam on the surface of the pavement and the image of the line which takes the exact shape of the transverse profile is captured. The transverse profile obtained is made up of 4.000 points and covers a 4 meters width. This profile is then used to determine the rut depth for each wheel path in accordance with standard ASTM E 1703[7].

[4] ASTM E950 / E950M-09 (2018), Standard Test Method for Measuring the Longitudinal Profile of Travelled Surfaces with an Accelerometer Established Inertial Profiling Reference, ASTM International, West Conshohocken, PA, 2009.
[5] ASTM E 1926-08(2015), Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements, ASTM International, West Conshohocken, PA, 2015.
[6] Sayers, M.W. and Karamihas, S.M. (1998). The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles, University of Michigan Transportation Research Institute, Ann Arbor, MI.
[7] ASTM E1703 / E1703M-10(2015), Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge, ASTM International, West Conshohocken, PA, 2015.

The level of accuracy of the rut depth measurement is approximately +/-1 mm. Average rut depth is computed for 50 m segments in each travelled lane by averaging the left and right wheel path values.

Skid resistance measurement

The annual pavement friction testing for the 407-East Extension phase 1 was completed between 2016 and 2023. The friction tests were conducted according to ASTM Standard E274. This test method provides a measurement representing the steady-state friction force on a locked test wheel as it is dragged over a wetted pavement surface under constant load and at a constant speed, while its major plane is parallel to its direction of motion and perpendicular to the pavement. The friction data were collected at 500 m roadway intervals on the mainline highways. The Friction number (FN) was reported to determine compliance with agreement requirements.

Structural capacity evaluation

The structural capacity of a pavement is an important characteristic when determining the required intervention and it plays a decisive role in the distress that occurs in surface conditions over the mid and long term.
The pavement strength of the Highway 407 extension phase 1 was evaluated in 2023 using pavement deflection measurements determined with a Falling Weight Deflectometer (FWD). At each test location, a dynamic load was conducted by dropping weights at various drop heights onto a dampening system and a loading plate. Five load levels (ranging between 30 kN to 85 kN) were applied by using a circular plate of 300 mm in diameter to determine the deflection response of the existing pavement structure. The magnitude of the load is measured by means of a load cell placed in the center of the load plate while the temporary pavement deflection is obtained from nine geophones in accordance with the SHRP specifications and MERO-019 requirements. The FWD data were analyzed using the approach based on AASHTO 1993 guide and the Asphalt Institute MS17 manual.

Performance criteria

The Asset Preservation Performance Measures (APPMs) define the minimum performance criteria to maintain the road assets to achieve the desired levels of service and maintain or limit the extent of asset consumption. Since the project is a private-public partnership, the performance criteria were fixed in the Project Agreement. The threshold for each pavement performance criteria is presented in the table 1:

Table 1. Performance criteria for Highway 407

Performance indicator	50 m average threshold
DMI	7
IRI (m/km)	2.5
Rut depth (mm)	20
FN	30*

*500 m average threshold

Pavement performance modeling

The objective of pavement performance modelling is to use the best available tools and data to capture as much as possible the evolution of distress over time to plan maintenance and rehabilitation actions.

Pavement performance history

The pavement performance history (2016-2023) was used to develop the degradation curves for each of the parameters (DMI, IRI, Rut and FN) to predict the pavement performance trends.
Figures 6 to 8 shows an overview of the evolution of the average value of DMI, IRI and rut depth between 2016 and 2023 for the Highway 407 extension phase 1 based on the annual pavement assessment surveys.
As it can be seen, the network pavement meets the allowable criteria and there is no significant deviation between one-year periods. However, the DMI shows a downward trend with a slight improvement for 2021. This improvement could be explained by an important crack sealing campaign for fall 2020 and spring 2021.

