Development of an Integrated Platform for Pavement Rehabilitation Design Optimization

by

Luigi CAPOTOSTO

THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT FOR A MASTER'S DEGREE
WITH THESIS IN CONSTRUCTION ENGINEERING
M. A. Sc.

MONTREAL, 2 FEBRUARY 2022

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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Mr. Gabriel J. Assaf, Thesis Supervisor
Department of Construction Engineering, École de technologie supérieure

Mr. Constantine J. Katsanis, Member of the jury
Department of Construction Engineering, École de technologie supérieure

Mr. Steve Babb, External Evaluator
Department of Civil Engineering, Dawson College

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND PUBLIC

MONTREAL, 20 JANUARY 2022

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

ACKNOWLEDGMENT

I would like to express my gratitude to my research director, Gabriel J. Assaf, professor in the Department of Engineering at l'École de Technologie Supérieure for his constant availability, financial and technical support all along this journey.

I would also like to thank the City of Chateauguay and MITACS subsidy program, for their financial support.

I would like to thank Mr. Jasmin Fournier, Director of Engineering at the City of Chateauguay, for their collaboration in providing me the necessary data and information presented in this dissertation.

Finally, I would like to thank my parents, and three children, Julia, Davide and Bianca for their support and encouragement throughout my studies.

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ABSTRACT

This thesis develops an integrated and efficient approach to evaluate pavement surface distress and riding comfort on road sections of a municipal network in order to determine the most likely cause of deterioration, suggest relevant tests to confirm the diagnosis and determine the most appropriate interventions on technical and economic grounds.

The thesis then applies that framework to the evaluation of the road network of the City of Chateauguay. All the distress present on the surface of all the road network are assessed alongside the riding comfort. The preliminary diagnosis regarding the most likely cause of deterioration associated to every road section is provided, followed by the relevant tests to perform to confirm the preliminary diagnosis for all the road sections of the network. The determination of the most relevant type of intervention is also provided from three main options depending on the cause of failure. A preliminary structural design is also provided to address highly trafficked roads for every type of subgrade.

A detailed cost evaluation of every intervention option is provided, taking into account materials and site execution processes. User cost savings are projected over the life of the pavement based on projected routine and periodic maintenance needs established by the Ministry of Transport of Quebec. The estimated internal rate of return is provided for every candidate section, based on its roughness, distress condition, traffic levels, maintenance projections and cost of materials.

Keywords: Pavement management system, diagnosis of road degradations, road maintenance, pavement rehabilitation, pavement distress.

Développement d’une plateforme intégrée d’optimisation de la réhabilitation des chaussées

Luigi CAPOTOSTO

RÉSUMÉ

Ce mémoire développe une approche intégrée et efficace pour évaluer les dégradations et le confort au roulement des sections de chaussées d’un réseau routier municipal, dans le but de poser des diagnostics préliminaires quant aux causes de détérioration, de suggérer les essais requis pour confirmer ces causes et de déterminer les interventions qui sont techniquement et économiquement justifiées.

Le mémoire présente ensuite un cas d’application, soit le réseau routier de la ville de Châteauguay. L’évaluation des dégradations sur l’ensemble des sections du réseau routier, suivi de l’appréciation du confort au roulement est décrite. La pose du diagnostic préliminaire, suivie des essais à effectuer pour confirmer ces diagnostics est présentée pour toutes les sections du réseau. La détermination de l’une de trois options d’intervention est effectuée pour chaque section du réseau, notamment pour répondre à la cause de détérioration. Une analyse de dimensionnement structural est présentée selon les niveaux de trafic estimés.

Une évaluation détaillée de chaque intervention retenue est fournie selon les matériaux et les opérations de chantier envisagées, ainsi que les économies projetées en termes de réduction des coûts d’exploitation des véhicules. Les interventions en matière d’entretien pour chaque solution de réhabilitation sont projetées sur 25 ans selon les pratiques du ministère des Transports du Québec. Ces flux monétaires sont ensuite utilisés pour calculer le taux de rendement interne estimé pour chaque intervention préliminaire retenue et son horizon d’application.

Mots-clés: système de gestion des chaussées, diagnostics de dégradations, entretien routier, réhabilitation de la chaussée, détresse de la chaussée.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Pavement Association
APWA	American Public Works Association
ARAN	Automatic road analyzer
ASTM	American Society of Testing and Materials
BCMoT	British Columbia Ministry of Transportation
CCDG	Cahier des charges et devis généraux
CDV	Corrected deduct value
CGRA	Canadian Good Roads Association
CRS	Condition Rating Survey
DOT	Department of Transportation
DTN	Design Traffic Number
ERR	Economic Rate of Return
ETS	École de technologie supérieure
FHWA	Federal Highway Association
GIS	Geographic Information System
GPS	Global Positioning System
HDM-4	Highway Development and Management System
HMA	Hot Mix Asphalt

IRI	International Roughness Index
IRR	Internal rate of return
IRRE	International Road Roughness Experiment
ISTEA	Intermodal Surface Transportation Efficiency Act
LCCA	Life Cycle Cost Analysis
LRM	Location Referencing Methods
LRS	Location Referencing System
LTPP	Long-Term Pavement Performance Program
M&R	Maintenance and rehabilitation
MAP-21	Moving Ahead for Progress in the 21st Century Act
MITACS	Mathematics of Information Technology and Complex Systems
MRM	May's Ride Meter
MTCO	Ministry of Transportation and Communications of Ontario
MTQ	Ministère des Transports du Québec
NCHRP	National Cooperative Highway Research Program
NPV	Net Present Value
NRC	National Research Council Canada
ODOT	Ohio Department of Transportation
PASER	Pavement Surface Evaluation and Rating
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PIARC	World Road Association
PMD	Pavement Management Dashboard

PMS	Pavement Management Systems
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
RCI	Ride Comfort Index
RED	Roads Economic Decision Model
RTAC	Road and Transportation Association of Canada
RTRRMS	Response-type road roughness measuring systems
SHA	State Highway Agencies
SHRP	Strategic Highway Research Program
TAC	Transportation Association of Canada
TDV	Total deduct value
TIC	Transportation Information Center
VDOT	Virginia Department of Transportation
VOC	Vehicle operating costs

INTRODUCTION

0.1 Background

In addition to being vital to the movement of people and goods, as well as providing accessibility to a wide variety of commercial and social activities, road networks are also one of the most valuable assets of any society (Meyer & Miller, 2001).

Maintaining the road infrastructure in good condition reduces the cost of transportation to users and goods (Motamed et al., 2014) and contributes to the social well-being and thriving of economies (Ng et al., 2019). Keeping roads in good condition is equally important to protect the value of the asset. To put this in perspective, suffice to mention that the cost of a road can easily surpass 1 million dollars per km lane, and the asset value for a city with 500 km of double-lane roads can surpass 1 billion dollars. In addition to represent significant national assets due to their elevated cost, roads are also key to economic growth. The need for road maintenance is therefore crucial to preserve the value of the investment, keep the cost of travel at its lowest and enhance social and economic benefits.

Pavement Management Systems (PMS) have been developed to properly design and time road maintenance and rehabilitation (M&R) programs (Hudson et al., 1979) in order to reduce the cost of transport and preserve the value of the asset, both of which are accomplished by keeping the rate of depreciation low. PMS relies on data such that pertaining to the soils, the pavement characteristics and properties, the surface condition data, the traffic loading spectra and the environmental condition, in order to determine present and future condition and M&R needs that would minimize vehicle operating costs (VOC) to users and M&R costs to road agencies (PIARC, 2014), which sum is designated as “society costs”.

The concept of PMS was first introduced in 1965 in “A Guide to the Structural Design of Flexible Pavements in Canada”, published by the Pavement Design and Evaluation Committee of the Canadian Good Roads Association (CGRA, 1965). The Road and Transportation

Association of Canada (RTAC) published the first guide on PMS titled "Pavement Management Guide" in 1977. Soon after, the Guide paved the road to the development and implementation of pavement management systems (PMS) by federal, state, and local governments (TAC, 2011; Haas, 2011).

However, while larger agencies like state or provincial departments of transport have the funding, resources and expertise to determine their needs and operate a PMS, most small municipalities are faced with the daunting challenge to develop and implement a PMS, such as: 1) lack of funds to undertake such, 2) lack of expertise to assess their needs, define the scope of services for consultants, accept the deliverables, estimate costs, and most importantly 3) lack of know-how to enforce the terms of references and refuse inaccurate data or an inadequate system (Assaf, 2020; He et al., 2017; Wolters et al., (2011b) that prioritizes needs based on condition and not based on cost-effectiveness. Another issue for small municipalities is the breadth required as the implementation of a PMS is a long and tedious effort, spanning many years, to build a reliable database on soils and pavement characteristics and properties, develop pavement performance models, collect surface distress condition, assess structural capacity, etc. (Haas et al., 2015).

For instance, a thorough and reliable surface distress condition evaluation can be very expensive and time-consuming. There are a variety of data collection methodologies and corresponding rating systems, and the most common are the Pavement Condition Index (PCI) developed by the US Corps of Engineers, the Pavement Surface Evaluation and Rating (PASER) developed by the Transportation Information Center of the University of Wisconsin-Madison, and the Condition Rating Survey (CRS) Index developed by the Illinois DOT (Wolter et al, 2011a). The level of detail and the reliability of the distress data is key to establish a diagnosis of the most likely cause of deterioration and determine the relevant tests to perform in order to ascertain the cause of failure before substantial amounts of money are invested in a rehabilitation treatment. In other words, M&R interventions at the least life cycle cost for society, i.e. users and agencies, need to address the cause of deterioration or failure, and any optimization of pavement maintenance rehabilitation strategies is dependent on reliable distress data.

Based on the above, many agencies and consulting firms have developed various PMS software, most of which essentially follow the same principle. The Highway Development and Management System (HDM-4), which was developed under the auspices of the World Bank, the Asian Development Bank, and others, and MicroPaver, developed by the U.S. Army Corps of Engineers (Mallick & El-Korchi, 2017) are good examples of such software.

0.2 Problem Statement

The City of Chateauguay (City), a small to medium-sized city with a road network above 500 lane kilometres, and therefore a replacement value of approximately 1 billion dollars, is undergoing substantial residential and industrial growth. With an aging network, an increasing traffic and an appreciable number of industrial roads, its pavements are deteriorating at a faster rate than originally anticipated. As most Canadian municipalities, the problem lies in that the annual budget to maintain these constantly deteriorating roads, at an acceptable level, is not sufficient, resulting in a substantial backlog of accumulated or delayed M&R works to perform at a higher cost. Therefore a sound, reliable and easy to implement PMS based on the following is crucial, namely: 1) reliable data, 2) recognition of the cause of deterioration, 3) confirmation of such with relevant testing, 4) selection of the interventions that can solve the cause of deterioration and 5) an economic life cycle cost analysis to identify the cheapest long-term maintenance and rehabilitation solution and therefore optimize the investment.

0.3 Scope

This project is being conducted at the *École de technologie supérieure* (ETS), in partnership and with funding from the City of Chateauguay (City) and MITACS in order to help improve the management of the road network of the City and develop an application to other cities.

0.4 Objectives of the project

The objectives of the project are:

1. To develop a low-cost pavement condition survey geared towards the most relevant tests to perform in order to confirm the likely cause of deterioration so that appropriate solutions are identified on solid technical grounds;
2. To develop a simple fast track procedure to assess the internal rate of return (IRR) of different M&R solutions for needy sections;
3. To develop PMS executive dashboard indicators akin to those found in project management to simplify communication regarding present and future condition and needs of the network and economic benefits to upper management and elected council.

0.5 Research Methodology

An extensive literature review was conducted to : 1) review the state-of-the-art in PMS in order to select an easy pavement distress identification protocol and a low-cost video-camera to record geo-referenced road distress, and 2) develop a simplified PMS for small to medium sized municipalities that would focus on: 2a) how to optimally select M&R strategies based on the most likely causes of deterioration, the associated relevant tests to confirm such, and an assessment of the internal rate of return (IRR) of any M&R decision on a life cycle cost basis; and 2b) a pavement management dashboard (PMD) akin to those used in *construction project management* that would inform decision makers on key performance metrics, so that they are aware, on a life cycle cost basis, of the impact of various decisions based on the IRR. The literature review consisted of a synthesis of road data inventory, data collection, pavement deterioration prediction models, and M&R optimization based on Life Cycle Cost Analysis (LCCA).

This literature review raised the importance of sub-sectioning or segmenting a road network into sections classified by road name and bound by their closest intersections. Sub-sectioning would be followed by a condition survey to assess surface distress by type, severity and coverage.

The city’s road network should therefore be segmented into sections and entered into a database by road names and/or boulevards. The field work would then consist of a comprehensive network level survey with preferably a slow-moving vehicle. The distress data would be collected via a low-speed visual windshield survey and a dash cam video mounted on the front windshield.

The network, *initially evaluated visually during the recording with the slow-moving vehicle,* would be reassessed after viewing the video recording and rated per the PASER method (Walker et al., 2002).