Figure 6 Evolution of the average value of DMI between 2016 and 2023

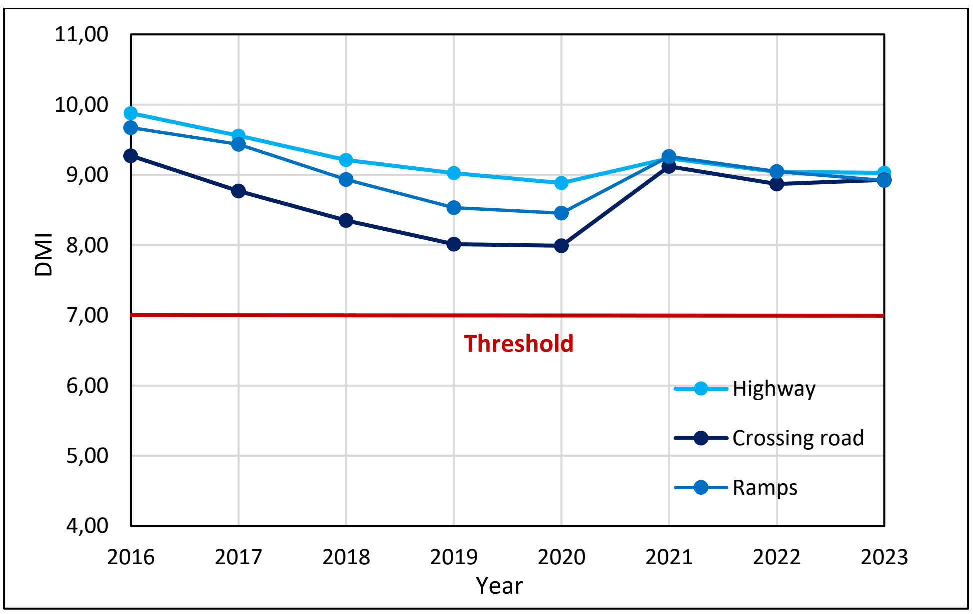


Figure 7 Evolution of the average value of IRI between 2016 and 2023

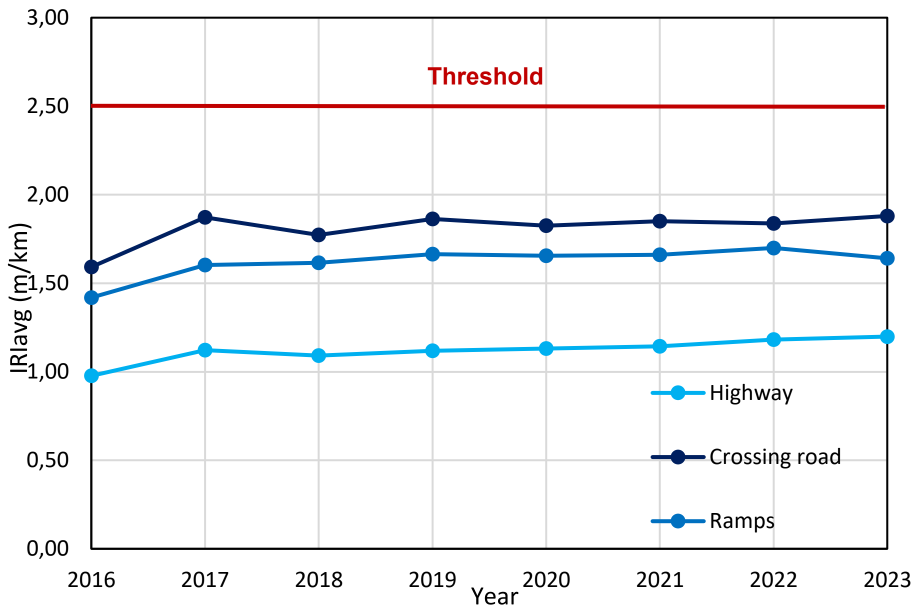
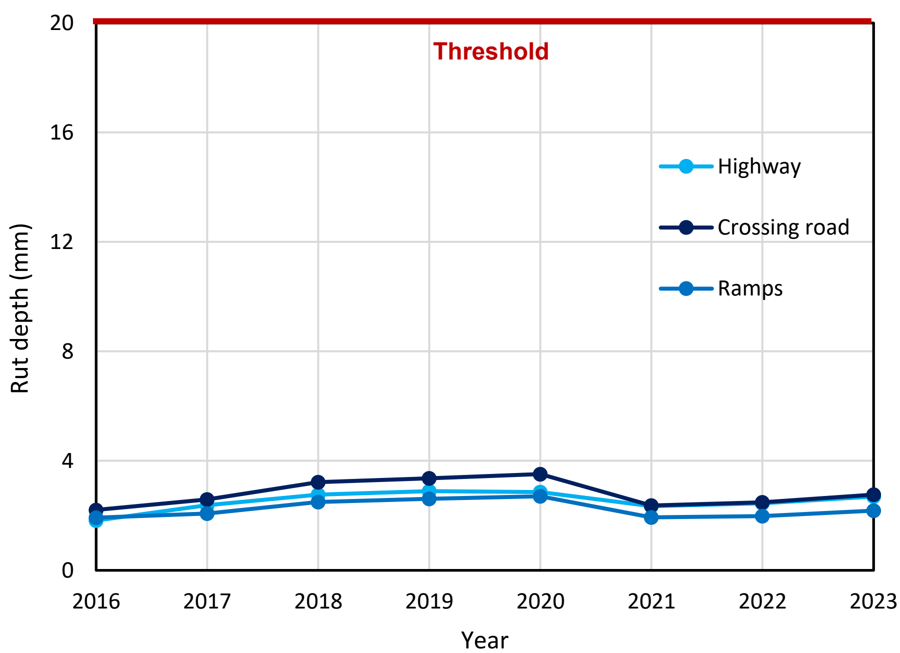