In addition to the distress survey, a comfort rating on a 1 to 10 scale, where 1 represents a distorted and failed pavement, and 10 represents a new pavement needs to be performed in accordance with the Ride Comfort Index (RCI) developed by the Transportation Association of Canada (TAC, 2012a; Argue, 1972).

Based on the literature review, Table 0.1 was prepared, providing a link between all potential types, severity and coverage of distress *(lines 2 and 3 in yellow)*, associated causes of deterioration (line 1 with purple background) and tests to confirm these *(2nd column from the right),* and technically responsive treatment solutions and horizon to implement *(last column).*

Table 0.1 Excel sheet portraying types of distress, causes, tests, and response treatment

DIAGNOSTIC PRÉLIMINAIRE DES CAUSES DE DÉTÉRIORATION →							CJ: COUPES/JOINT		G: GÉLIVITÉ				SE: ENROBÉ		OD: OXYDATION/DÉGEL		ESSAIS	Action	
Qualité	Fissures Tranvsersales		Fissures en Mailles		Fissures en Rives		Fiss. Longitudinales		Soulèvements		Tassements		Ondulations/Omières		**Desintégrations/Trous**				
	Espacem. (m)	Sév (P,T)	% surface	Sév (P,T)	% surface	Sév (P,T)	% de long.	Sév (P,T)	% surface	Sév (P,T)	% surface	Sév (P,T	% surface	Sév (P,T)	% surface	Sév (P,T)	CARACTÉRISER	INTERVENTION	HORIZON
40%	6	P	20%	P			60%	P									Fondation (granulaire/eau)	Planage/Resurfaçage	2026 - 2030
40%	6	P	20%	P			60%	P									Fondation (granulaire/eau)	Planage/Resurfaçage	2026 - 2030
30%	7	P	5%	P			70%	P			2%	P					Fondation (granulaire/eau)	Planage/Resurfaçage	2026 - 2030
30%	6	P					70%	P			1%	P			1%	P	Fondation (granulaire/eau)	Planage/Resurfaçage	2026 - 2030
100%																	Enrobé	Planage/Resurfaçage	Après 2030

For reference, the MS Excel file titled “*Châteauguay - Evaluation Sommaire, Diagnostic Préliminaire, Caractérisation Requise, Intervention et Horizon*” is available on this link: https://91800060qi.securevdr.com/ds389ecc0ec67447d49f8ef26851674066

0.6 Thesis Organization

The introduction introduces the context of the thesis and lists the objectives. Chapter 1 summarizes the relevant literature review that was performed and introduces Chapter 2 which details the methodology developed as part of this thesis as well as the application to the City of Chateauguay, followed by the findings, recommendations and conclusions.

CHAPTER 1

LITERATURE REVIEW

1.1 Pavement Roughness and Condition Rating Systems

1.1.1 History and Development

The concept of pavement serviceability, *which has now evolved into the International Roughness Index (IRI) as will be shown thereafter,* was initially developed by AASHO in the 1960s at a road test facility in Ottawa, Illinois. A panel of raters subjectively rated road comfort on 138 pavement sections from 0 to 5, where 0 is very poor and 5 is very good. These subjective numerical ratings were referred to as the Present Serviceability Rating (PSR). In order to find a faster, less subjective way to obtain the PSR, various pavement condition data was collected on the road sections of the AASHO test, namely cracking, rutting, patching and roughness. The latter was a metric conveying the standard deviation of the pavement surface to a perfectly horizontal plane, or distortion of the road to the average elevation (Carey & Irick, 1960). With regression analysis, a Present Serviceability Index (PSI) model was developed based on PSR and the physical measurements of the pavement (Watson et al., 2007). It was found that the subjective PSR can be very well estimated with the faster and rationally measured PSI which in turn is a function of the pavement surface roughness, the rutting depth, the cracking and patching areas. Concurrently, the Canadian Riding Comfort Index (RCI) was developed by the Canadian Good Roads Association (CGRA), *now known as the Transport Association of Canada* (TAC, 2012a) on a 0 to 10 scale, whereby 1 refers to a very uncomfortable distorted road and 10 is an excellent road.

While a surface roughness index is important to convey how comfortable the road is, a pavement condition index, aggregating the many distress present on the pavement surface, is equally important to convey the level of deterioration of the road. It is in this perspective that the pavement condition index (PCI) was developed by the U.S. Corps of Engineers (1982) for airports and airfields and adopted thereafter by the American Public Works Association (APWA) and ASTM International, and documented in ASTM D6433 (Wolters et al., 2011a).

The methodology to conduct a pavement condition evaluation is to divide the network into branches, sections, and sample inspection units. A PCI of 100% is considered a perfect score, and the PCI value for the sample units are determined by a process of deduct values deducted from 100-point measurement based on type, quantity, and severity level of about twenty distress in asphalt pavements (US Army, 1982).

Many other similar indices were developed, such as the Pavement Condition Rating (PCR), a metric obtained from a combination of pavement surface distresses and pavement roughness (FHWA, 2009a). It is based on a visual inspection of pavement distress and is computed by deducting the cumulative deduct points for each type of observable distress from a PCR value of 100 being a perfect pavement. The deduction of each distress type, which is a function of severity and extent, is calculated by multiplying distress weight times the weighted values (Ohio DOT, 2006).

The Pavement Surface Evaluation and Rating System (PASER) was developed by the University of Wisconsin-Madison. It is a manual assessment based on visually rating the pavement surface condition based on a PASER evaluation manual, which displays photographs and descriptions with rated distresses assigned for each of the individual rating categories. The rating scale is from 1 to 10, with 1 representing a structural failed pavement and 10 representing a new pavement (Walker et al., 2002).

Pavement condition data used in a PMS are represented either as individual indices or as composite indices. Individual indices are usually calculated in terms of individual distress type, severity, and extent, whereas composite indices are combinations of different types of condition data represented as a single index of the overall condition of a pavement (AASHTO, 2012).

Composite indices are further broken down into subjective or biased and objective or rational composite indices. A visual, subjective method that doesn't require detailed measurements is the Pavement Surface Evaluation Rating (PASER), developed by the University of Wisconsin (AASHTO, 2012). In contrast, objective methods require detailed measurements and calculations to obtain an overall condition index such as in the Present Serviceability Index (PSI), and Pavement Condition Index (PCI) (FHWA, 2013).

1.1.2 Pavement Condition Index

The development of ASTM standard D6433 was inspired from the Pavement Condition Index (PCI) developed in the late 70s by the Army Corps of Engineers. It is an objective survey procedure to evaluate pavement surface distresses, where deduct values are assigned based on the type, severity, and extent. The summation of the deduct values is deducted from 100 representing a perfect pavement (PCI=100) (Hussain & Al-jameel, 2018; AASHTO, 2012; Adarkwa & Attoh-Okine, 2013). Figure 1.1 illustrates how to convey the PCI condition of a network for a municipal council to appreciate the condition and needs of the network.

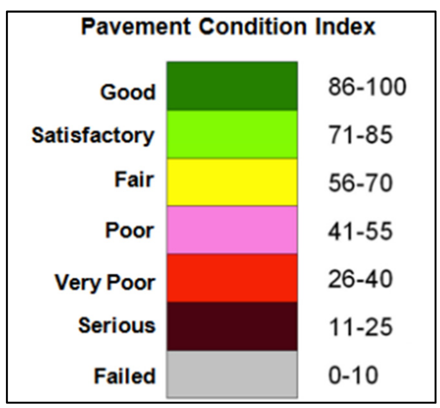


Figure 1.1 Pavement condition index ratings
Taken from Wolters et al. (2011b)

The PCI calculation is based on the ASTM standard D6433-09, where distress type, severity, and extent are recorded (FHWA, 2014).

The procedure to conduct a pavement condition survey and obtain PCI rating consists of the following (PAVER 1982; ASTM D6433-09; Shahin et al.,1979):

- The candidate roadway is divided into sample segments;
- Sample units only from each segment are inspected;
- Distress types, severity and extent are identified, and density is measured;
- Sample unit density from individual distress type and severity is obtained;
- Deduct values are determined for each distress type, severity and coverage;
- Individual deduct values are summed to obtain a total deduct value (TDV);
- Corrected deduct value (CDV) is determined from the correction curves;
- Any individual deduct value greater than CDV, the CDV is set to equal that value;
- PCI is determined by subtracting CDV from a perfect pavement rating of 100.

1.1.3 PASER Rating System

The PASER method is a manual form of pavement condition assessment, developed by the University of Wisconsin. It is a windshield survey procedure that assigns subjective composite index rating based on observed distresses. Ratings for asphalt roads range from 1 to 10, where 1 represents a structurally failed pavement, and 10 represents a new pavement. During the survey, distresses are observed, identified, and an appropriate score is assigned to each section based on photographs and description provided in the PASER rating manuals (Walker et al., 2002; AASHTO, 2012). The PASER ratings given to pavement sections come with the recommended actions for maintenance and repairs (Walker et al., 2002). Local agencies, such as cities, counties, and towns are limited with resources, and prefer the PASER method to evaluate pavement condition (Montgomery & Haddock, 2019a). Cambridge Systematics (2006) claims that PASER requires fewer resources, and less training to assess pavement condition, and is convenient for local agencies with limited resources. Although a subjective method, the accuracy in assigning PASER ratings were more apparently consistent and accurate amongst engineer, engineer technician, or engineer assistant (Montgomery et al., 2019b). The main problem with the PASER rating is that it is not directly related to the cause of deterioration**, as two road sections can have the same rating but due to two different causes that require different interventions**. Table 1.1 and Table 1.2 illustrate PASER Rating Systems for asphalt and concrete pavements.

Table 1.1 PASER Rating System for Asphalt Pavements
Taken from Michigan Transportation Asset Management Council (2018)

	Asphalt 10	**Asphalt 9**	**Asphalt 8**
Good	New construction (<1 year old) No defects Recent base improvement *Possible Action:* *PPM*	Like new condition (>1 year old) No defects Recent overlay with or without a crush and shape *Possible Action:* *PPM*	◆ Transverse cracks: >40' apart Cracks: tight (hairline) or sealed Longitudinal cracks: few, on joints Recent seal coat or slurry seal (*see below) *Possible Action:* *Crack seal (PPM)*
	Asphalt 7	**Asphalt 6**	**Asphalt 5**
Fair	◆ Transverse cracks: 10'-40' apart Cracks: open < ¼" Crack erosion: none or little Surface raveling: none or little Patches: none or few in excellent condition First signs of wear *Possible Action:* *Maintain with crack seal, fog seal*	◆ Transverse cracks: < 10' apart ◆ Block cracking: 6'-10' Blocks (large, stable) Cracks open ¼" – ½" Surface raveling: slight Patches: few in good condition Polishing or flushing: slight, moderate Sound structural condition *Possible Action:* *Maintain with sealcoat*	◆ Block cracking: 1' – 5' blocks ◆ Longitudinal cracks: first signs, at edge ◆ Secondary cracks: first signs Cracks open >½" Surface raveling: moderate Patches/wedging: good condition Flushing & polishing: extensive, severe Sound structural condition *Possible Action:* *Maintain with sealcoat or thin overlay*
	Asphalt 4	**Asphalt 3**	**Asphalt 2**
Poor	◆ Block cracking: <1' blocks ◆ Wheel-path cracking (longitudinal) ◆ Rutting: ½" - 1" deep Transverse cracks: slight erosion Longitudinal cracks: slight erosion Surface raveling: severe Patches: fair condition First signs of structural weakening *Possible Action:* *Structural overlay >2"* *Underseal*	◆ Block cracking: severe (like alligator) ◆ Alligator cracking: initial, < 25% ◆ Rutting: 1"- 2" deep Transverse cracks: extensive erosion Longitudinal cracks: extensive erosion Patches: fair/poor condition Potholes: occasional *Possible Action:* *Structural overlay >2"* *Patching & repair prior to an overlay* *Milling to extend overlay life*	◆ Alligator cracks: > 25% ◆ Rutting or distortion: >2" Cracks: closely spaced, with erosion Patches: extensive, in poor condition Potholes: frequent *Possible Action:* *Reconstruction with base repair* *Crush and shape* **Asphalt 1** Like PASER 2 but with visible base and: Surface integrity: lost Surface distress: extensive *Possible Action:* *Reconstruction with base repair*

Table 1.2 PASER Rating System for Concrete Pavements
Taken from Michigan Transportation Asset Management Council (2018)

	Concrete 10	**Concrete 9**	**Concrete 8**
Good	New construction (< 1 year old) No defects Recent reconstruction *Possible Action:* *None*	Like NEW (> 1 year old) ◆ Joint rehabilitation: recent, only if no other defects are present Map cracks: slight Pop outs: few Surface wear: light, in wheel path Recent concrete overlay *Possible Action:* *None*	◆ Joint sealant: partial loss ◆ Joints: good condition ◆ Transverse cracks: none Meander cracks: isolated, well-sealed/tight Cracks: at manholes – isolated, well-sealed/tight Map cracks: minor Scaling: slight (first signs) Pop outs: minor Surface wear: light *Possible Action:* *Little to no maintenance*
	Concrete 7	**Concrete 6**	**Concrete 5**
Fair	◆ Full-depth repairs: excellent condition ◆ Transverse cracks: isolated Joints: some open Cracks: at manholes – some Settlement/heaves: isolated Scaling: minor Pop outs: could be extensive but sound *Possible Action:* *Seal open joints* *Spot repair surface defects*	◆ Transverse joints: open ¼" ◆ Longitudinal joints: open ¼" ◆ Transverse & meander cracks: open ¼" Cracks: at corners – several, well-sealed/tight Shallow reinforcement: cracking – first signs Scaling: <25% surface *Possible Action:* *Seal open joints and cracks* *Overlay surface raveling areas*	◆ Joint/crack spalling: first signs ◆ Joint/crack faulting: up to ¼" Cracks: at corners – multiple, w/ broken pieces Shallow reinforcement: spalling Scaling: 25% to 50% surface Polishing: 25% to 50% surface *Possible Action:* *Some partial depth joint repairs or patching may be needed*
	Concrete 4	**Concrete 3**	**Concrete 2**
Poor	◆ Joint/crack spalling: open 1" on several slabs ◆ Joint/crack faulting: up to ½" ◆ Transverse or meander cracks: multiple Cracks: at corners – missing pieces or patches Pavement blowups Spalling: >50% surface Map cracks: >50 % surface Scaling: >50% surface Polishing: > 50% surface *Possible Action:* *Some full depth repairs* *Asphalt overlay or extensive surface texturing of surface scaling*	◆ Joint, transverse, and meander cracks: open 1" on most slabs severely spalled ◆ Joint/crack faulting: up to 1" ◆ D-cracking: evident Patches: extensive, fair to poor condition *Possible Action:* *Extensive full depth repairs* *Some full slab replacements*	Joints: failed Settlement/heaves: extensive, severe Spalling (of slab cracks): extensive, severe Patches: extensive, failed condition *Possible Action:* *Recycle or rebuild pavement* **Concrete 1** Pavement integrity: total loss Potholes: extensive Restricted speeds *Possible Action:* *Total reconstruction*

1.1.4 Pavement Roughness

Pavement roughness expresses the deviations of the road surface over a planar and smooth surface, which affect the vertical movements of a vehicle on the road and therefore user comfort. Surface roughness consists of multi-frequency random-wave roughness with different amplitudes and wavelengths (Bidgoli et al., 2019; Hudson, 1981; Radović et al., 2016). Haas et al. (1994) refer to pavement roughness as the distortion of pavement surface, which affects ride quality (Haas et al., 1994). Sayers et al. (1998) defines pavement roughness as a continuous longitudinal profile measured along any continuous imaginary line (Sayers et al., 1998). Road roughness develops through pavement distresses such as cracking, raveling, potholes, edge breaks and deformations (Radović et al., 2016). Figure 1.2 illustrates pavement roughness in the wheel-paths.

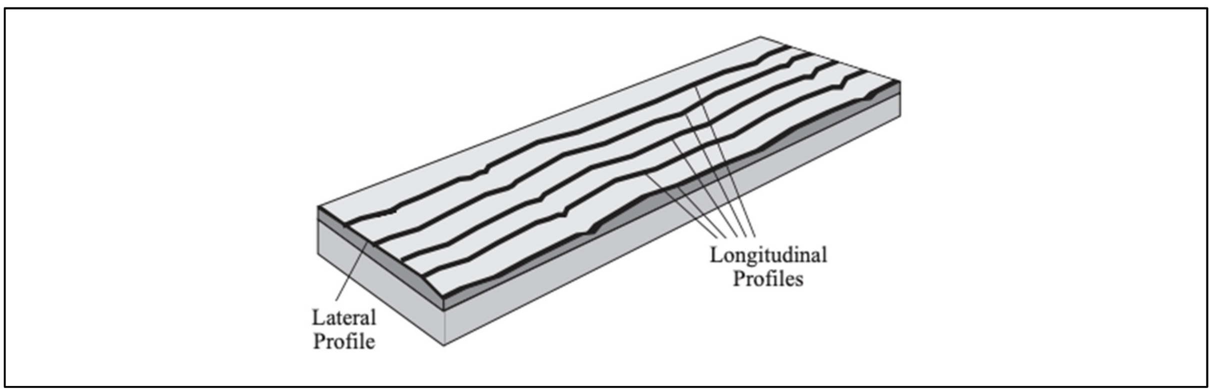


Figure 1.2 Pavement roughness in wheel-paths
Taken from Sayers et al. (1998)

The American Society of Testing and Materials (ASTM, E867) defines road roughness as:
"The deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile, and cross slope."

1.1.4.1 Characteristics of Pavement Roughness

Pavement roughness can be measured with different techniques and methods. The measurement can be categorized in four groups per the World Bank (Sayers et al., 1986a, 1986b):

- Direct profile measurements which qualify as class I;
- Indirect profile measurements (usually lasers) which qualify as class II;
- Response-type road roughness measuring systems (usually mechanical) (RTRRMS) which qualify as class III;
- Subjective ratings panels which qualify as class IV.

They are many devices for road roughness measurement, which are based on two approaches: the direct measurement of road profile and measurement based on road/vehicle interaction. Direct measurement devices are rod and level survey, dipstick, profilograph, lightweight profiler, and high-speed inertial, whereas automatic road analyzer (ARAN) and May's Ride Meter (MRM) are based on road/vehicle interaction response (ASTM E950/E950M-09,2018; ASTM E1364-95, 2017; Walker & Hudson, 1973; FHWA, 2014).

Road roughness measurement methods and equipment were classified according to margin of error and methodology to obtain IRI and were grouped into four classes (ASTM E950/E950M-09 (2018). Class 1 devices are high precision with negligible error of measurement, Class 2 profilers utilizes other profile measurement methods with lower precision, Class 3 determines roughness estimates based on correlation equations, and Class 4 are subjective and uncalibrated measurements. Shown in Table 1.3 are different roughness measuring devices and class type (Bennett et al., 2006).

Table 1.3 Roughness measuring devices
Taken from Bennett et al. (2006)

Class	Devices
Class I Precision profiles	**Laser profilers**: Non-contact lightweight profiling devices, portable laser profilers **Manually operated devices**: e.g. TRL beam, Face Dipstick/ROMDAS Z-250, ARRB Walking Profiler
Class II Other profilometer methods	APL profilometer, profilographs (e.g., California, Rainhart), optical profilers, high speed inertial profilers (GMR) and Automatic Road Analyzer (ARAN)
Class III IRI estimates from correlation equations	Roadmaster, ROMDAS, Roughometer, TRL Bump Integrator, rolling straightedge and May's Ride Meter (MRM)
Class IV Subjective ratings/uncalibrated measures	Key code rating systems, visual inspection, ride over section and rod and level survey

1.1.4.2 International Roughness Index (IRI)

The International Roughness Index (IRI) is an indicator used worldwide to characterize longitudinal roughness in the wheel-paths (Mùčka, 2017; Sayers et al., 1986c). In an effort to standardize road roughness measurements between different equipment and roughness indices, the World Bank conducted "The International Road Roughness Experiment (IRRE)" in the 1980s in Brazil, where the IRI was developed (Sayers et al., 1986c). The IRI is a roughness scale expressed in m/km or in/mile, where the ratio is based on accumulated vertical displacement in response to road surface roughness of a standard quarter-car suspension travelling at a speed of 80 km/h to a horizontal distance travelled (Mathew et al., 2018; Mùčka, 2017). The quarter-car model is shown in Figure 1.3.

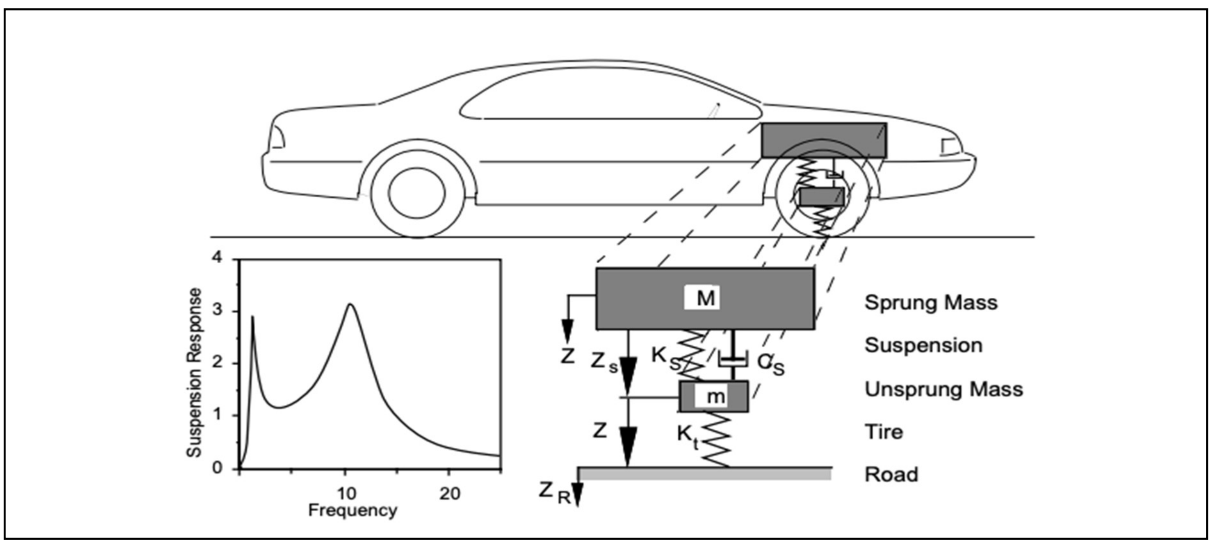


Figure 1.3 Quarter Car Model
Taken from Sayers et al. (1998)

The IRI has become a popular standard for the assessment of road roughness (Abulizi et al., 2016) with four types of equipment classified as: the direct profile measuring equipment, the indirect profile measurements, the response-type road roughness measuring systems (RTRRMS), and the subjective rating panels (Sayers et al., 1986a, 1986b).

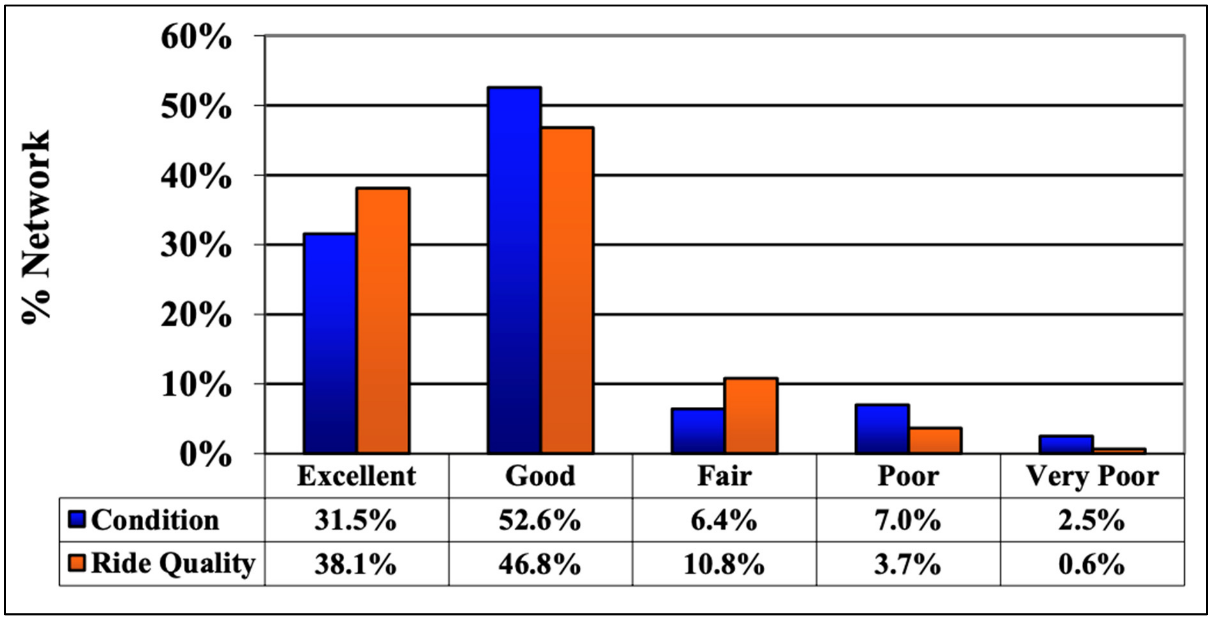
An effective pavement management system requires the network road classification and their corresponding threshold IRI rating to establish pavement ride quality categories. The established categories convey a clear picture to the city engineers and electives of the status of the road network.

Virginia Department of Transportation (VDOT) established categories for pavement ride quality based on IRI thresholds for its Interstate, Primary, and Secondary systems (VDOT, 2019). Table 1.4 defines the ride quality category for IRI rating of different road classes and values.