Figure 8 Evolution of average value of Rut depth between 2016 and 2023



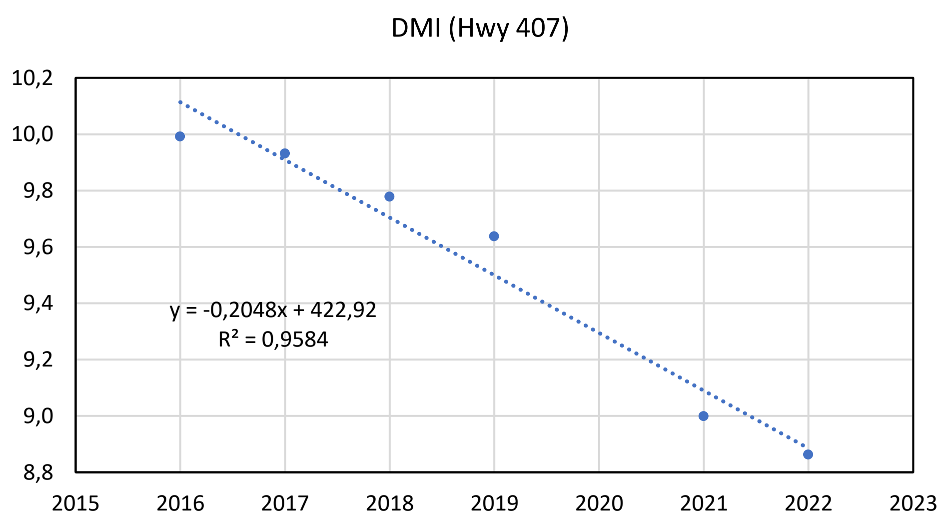
Curves degradation models

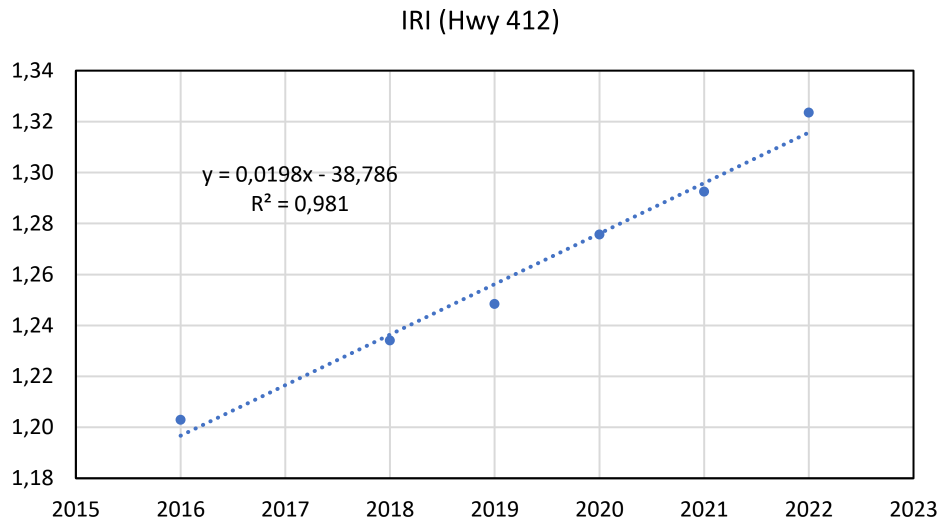
This part of the analysis is to determine the performance trends for each of the main criteria using the pavement performance history. In the annual performance assessment, the pavement network was divided into segments mainly measuring 50 m in length. To manage the network more easily and create the curve degradation, the 50 m segments of the Highways were assembled in 8 homogeneous sections, while the ramps were analysed individually. The following elements are similar for a homogeneous section:

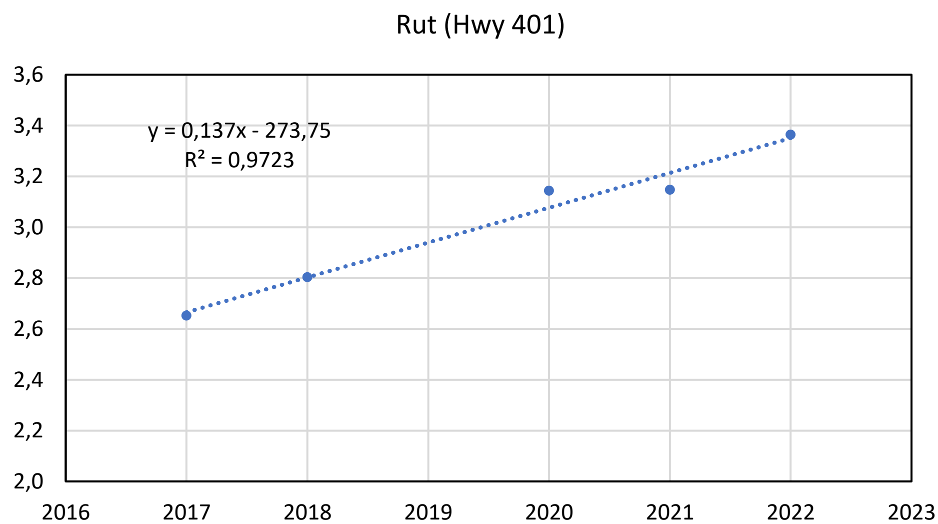
- Pavement structure: layers materials and thicknesses (asphalt, base, subbase)
- Subgrade soils: soil type and resilient modulus (Mr)
- Traffic data

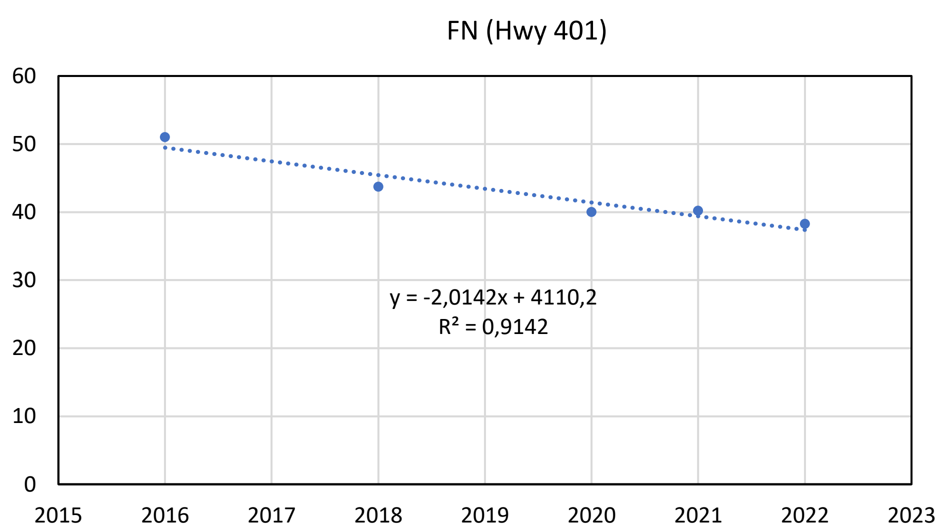
The average of each performance indicator was calculated for all the homogenous sections and the ramps for every year between 2016 and 2023. The performance history showed a linear evolution of the performance indicators over time. Using the linear trends, regression models are developed to predict each indicator evolution over the years. The following figures show some trend line equation of the various performance indicators for the homogeneous sections in Highways 407, 412 and 401. As observed, the root mean square coefficients (R^2) of determination are closer to 1, which shows a good correlation. It is important to mention that even if those curves were prepared specifically for the Highway 407 East Extension project those curves could also be used for other projects in the GTA having similar pavement characteristics according to a pavement engineer's judgment.