Table 1.4 Pavement Ride Quality Definition
Taken from VDOT (2019)

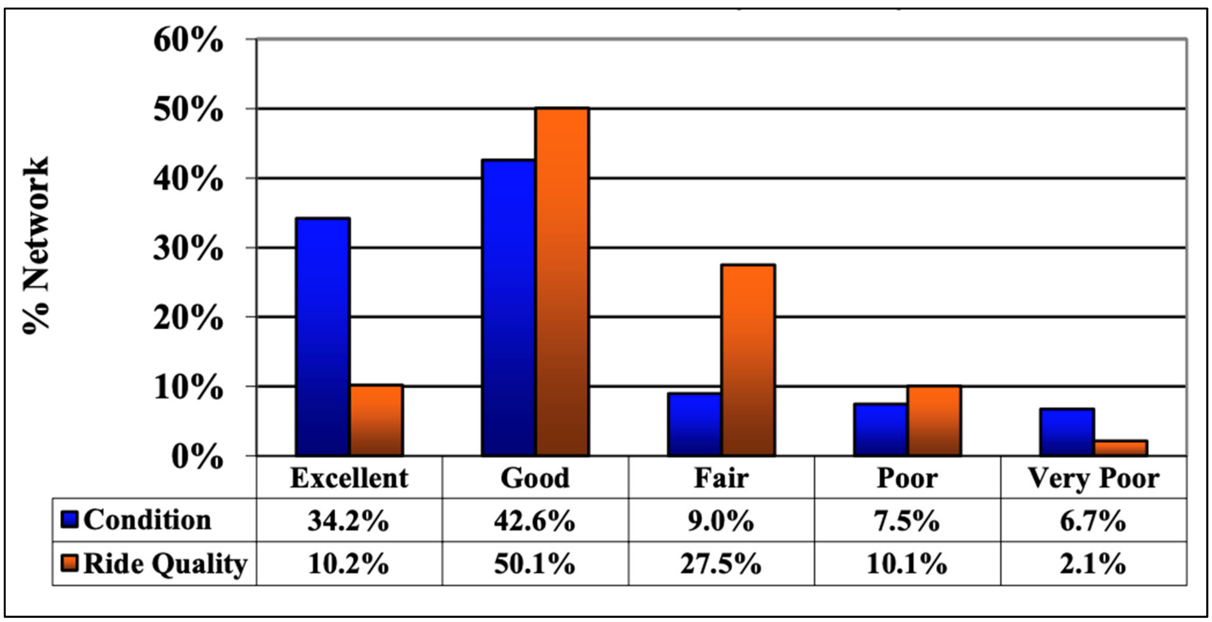
Ride Quality Category	IRI Rating (inch/mile)	
	Interstate & Primary	Secondary
Excellent	< 60	< 95
Good	60 to 99	95 to 169
Fair	100 to 139	170 to 219
Poor	140 to 199	220 to 279
Very Poor	≥ 200	≥ 280

The statewide pavement condition and ride quality of the road network are classified as Interstate, Primary, and Secondary (VDOT, 2019). The pavement condition and ride quality categories are shown in Figure 1.4, Figure 1.5, and Figure 1.6.



	Excellent	Good	Fair	Poor	Very Poor
Condition	31.5%	52.6%	6.4%	7.0%	2.5%
Ride Quality	38.1%	46.8%	10.8%	3.7%	0.6%

Figure 1.4 Pavement Condition and Ride Quality - Interstate
Taken from VDOT (2019)



	Excellent	Good	Fair	Poor	Very Poor
Condition	34.2%	42.6%	9.0%	7.5%	6.7%
Ride Quality	10.2%	50.1%	27.5%	10.1%	2.1%

Figure 1.5 Pavement Condition and Ride Quality - Primary
Taken from VDOT (2019)

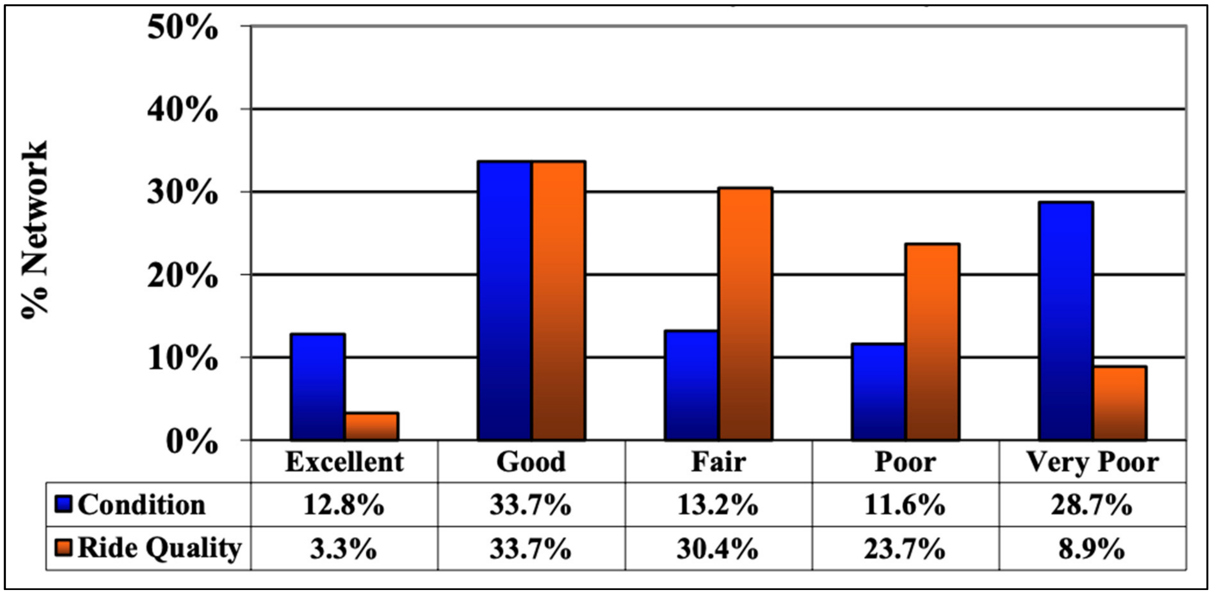


Figure 1.6 Pavement Condition and Ride Quality - Secondary
Taken from VDOT (2019)

The ride quality threshold that impacts vehicle response depends on roadway type and pavement age. Shown in Figure 1.7 is the IRI range (inches/mile) for different classes of roadway.

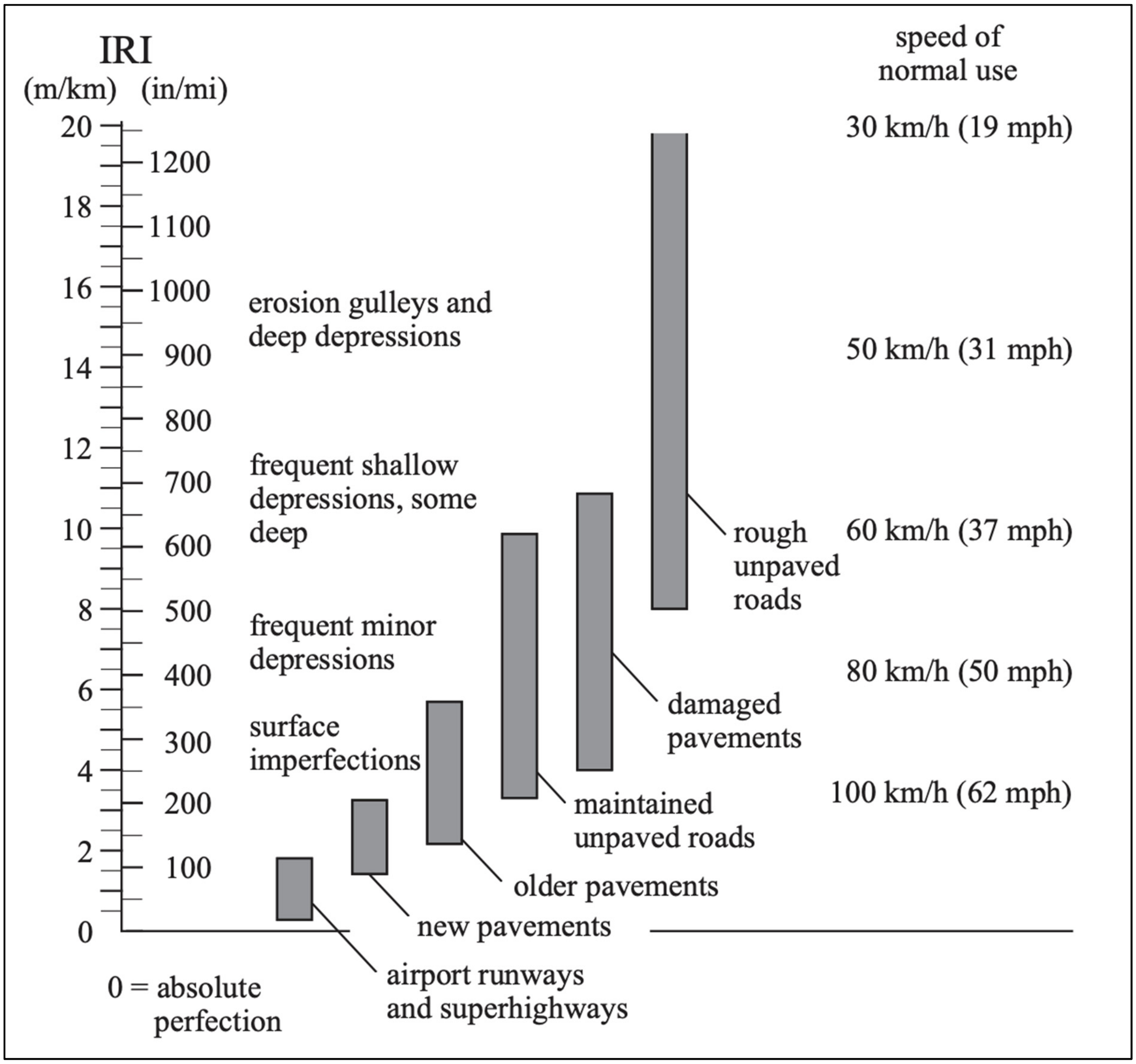


Figure 1.7 IRI Range by Roadway Type
Taken from Sayers et al. (1998)

1.2 Pavement Distress Types

1.2.1 Transverse cracks

These are cracks that are predominantly perpendicular to the pavement and may extend fully or partially across the pavement (BCMoT, 2020; ODoT, 2019; MTQ, 2007). Theses cracks are predominantly due to temperature fluctuations. At low temperature, the hot-mix asphalt

(HMA) layer contracts, and tensile stress develops within the HMA (Fwa, 2006). Individual cracks are assigned severity levels and recorded in linear feet or meters. Severity levels are based on crack width, ramifications, and degree of spalling (Miller & Bellinger or FHWA, 2014; BCMoT, 2020; MTQ, 2007). Shown in Figure 1.8 are transverse cracks on a roadway.

Figure 1.8 Transverse cracks
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (Assaf, 2020; BCMoT, 2020; MTQ, 2007):

- Shrinkage of the surface caused by low temperatures;
- Thermal shrinkage of the lower layers;
- Hydraulic movement;
- High temperature susceptibility of the asphalt cement binder in asphalt mixes;
- Frost action;
- Reflection cracks;
- Unsuitable class of bitumen for the zone.

1.2.2 Meandering Longitudinal Cracks

These longitudinal cracks travel from edge to edge across the pavement surface or may be located in the middle of the lane, parallel to the centreline. Sinuous longitudinal cracks are usually single cracks, but secondary cracks can develop when transverse cracks are present. Theses cracks are predominantly due to frost, they are recorded in linear feet or meters, and the severity levels are based on cracks width, single or multiple cracks and degree of spalling (BCMoT, 2020; MTQ, 2007). Shown in Figure 1.9 is a frost-related crack on a roadway.

Figure 1.9 Cracking due to the effects of frost
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- Frost action with greater heave at the centre of the street than at the edges. This is more common in mixes with considerable asphalt milling;
- Faulty construction equipment can cause weak planes in the mix, which can fail due to thermal shrinkage;
- Poor longitudinal joint construction;

- Differential frost penetration;
- Thermal shrinkage of the lower layers;
- Inadequate drainage;
- Frost susceptible subbase and/or subgrade.

1.2.3 Alligator cracks

Alligator cracks are interlocking pieces of cracked asphalt of various sizes, resembling the skin of an alligator with detached pieces forming many-sided, sharp-angled patterns with average size of 300 mm or less. The affected area is recorded in square feet or square metres, and the severity levels are based on crack patterns with different degrees of opening between pieces (BCMoT, 2020; MTQ, 2007; Fwa, 2006; Mallick & El-Korchi, 2017). Figure 1.10 illustrates a roadway with alligator cracks.

Figure 1.10 Alligator cracks
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- Most common in areas subject to repeated traffic loads;
- Insufficient bearing support due to poor quality material base or saturated base with poor drainage;
- Stiff or brittle asphalt mixes at cold temperatures;
- Oxidation and natural aging of bitumen;
- Overheating of bitumen during production.

1.2.4 Edge cracks

These are cracks that are parallel to and within 600 mm of the pavement edge. They occur due to insufficient lateral support, which occurs on roadways with unpaved shoulders. Traffic loading or weakened base from frost or inadequate drainage are the main causes. The cracks may be crescent-shaped cracks or cracks that intersect the edge of the pavement. Cracks are recorded in linear feet or meters and the severity levels are based on cracks width, single or multiple cracks, and degree of spalling (BCMoT, 2020; MTQ, 2007; Miller and Bellinger or FHWA, 2014; Mallick & El-Korchi, 2017). Figure 1.11 illustrates edge cracks on a roadway.

Figure 1.11 Edge cracks
Taken from Guide de mesure et d'identification des dégradations des chaussées souples MTQ (2007)

The most probable causes are as follows (BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- Frost action;
- Insufficient structural support of the pavement edge and/or excessive traffic loading;
- Poor drainage at the pavement edge and shoulder;
- Water infiltration from the sides;
- Vertical movement of poorly compacted layers;
- Settlement caused by a landslide;
- Thawing and settlement due to reduced bearing capacity;
- Inadequate pavement width forces traffic too close to the edge of the roadway;
- Discontinuity in the structure (e.g., widening).

1.2.5 Longitudinal and Joint Cracking

These are cracks that occur outside the wheel-paths, within the vicinity (i.e., +/- 300 mm) of the longitudinal centre or cold joint of the pavement lane line. Individual cracks are assigned severity levels and recorded in linear feet or meters. Severity levels are based on cracks width, single or multiple cracks, and degree of spalling (BCMoT, 2020; MTQ, 2007; ODoT, 2019; Miller & Bellinger or FHWA, 2014; Shahin & Walther, 1990). Figures 1.12 and 1.13 illustrate non-loading longitudinal cracks on a roadway.

Figure 1.12 Longitudinal cracking
Taken from Guide de mesure et d'identification des dégradations des chaussées souples MTQ (2007)

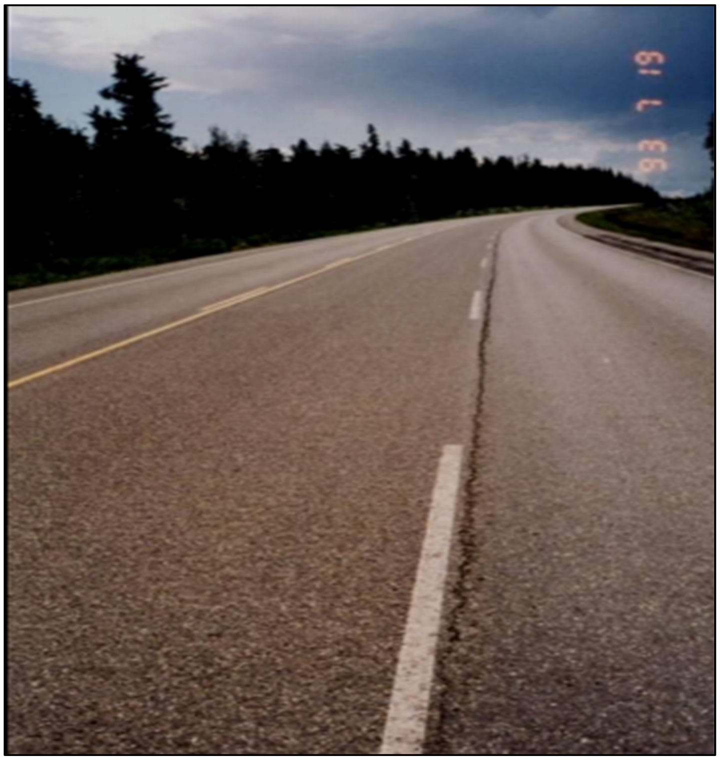


Figure 1.13 Longitudinal joint cracking
Taken from Pavement Surface Condition Rating Manual
BCMoT (2020)

The most probable causes are as follows (BCMoT, 2020; MTQ, 2007; Mallick & El-Korchi, 2017):

- Poor construction or location of the longitudinal joint;
- Frost action on adjacent lanes differ due to different granular depth;
- Differential frost heave along the centreline due to pavement edge snow (insulating value);
- Moisture changes resulting in swelling and shrinkage;
- Segregation of the asphalt during paving (e.g., centre of the spreader).

1.2.6 Longitudinal fatigue cracks (wheel-paths)

Longitudinal fatigue cracks occur in the wheel-paths. They generally originate as longitudinal cracks in the wheel-paths, and eventually to alligator-cracking pattern. They can be either load-related, where repeated traffic loading (wheel-path) causes fatigue failure or non-load-related, where oxidation and stiffness of the asphalt layer is the cause. The affected area is recorded in square feet or square metres (BCMoT, 2020; MTQ, 2007; Fwa, 2006; Mallick & El-Korchi, 2017). Figure 1.14 illustrates load-related cracks on a roadway.

Figure 1.14 Longitudinal fatigue cracks (wheel-paths)
Taken from Guide de mesure et d'identification des dégradations des chaussées souples MTQ (2007)

The most probable causes are as follows (MTQ, 2007; BCMoT, 2020; Fwa, 2006; Assaf, 2020):

- Pavement fatigue (heavy traffic);
- Structural capacity deficiency caused by insufficient structural design of the pavement;
- Weakening due to poor drainage of granular pavement layers (e.g. during thawing);
- Unsuitable grade of bitumen for traffic.

1.2.7 Distortion

Distortion is defined as a deviation of the pavement surface from its original shape, excluding shoving and rutting. These deformations include settlement, slope failure, volume changes due to moisture variations and frost, and residual effects of frost heave. The affected area is measured in square feet or square metres, and the severity level Low, Moderate or High is assigned according to vertical displacement measured in inches or millimetres (MTQ, 2007; BCMoT, 2020; Fwa, 2006; Mallick & El-Korchi, 2017). Shown in Figure 1.15 is settlement on a roadway.

Figure 1.15 Settlement
Taken from Guide de mesure et d’identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (MTQ, 2007; BCMoT, 2020; Shahin & Walther, 1990; Assaf, 2020):

- Differential frost heaves due to poorly drained cuts, transitions, and at pavement edges or centre;
- Differential frost heaves (dips) at culverts;
- Differential settlement of subgrade or base materials;
- Lack of subgrade support;
- Embankment slope failure.

1.2.8 Shoving (Corrugations)

Shoving results from the longitudinal shift of a localized area of the roadway surface, typically caused by braking or accelerating vehicles and typically found on hills, curves, or intersections.

Shoving can take form as upheaval, ripples or crescent-shaped bulging. The affected area is measured in square feet or square metres, and the severity level Low, Moderate or High is assigned according to vertical displacement measured in inches or millimetres (BCMoT, 2020; Fwa, 2006; MTQ, 2007; Miller and Bellinger or FHWA, 2014; Shahin and Walther, 1990). Shown in Figure 1.16 is a series of waves on a roadway.

Figure 1.16 Shoving (Corrugations)
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (BCMoT, 2020; MTQ, 2007; Mallick & El-Korchi, 2017; Assaf, 2020):

- Heavy traffic on steep downgrades or upgrades;
- Lack of adhesion of asphalt surface and underlying layer;
- Unstable granular base;
- Frequent braking;
- Poorly placed asphalt mix;
- Adhesion at the interface;
- Smooth and rounded aggregate in asphalt mix;
- High sand content in asphalt mix;
- Too much or too soft asphalt.

1.2.9 Rutting – Deformation

These are longitudinal depressions left in the wheel-paths after repeated loading, with or without lateral displacement of pavement material. Physical distortion of this nature can affect roughness and skid resistance. Accumulated water in the ruts may lead to hydroplaning-related accidents. The mean rut depth measurement is recorded in inches or millimetres and a severity level (Low, Moderate or High) is assigned according to rut depth. (BCMoT, 2020; MTQ, 2007; Fwa, 2006; Mallick & El-Korchi, 2017; Shahin and Walther, 1990). Figure 1.17 illustrates rutting on a roadway.

Figure 1.17 Rutting
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (Fwa, 2006; Mallick & El-Korchi, 2017; Shahin & Walther, 1990; BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- Unstable asphalt mixes due to high temperature or low binder viscosity;
- Insufficient lateral support of the shoulder due to unstable materials;
- Permanent deformation of an overstressed subgrade;

- Thawing and weakening of the bearing capacity;
- Aggregates of the mixture too rounded (not very angular);
- Vertical movement in poorly compacted layers;
- Deficient bitumen dosage / overdosage of bitumen;
- Wear and tear of the mix.

1.2.10 Disintegrations/Potholes

Potholes in the roadway are defined as bowl-shaped holes of various sizes and depths. The process is accelerated when water enters the pavement surface, and continues to disintegrate the asphalt mixtures, loosen and weaken the base and subgrade. Pothole is quantified by recording the number potholes, and assigning severity level Low, Moderate or High according to depth of the hole (BCMoT, 2020; Mallick & Korchi, 2017; Miller & Bellinger or FHWA, 2014; Shahin & Walther, 1990). MTQ (2007), defines it as a localized loss of bitumen thickness forming holes of generally rounded shape and variable depth. Figure 1.18 illustrates disintegration/potholes on a roadway.

Figure 1.18 Disintegration/Potholes
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (Mallick & Korchi, 2017; Shahin & Walther, 1990; BCMoT, 2020; MTQ, 2007):

- A thin spot in the asphalt layer;
- Localized drainage problems such as water infiltration through poorly bonded structural pavement layers or segregated spots in the asphalt mix where patches allow water intrusion;
- Asphalt mix design defects;
- Localized weakness of the foundation.

1.2.11 Bleeding

Bleeding is the excess asphalt binder surfacing, and forming a film of glass-like, reflective on the pavement surface. This is often seen in the wheel-paths. The affected area is measured in square feet or square metres, and the severity level Low, Moderate or High is assigned according to the amount of asphalt binder on the surface, and the degree of visibility of aggregates (MTQ, 2007; BCMoT,2020; Mallick & El-Korchi, 2017; Fwa, 2006; Miller & Bellinger or FHWA, 2014). Shown in Figure 1.19 is bleeding on a roadway.

Figure 1.19 Bleeding
Taken from Guide de mesure et d'identification des dégradations des chaussées souples MTQ (2007)

The most probable causes are as follows (Mallick & Korchi, 2017; Shahin & Walther, 1990; BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- High asphalt content relative to voids;
- Paving over existing severe bleeding surfaces;
- Heavy prime or tack coat under new pavement layer;
- Poor construction of surface seal coats;
- Too soft asphalt layer.

1.2.12 Raveling

Raveling is a process where bituminous binder and aggregate particles are slowly separated from the pavement surface. The affected area is measured in square feet or square metres, and the severity level Low, Moderate or High is assigned according to the amount of dislodged aggregates in the wheel paths (Fwa, 2006; Mallick & Korchi, 2017; Shahin & Walther, 1990; BCMoT, 2020; MTQ, 2007; Assaf, 2020). Figure 1.20 illustrates raveling on a roadway.

Figure 1.20 Raveling
Taken from Guide de mesure et d'identification des dégradations des chaussées souples
MTQ (2007)

The most probable causes are as follows (Fwa, 2006; Mallick & Korchi, 2017; Shahin & Walther, 1990; BCMoT, 2020; MTQ, 2007; Assaf, 2020):

- Insufficient compaction or segregation of the asphalt;
- Dirty or disintegrated aggregate;
- Underdosing of bitumen;
- Fracture of aggregate particles by heavy loads or natural causes;
- Overheating of mix or aging of the asphalt (oxidation and embrittlement).

1.3 Causes of Deterioration and Potential Treatments

As indicated above, the determination of the cause of deterioration is essential in road engineering in order to determine the right intervention. It is paramount to take all appropriate measures to establish with no doubt why the pavement has failed.

The cause of deterioration will help identify the technically justified and appropriate rehabilitation treatment that will address the cause.

Only these rehabilitation treatments should be simulated as potential scenarios in an economic analysis.

To illustrate the above, consider a pavement that has failed due to poor drainage; the economic simulation of an overlay might show excellent internal rate of return but, in reality, will only result in a waste of funds.

The cause of deterioration can be suspected from the types of distress present on the road surface which in turn suggests the supplementary tests to perform to confirm the cause.

Once the cause is confirmed, all other similar or comparable sections would have or would develop the same cause.

Maintenance and rehabilitation needs can then be projected based on performance or deterioration-time curves per family of similar sections.

The Table 1.5 below provides a list of mechanisms and agents of pavement deterioration.

Table 1.5 Mechanisms and Agents of Pavement Deterioration
Taken from Assaf (1993)

SETS OF DETERIORATION MECHANISMS	AGENT
Structural Deficiency	Traffic
Materials Deterioration	Water
Shrinkage and Creeping (with potentially freeze thaw)	Temperature
Mix Problems	Bitumen, Aggregate

Common road performance models primarily address the structural deficiency mechanism of deterioration, without proper consideration of material deterioration, shrinkage and creeping and mix problems. Many road agencies still rely on deflection or structural capacity and surface distress to select a structurally sound rehabilitation solution, without identifying the cause of why the pavement has failed and finding an optimal, cost-efficient solution that addresses the actual cause.