Figure 9 Curves degradation models




IRI (Hwy 412)
y = 0,0198x - 38,786
R² = 0,981
1,34
1,32
1,30
1,28
1,26
1,24
1,22
1,20
1,18
2015 2016 2017 2018 2019 2020 2021 2022 2023


Rut (Hwy 401)
y = 0,137x - 273,75
R² = 0,9723
3,6
3,4
3,2
3,0
2,8
2,6
2,4
2,2
2,0
2016 2017 2018 2019 2020 2021 2022 2023


FN (Hwy 401)
y = -2,0142x + 4110,2
R² = 0,9142
60
50
40
30
20
10
0
2015 2016 2017 2018 2019 2020 2021 2022 2023

In order to validate the curve models, the predicted 2023 pavement performance indicators were compared to those measured during the 2023 condition surveys. In cases of a low $\mathbf{R^2}$ values, the curve models were adjusted until minimizing the difference between the 2023 predicted and measured values.

Results summary

The curve degradation models were used to predict the performance indicators evolution from 2024 to 2027. Table 2 presents the summary of the failed highway segments in terms of the performance indicators mentioned above. According to the results, some segments would require rehabilitation and for some of them the friction resistance would begin to become problematic starting by 2026.

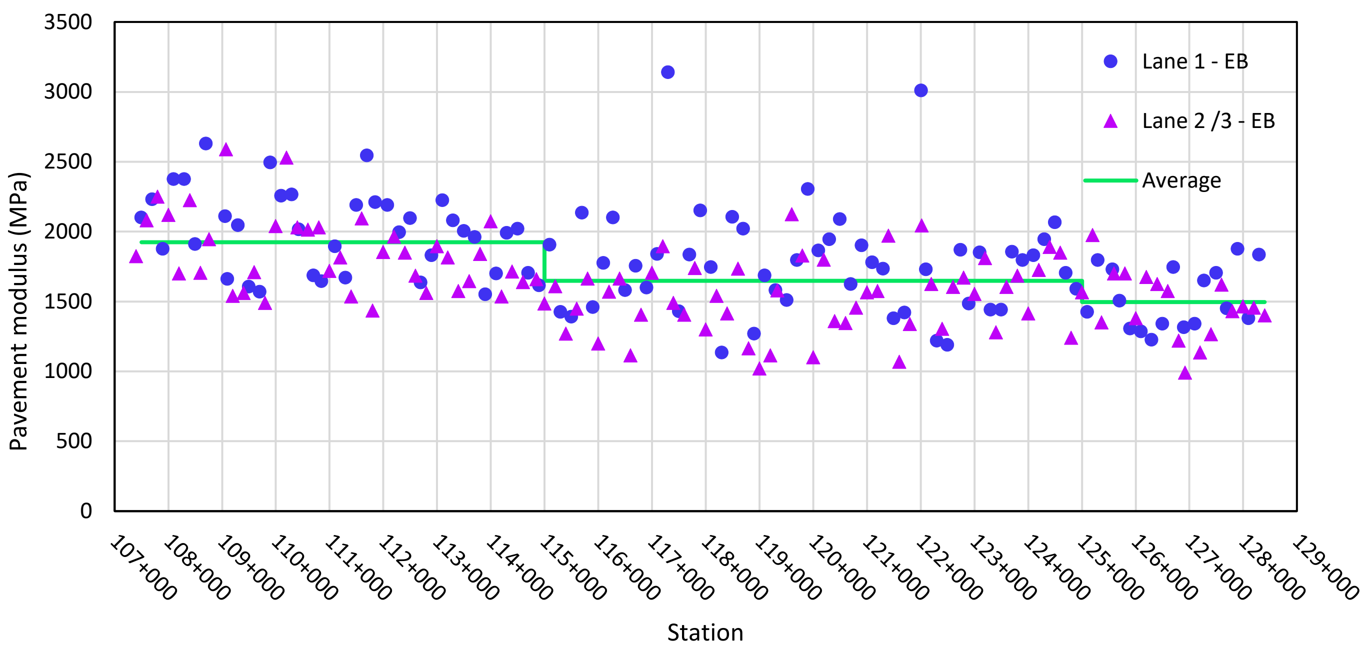
Table 2 Predicted failed segment summary for highways (2024-2027)

Highways	Performance indicators	2024	2025	2026	2027
Hwy 407	DMI	0.0%	0.0%	0.0%	0.6%
	IRI	0.4%	0.7%	0.8%	0.8%
	Rut	0.0%	0.0%	0.0%	0.0%
	FN	0.0%	0.0%	0.0%	0.0%
Hwy 412	DMI	0.0%	0.0%	0.3%	1.4%
	IRI	0.3%	0.3%	0.3%	0.3%
	Rut	0.0%	0.0%	0.0%	0.0%
	FN	0.0%	0.0%	0.0%	0.0%
Hwy 401	DMI	0.3%	0.7%	1.0%	1.4%
	IRI	0.7%	0.9%	1.0%	1.0%
	Rut	0.0%	0.0%	0.0%	0.0%
	FN	0.0%	0.8%	3.8%	9.2%

The evaluation of the structural capacity based on the FWD testing performed in 2023 has been used to validate the in-situ structural capacity. The pavement strength was assessed using 425 FWD tests. The pavement subgrade resilient modulus and the pavement structure modulus were determined, according to the 1993 AASHTO guide. The remaining life of the pavement was determined based on the deflections, the Asphalt Institute fatigue curve (MS-17) and the number of ESAL anticipated over the next 23 years, according to the Asphalt institute manual MS17.