A more complete understanding of the cause of deterioration will allow the engineering team to identify the most appropriate and lowest-cost solution that fixes the problem, very possibly re-using the same material that would have been rejected if viewed only from the lens of a structural deficiency.

This basic analysis of deterioration should be the basis for the engineering design solutions proposed and relate pavement distress to causes of deterioration, tests to be performed and interventions to consider as described in chapter 2.

Based on the observed surface distress, a diagnosis may be established, and specific tests carried out to confirm the acting mechanism of deterioration depending on the judgment of the Engineer. The tests do not need to be performed on many bores, but on a sample of some ten bores from distressed sections, and ten bores from non-distressed sections so that the difference in parameters may be pointed out.

The knowledge of which parameters affect the presence of distress, with a statistical variance analysis and a discriminant analysis, allows to confirm which mechanism of deterioration is taking place.

In such an analysis, one is concerned with knowing:

a. which parameters out of the tests carried out are related to the presence or absence of distress, i.e. presence of fines in the subbase along with subbase density affect the presence of potholes and all other parameters have no effects;

b. the degree of contribution of each of these parameters toward this differentiation, i.e. subbase fines explain 70% of pothole presence, whereas subbase density explains 30%;

c. the combined intervals of each of these parameters within which distress is present or absent, i.e. when subbase fines > 25%, liquid limit is > 40 and subbase density over 2.4;

d. the associated confidence in these assertions, i.e. the above assertions are 95% confident.

Commonly reported test spacings in the literature are every 50 to 200 metres. For homogenous sections, where the pavement surface is similar, they may be spaced up to 500 metres.

1.4 Transportation Asset Management

The concept of infrastructure management is not new in North America. In the 1960s, management focused on individual assets and classes of assets such as pavement, bridge, tunnel, traffic equipment, congestion, and public transportation (FHWA, 2009b). The first policy to be implemented was “The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), which required states to implement highway pavement, bridge, highway safety, traffic congestion, public transportation facilities and equipment, and intermodal transportation facilities and systems (FHWA, 1997).

Since 1991, there has been many changes to transportation planning and policy, where the last policy was “Moving Ahead for Progress in the 21st Century Act (MAP-21), which was enacted to integrate performance to all transportation agencies at all level of governments to establish risk-based asset management plans that include all infrastructure assets (TAC, 2016).

The U.S. Department of Transportation defines asset management as “a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short-and long-range planning” (NRC, 2002).

1.5 Pavement Management Systems

Pavement management was first introduced in North America in the mid-1960s. The concept of pavement management was initially focused on the project level, where the areas of interest was coordinating improvements in design, rehabilitation, maintenance, and pavement performance modelling. By the mid-1970s, pavement management was initiated at the network-level, where planning, programming, and budgeting of funds was of essence (Hudson, 1994).

Haas et al. (1994) defines pavement management system (PMS) as: “a set of tools or methods that assist decision-makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time”. Hudson et al. (1991) stated that pavement management is: “in its broadest sense, encompasses all the activities involved in the planning, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program.”

Pavement management systems are designed to provide road agencies a structured and comprehensive approach by assisting decision-makers to find cost-effective strategies in managing their network at an acceptable serviceable condition over a given period of time (Gendreau & Soriano, 1998). As stated in Haas et al. (1994) " the function of a PMS is to improve the efficiency of decision-making, expand the scope, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization."

1.6 Pavement Performance Modeling

In pavement management, the commonly used models to predict future pavement conditions are Deterministic, Probabilistic, Bayesian, and Subjective (or expert-based) models. Depending on the variables used, the models can be classified as mechanistic, mechanistic-empirical, or empirical (AASHTO, 2012). Hass (1994) argues that there are two basic types or classes of models, which are deterministic and probabilistic. The deterministic model includes primary response, structural, functional, and damage. On the other hand, the probabilistic model includes survivor curves, and transition processes (Hass, 1994).

1.6.1 Deterministic Models

These models are developed from regression analysis, where a statistical relationship between variables is established, and used to predict pavement condition from variables such as pavement age, past cumulative traffic, environment, and pavement construction characteristics. Often used by road agencies with historical pavement condition information or sufficient survey data to identify pavement deterioration trends (AASHTO, 2012).

1.6.2 Probabilistic Models

These models predict a range of values, such as the likelihood of a pavement being in one of several condition states. Probabilistic models are not commonly used, likely because most pavement management software is designed to use deterministic models (AASHTO, 2012). However, for pavement management purposes, Markov and Semi-Markov transition probabilities are used (Walls III & Smith, 1998; Cation et al., 1987, 1987; Shahin, 2005; Haas et al., 1994). The Markov probabilistic approach is based on current pavement condition, and assumes time is independent of the changes that occur from one state to another. On the other hand, the semi-Markov approach is designed to include time as a variable when changing from one pavement condition state to another (AASHTO, 2012).

1.6.3 Bayesian Models

These models use subjective data in the regression analysis, where the assumed random variables each have an associated probability distribution. These models combined with both objective and subjective data are used to predict performance, where the subjective data can be used to supplement the objective data (AASHTO, 2012; Heba & Assaf, 2018). The Bayesian approach offers the possibility to make use of previous experience to supplement existing knowledge (Winfrey & Zellner, 1971). Hong and Prozzi (2006) raise the fact that the Bayesian approach is useful to address the issue of interest, as well as a realistic parameter distribution can be obtained with the use of existing knowledge and new information from updated data.

1.6.4 Subjective (or Expert-Based) Models

These models are similar to deterministic models, except that pavement condition prediction is based on expert opinion rather than historical data, and the performance models may be informal or formal. This approach is useful where: historical data are not available, when condition data seems inaccurate, or when new practices or materials are being used (AASHTO, 2012).

1.7 Family Models

The family modelling is a simplified method to obtain pavement condition prediction, not requiring all the variables for modelling pavement performance. This approach requires a single independent variable, which is usually pavement age or traffic to predict future pavement conditions. This can be achieved by grouping other variables together in pavement sections with similar characteristics and performance pattern, known as families (AASHTO, 2012).

The classification of the road network in families of similar basic characteristics allows to draw a quality versus age curve for each family by comparing old road sections to younger road sections in order to interpolate the evolution of any section in time, subject to the same traffic and environmental conditions. Figure 1.21 illustrates the road family concept of similarity.

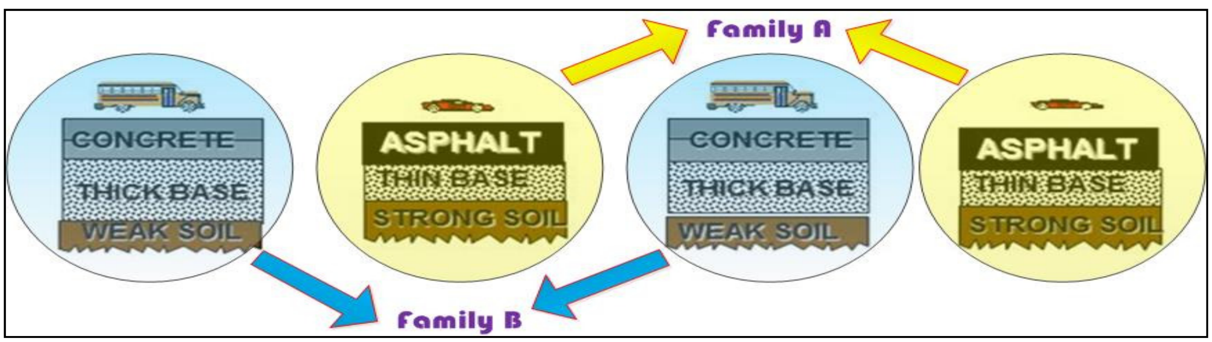


Figure 1.21 Example of Road Family Definition
Taken from Towles et al. (2014)

The rationale is that Family B with a concrete surfacing, a thicker base and a weaker soil, subjected to high traffic loads, will deteriorate differently than Family A. Figure 1.22 illustrates the deterioration rate between family A and B.

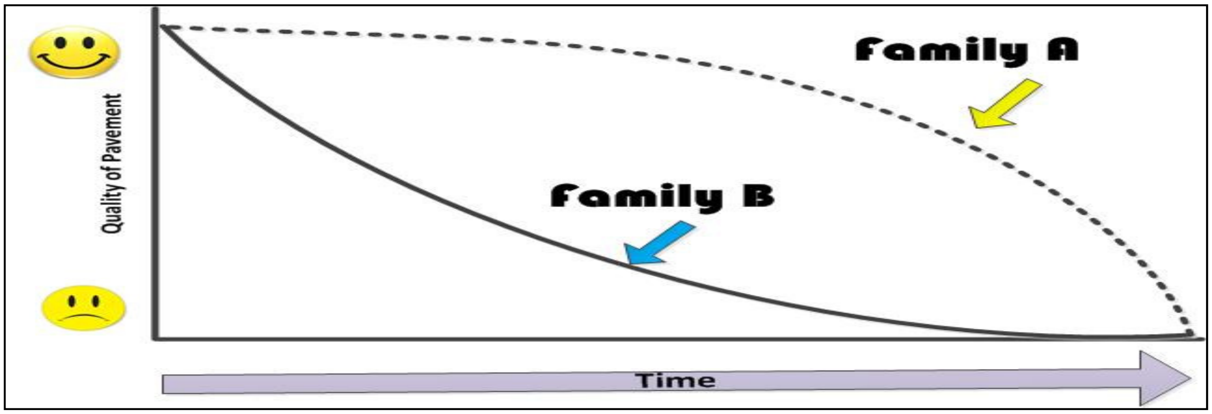


Figure 1.22 Deterioration rate between family A and B
Taken from Towles et al. (2014)

The key attributes that most influence pavement performance and road-user costs to be classified into families are:

- Pavement type (asphalt concrete, surface treatment, unpaved);
- Pavement condition (good, average, poor);
- Nature of the soils (gravel, sand, silt, clay, or a combination);
- Traffic volume (high, medium, low);
- Traffic loading (excessive, normal); and
- Environmental conditions (wet, dry).

1.8 Economic Evaluation of Rehabilitation and Maintenance Alternatives

In order to select the technically appropriate and economically cheapest M&R alternative on a life cycle cost basis, the condition status of every road section of the pavement network, the minimum acceptable level, and a representative pavement performance prediction model are required.

The definition of maintenance and rehabilitation activities are usually identical from agency to agency. The Ministry of Transportation and Communications of Ontario (MTCO) has its own definitions of M&R alternatives for flexible and rigid pavement, classified as rehabilitation, routine maintenance, and major maintenance. The latter can further be classified as preventive, palliative or corrective maintenance (Haas & Hudson. 2015). For instance, the laying of a thin asphalt concrete surface on a fairly new road is considered as preventive maintenance since this will rejuvenate the asphalt and slightly extend the service life of the road. However, the laying of the same on a deteriorated road section is considered a palliative maintenance as it only hides the problem and allows the flow of traffic to run its course, until a corrective, comprehensive solution is implemented.

Preventive treatments are applied to pavement deterioration levels considerably above the acceptable limits and corrective treatments to deterioration levels near or even below the acceptable limits (Haas et al. 1994; TAC, 2012).
The rehabilitation and maintenance alternatives used for flexible and rigid pavements in Ontario are shown in Figure 1.23 and for developing countries in Figure 1.24 for reference.

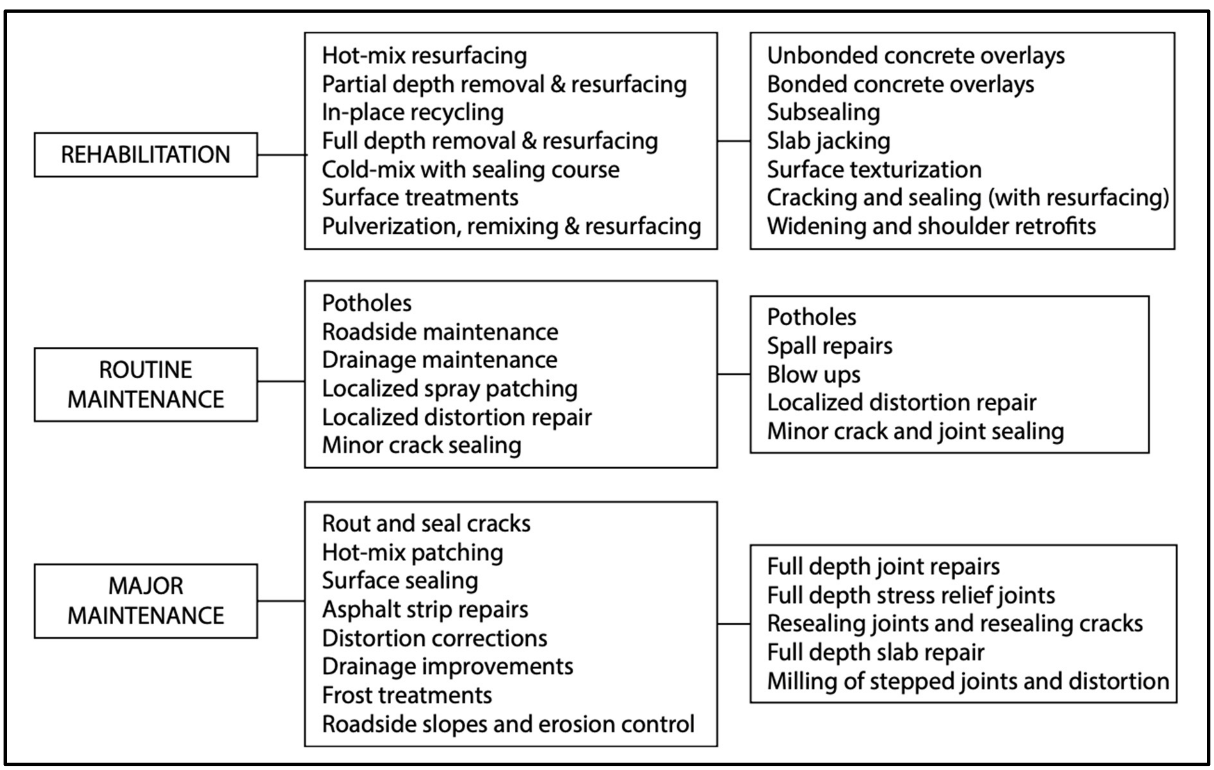


Figure 1.23 Rehabilitation and maintenance alternatives
Taken from Haas & Hudson (2015)

Works Category	Works Class	Works Type	Works activity/operation	Type of expenditure
Preservation	**Routine Maintenance:** These are works that are undertaken each year that are funded from the recurrent budget. Activities can be grouped into cyclic and reactive works types. Cyclic works are those undertaken where the maintenance standard indicates the frequency at which activities should be undertaken.	Routine Pavement	patching, edge repair, crack sealing, spot regravelling, shoulders repair, etc.	Maintenance
		Drainage	culvert repairs, clearing side drains, etc.	Maintenance
		Routine Misc.	vegetation control, line markings, signs, etc.	Maintenance
	Periodic Maintenance: These include activities undertaken at intervals of several years to **preserve** the structural integrity of the road, or to enable the road to carry increased axle loadings. The category normally excludes those works that change the geometry of a road by widening or realignment.	Preventitive Treatment	fog seal, rejuvenation, load transfer dowel retrofit, joint sealing, etc.	Maintenance
		Resurfacing	surface dressing, slurry seal, cape seal, regravelling, slab replacement, diamond grinding, etc.	Maintenance
		Rehabiliation: Treatments that provide a capital increase in the service life of the road	thick overlay, mill and replace, inlay, bonded concrete overlay, unbonded concrete overlay	Capital
		Reconstruction	partial reconstruction, full pavement reconstruction	Capital
	Special: These are activities whose need cannot be estimated with any certainty in advance.	Emergency	clearing debris, repairing washout/subsidence, traffic accident removal, etc.	Maintenance
		Winter	snow removal, salting/gritting	Maintenance
Development	Improvement	Widening	partial widening, lane addition	Capital
		Realignment	horizontal and vertical geometric improvements, juntion improvement	Capital
		Off-carriageway	shoulders addition, shoulders upgrading, NMT lane addition, side drain improvement, etc.	Capital
	Construction	Upgrading	upgrading by changing the road surface class	Capital
		New section	dualisation of an existing section, new section (link)	Capital

Source: HDM4 Manual Volume 4, Part D, pg. D1-3 with World Bank Defintions for Maintenance (http://www.worldbank.org/transport/roads/con&main.htm)

Figure 1.24 M&R Activities, operation and type of expenditure
Taken from HDM4 Manual Volume 4, Part D, pp. D1-3 with World Bank

The most widely preservation treatments for flexible and rigid pavements are listed in Table 1.6:

Table 1.6 Preventive Treatments
Taken from HDM4 Manual Volume 4, Part D, pp. D1-3 with World Bank

Flexible Pavements	Rigid Pavements
• Microsurfacing, slurry seals and fog seals • Crack sealing, spray patching, and full-depth patching • Thin overlays and milling plus overlay • Chip seals/seal coats	• Diamond grinding • Full or partial depth slab repairs • Dowel bar/load transfer retrofits • Joint and crack sealing • Hot mix asphalt overlay

The network rehabilitation and preventive/preservation treatment alternatives are shown in Figure 1.25.

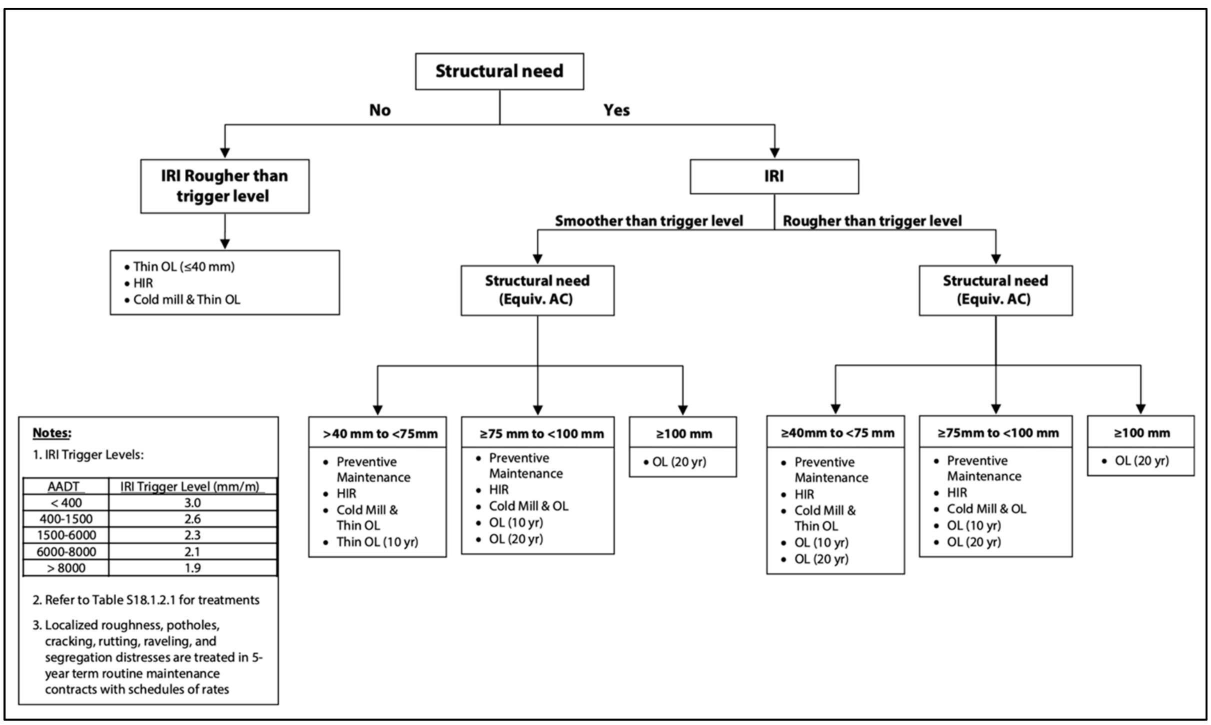


Figure 1.25 Guidelines for selecting flexible pavement rehabilitation and preventive maintenance treatments
Taken from Haas & Hudson (2015)

1.9 Priority Programming of Rehabilitation and Maintenance Alternatives

Pavement management encompasses a key component to compare investment alternatives at both the network and project levels to the available budget, and the comparison should result in the most effective alternative for each project or maintenance section (Hass et al. 1994). Network and project-level rehabilitation and maintenance alternatives should result in a priority program of new pavement construction, and/or rehabilitation, and/or maintenance. Any priority program should have answers to What, When, and How questions. The major steps in priority programing is shown in Figure 1.26 (Haas & Hudson, 2015).

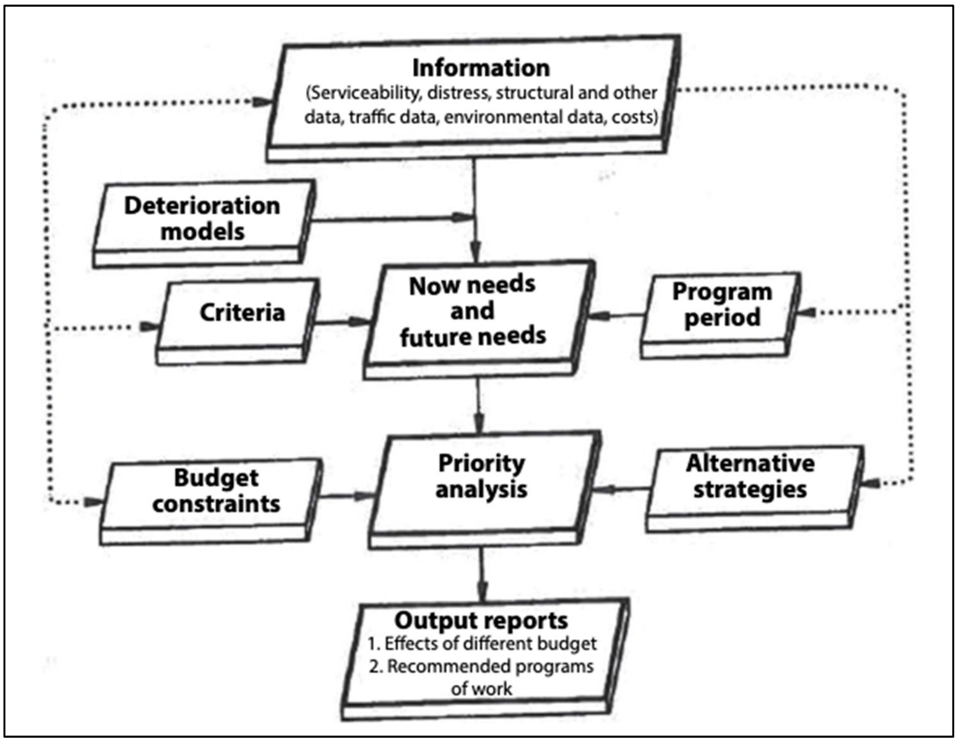


Figure 1.26 Major steps in priority programming
Taken from Haas & Hudson (2015)

1.10 Components of Whole Life Cost

Whole life costing is one of the tools that can assist decision-makers and engineers in developing acceptable overall management policies and strategies, it will help in the comparison to identify and select rehabilitations and maintenance options giving best value for money. Road agencies incur costs during the life of a road from design, construction, operation, rehabilitation and maintenance. In addition, costs to the road users, and local residents (PIARC, 2000). The estimated whole life costs are used to obtain the most cost-effective pavement alternative. The life-cycle costs include the initial construction cost and future maintenance and rehabilitation activities, as well as road user costs (NCHRP, report 703, 2011).

1.10.1 Road Agency Costs

Road agencies are responsible for the costs of construction, rehabilitation and maintenance work during the life of the pavement. The whole life costing is initiated at the design stage, where an analysis of the options available, comparing estimated construction, rehabilitation, and maintenance costs, as well as costs to the road users over the life of the road. However, whole life costing is not limited to new roads only, life-cycle analysis on existing roads to identify the consequences of alternative rehabilitation and maintenance options are to be considered as well (PIARC, 2000).

1.10.2 Road User Costs

Road users' costs include the time costs, which is subject to speed and the condition of the road pavement. Time costs are derived from the additional travel time required due to the road condition and traffic. Additional users' costs when maintenance work is being carried out due to the disruption of traffic. Vehicle operating costs vary depending on vehicle type and speed, and composed of fuel costs, tires, spare parts, vehicle maintenance, depreciation, oil and other lubricants (PIARC 2000). The costs to the users of the road are time delay costs, vehicle operating costs, crash costs, environmental costs, and discomfort costs due to work zones (NCHRP, report 703, 2011).

1.10.3 Road Accidents Costs

Vehicle accidents occur on the road network for a variety of reasons, and it is difficult to predict costs of accidents. The road accident costs are a component of the whole life cost analysis, and only changes resulting from pavement condition and maintenance activities are to be considered (PIARC, 2000).

1.10.4 Other Social Costs

Costs associated with the environment such as traffic noise, construction materials, and energy necessary for the construction and maintenance should be considered to evaluate the consequences of alternative policies. In a whole life cost analysis, the environmental cost of alternative pavement between options only should be considered (PIARC, 2000).

1.10.5 Network and Project Whole Life Costing

With the development of pavement management systems, the economic approach is used for the network-level analyses. The aim is to represent the future life of the roadway and anticipate the costs such as rehabilitation and maintenance costs, as well as costs associated to the road users and society during the pavement life cycle (PIARC, 2000). The life-cycle cost analysis is part of the pavement-type selection process, which considers time value of money occurring at different periods in the life cycle to determine the cost-effectiveness of various alternatives. Shown in Figures 1.27 and 1.28 are an example expenditure-stream diagram and the evaluation flow chart of life-cycle costs (NCHRP, report 703, 2011).