The results of the FWD campaign indicate that all the sections show a good structural condition, and no reinforcement is required. Most of the sections tested show a pavement modulus greater than 1000 MPa, as presented in the figure below for Highway 407.

Figure 10 Variation of pavement modulus in Highway 407



Based on the evaluation of failed segments, the rehabilitation schedule was established using the various maintenance and rehabilitation interventions. The proposed program could be optimized depending on the annual pavement performance assessment results.

Summary and conclusions

The main objective of this project was to establish the pavement rehabilitation strategic of the Highway 407 East Extension, Phase 1 in Ontario. To achieve this goal, the trend of the pavement performance evolution based on DMI, IRI, Rut and FN values were predicted for the next four years, between 2024 and 2027, using the pavement performance history. The structural capacity results using the FWD that was performed in 2023 was used to validate the in-situ structural capacity. Based on those testing and analysis we can state that the pavement condition of Highway 407 network is currently in good to excellent overall condition, and we anticipate that it will continue to be that way in the next years. However, some sections will eventually have some failed segments in the next few years and the correction will be needed.

The main conclusions that can be drawn from this study are the following:

- The good condition of Highway 407 pavement can be related to various factors, such as the effective pavement design and adequate maintenance.
- The pavement condition assessment represents an important element in the pavement management system.
- The roughness, surface distress, rutting and skid resistance measurements can reflect the pavement overall condition.
- The pavement performance criteria can be used to manage the network's pavement performance.
- Regular maintenance activities such as crack sealing or other help to maintain network pavement performance.
- The annual pavement conditions surveys and the pavement performance modelling can be used to schedule the M&R activities.
- The degradation evolution models presented in this paper represent pavement conditions in the Greater Toronto Area Highway network, ramps and crossing roads.
- The right treatment at the right time and for the right conditions are important considerations when preserving, maintaining, and rehabilitating roads.

References

1. D'AMOURS, L., CONTANT, A., & Ng, J. (2016). Assessment of Subgrade Soils for Pavement Design for Highway 407, East Extension Pickering to Oshawa, Ontario. Conference and Exhibition of the Transportation Association of Canada
2. Ministry of Transportation Ontario, ''Manual for Condition Rating of Flexible Pavements – Distress Manifestations'', SP-024, (1989)
3. Luo, X., Gong, H., Tao, J., Wang, F., Minifie, J., & Qiu, X. ''Improving data quality of automated pavement condition data collection: Summary of state of the practices of transportation agencies and views of professionals''. Journal of Transportation Engineering, Part B: Pavements, 148(3), 04022042, (2022)
4. ASTM E950 / E950M-09 (2018), ''Standard Test Method for Measuring the Longitudinal Profile of Travelled Surfaces with an Accelerometer Established Inertial Profiling Reference'', ASTM International, West Conshohocken, PA, (2009)
5. ASTM E 1926-08, ''Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements'', ASTM International, West Conshohocken, PA, (2015)
6. Sayers, M.W. and Karamihas, S.M., ''The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles'', University of Michigan Transportation Research Institute, Ann Arbor, MI (1998)
7. ASTM E1703 / E1703M-10, ''Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge'', ASTM International, West Conshohocken, PA, (2015)
8. Ministry of Transportation Ontario, "Falling Weight Deflectometer (FWD) Testing Guideline," MERO- 019, (2005)
9. Ministry of Transportation Ontario, "Adaptation and Verification Of AASHTO Pavement Design Guide For Ontario Conditions," Final Report, March (2008)
10. AASHTO. "Guide for Design of Pavement Structures." American Association of State Highway and Transportation Officials, Washington, D.C. (1993)
11. Asphalt Institute, ''Asphalt Overlays for Highway and Street Rehabilitation MS-17'', (1990)
12. AASHTO R 85, ''Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Pavement Images Utilizing Automated Methods'', (2018)