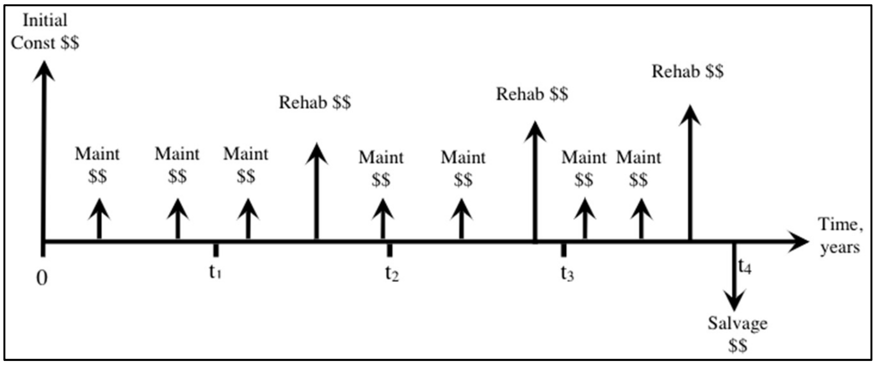


Figure 1.27 Example expenditure-stream diagram
Taken from NCHRP (2011)

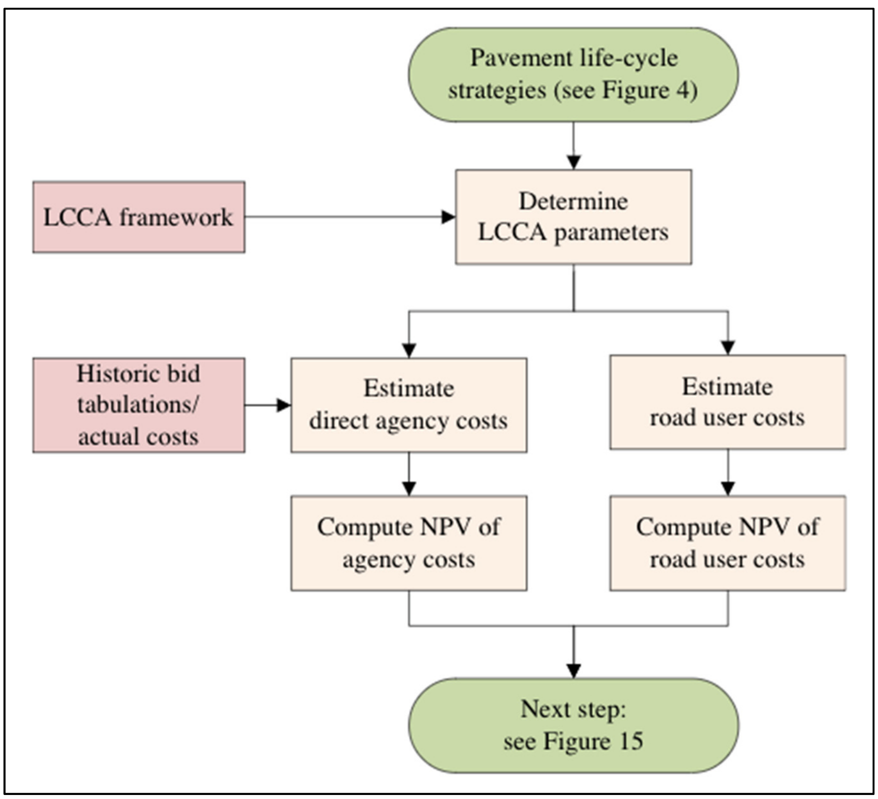


Figure 1.28 Evaluation process of life-cycle costs
Taken from NCHRP (2011)

1.11 Economic Analysis

1.11.1 Life-Cycle Analysis

Life Cycle Cost Analysis (LCCA) is an engineering tool for decision-making in the management of infrastructure.

LCCA is used by road agencies for the selection of cost-effective pavement designs, and the evaluation of future maintenance, rehabilitation, and/or reconstruction strategies.

LCCA is also used to promote project selection transparency, where road agencies decision-making is made based on highest return of their investment (Moges et al., 2017; Walls III & Smith, 1998).

Walls III and Smith (1998) define LCCA as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment."

LCCA encompasses the following seven parameters: analysis period, performance period and activity timing, discount rate, agency costs, user costs, environmental costs, and economic evaluation methods.

LCCA practices used in the provinces of Canada, as well as the FHWA, ACPA, APA and the World Bank (Moges et al., 2017) are compiled in Table 1.7.

Table 1.7 Summary of LCCA Practices
Taken from Moges et al. (2017)

Agency	LCCA Input Parameters										LCCA Computational Approach	LCCA Tools
					User Costs			Environmental Costs				
	Analysis Period	Discount Rate	Economic Evaluation Method(s)	Residual Value	Vehicle Operating Costs	User Delay Costs	Crash Costs	Emission Costs	Noise Pollution Costs	Energy Consumption		
Alberta	User-defined (Up to 80 years)	Real discount rate: 4 %	NPW, IRR, B/C Ratio, Break Even Point, PW Costs, PW Benefits	Considered	All three user cost components considered			Only Emission Costs considered			Deterministic (with optional Sensitivity Analysis)	MS Excel Spreadsheet
British Columbia	25 years	Real discount rate: 6%	NPW BC Ratio	Considered	All three user cost components considered			*Considered Independently			Deterministic (with Sensitivity Analysis)	ShortBEN, Safety-BenCost
Manitoba	50 years	Real discount rate: 3%	NPW	Considered	Not considered			Not considered			Deterministic	RealCost
Nova Scotia	40 years	Real discount rate: 4 %	NPW	Not considered	Not considered			Not considered			Deterministic	DARWin
Ontario	50 years	Nominal social discount rate: 4.5% (0 to 30 yrs.), 4% (31 to 75 yrs.)	NPW	Considered	Not considered			**Considered Independently			Deterministic, Probabilistic	MS Excel with Crystal Ball®, OPAC 2000
Quebec	50 years	Real discount rate: 5%	NPW	Considered	Only user delay costs considered			*** Considered Independently			Probabilistic	RealCost
Saskatchewan	60 years	Real discount rate: 4%	NPW EACF	Not considered	Not considered			Not considered			Deterministic	MS Excel, LCC
FHWA	Minimum 35 years	Real discount rate based on OMB	NPW (preferred), EUAC (also accepted)	Considered	Work zone user costs (VOC and delay) plus crash costs considered			Not considered			Probabilistic	RealCost
ACPA	45-50+ years	Real discount rate based on OMB	NPW EUAC	Considered	All three user cost components considered (if costs differ significantly among alternatives)			Not considered			Probabilistic	StreetPave
APA	Minimum 40 years	Real discount rate based on OMB	NPW	Considered	Only user delay costs considered			Not considered			Deterministic, Probabilistic	LCCA Original, LCCAExpress
World Bank	User-defined	User-defined	NPW, IRR, FYRR, BC Ratio	Considered	All three user cost components considered			All three components of environmental costs considered			Deterministic (with Sensitivity Analysis)	HDM-4

1.11.2 Analysis Period

The analysis period is a fixed time horizon, where future expenditures are compared between alternatives. The period of consideration includes the initial construction or major rehabilitation and one subsequent rehabilitation action, of which applies to all pavement projects including new or major rehabilitation projects as well as rehabilitation treatments (Walls III & Smith, 1998). Shown in Figure 1.29 is an analysis period for a pavement design alternative.

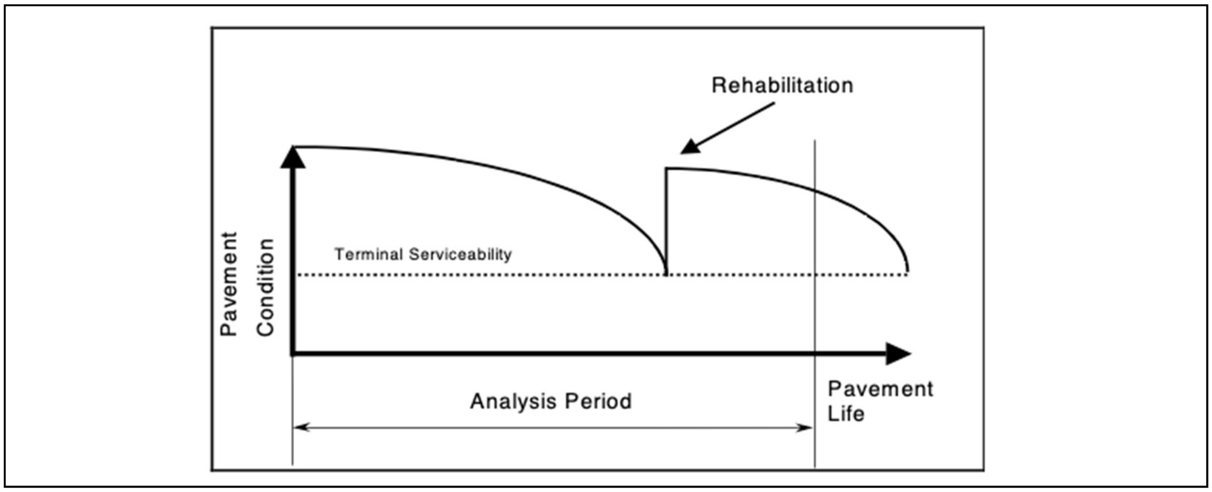


Figure 1.29 Analysis period for a pavement design alternative
Taken from Walls III & Smith (1998)

1.11.3 HDM-4 and the Economic Rate of Return of Road Investments

Economic models were developed around the engineering design process. The graphic below provides the Economic Rate of Return (ERR) framework for the entire road investment lifecycle. Figure 1.30 illustrates the primary benefit and cost stream data inputs and outputs as measured by HDM-4 or RED.

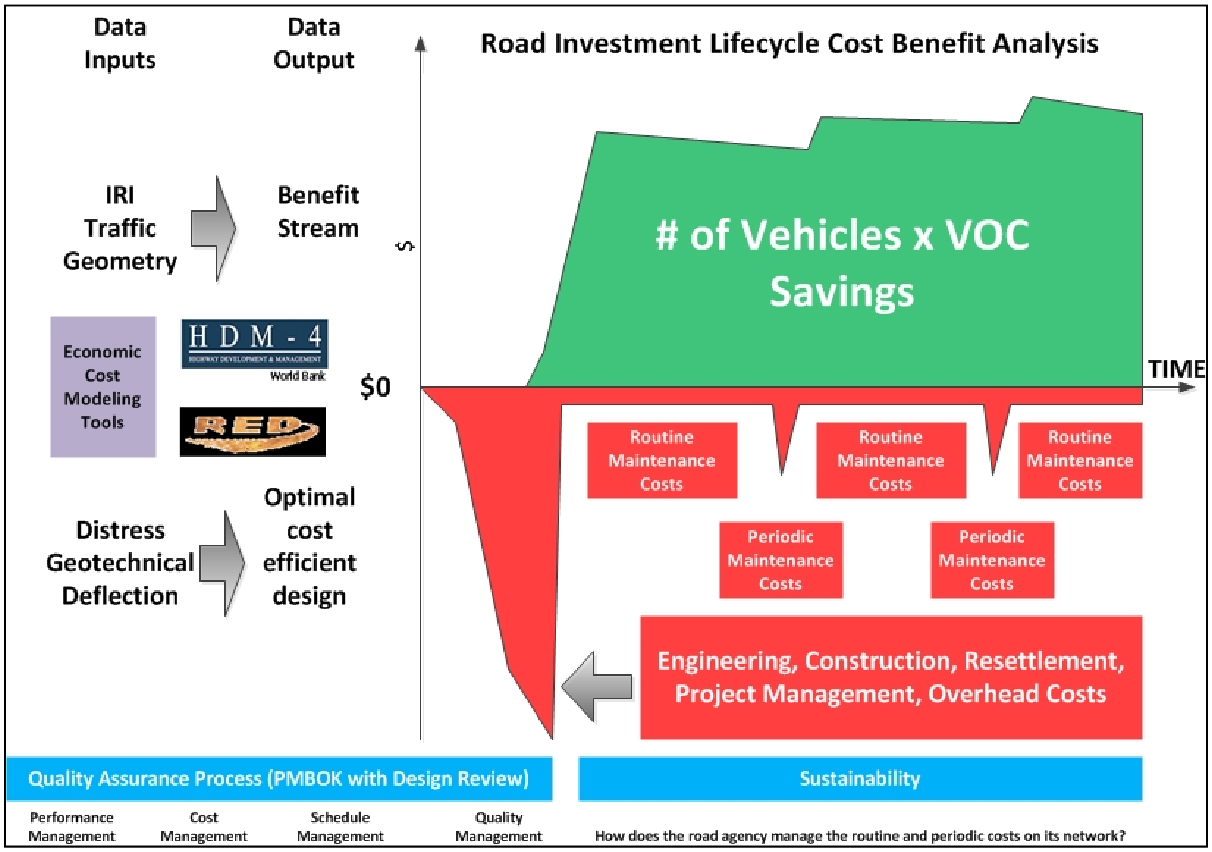


Figure 1.30 ERR Framework for the Road Investment Lifecycle
Taken from Towles et al. (2014)

The use of the RED Model is appropriate for rural roads above 50 vehicles per day (vpd) and usually up to 200 vpd. HDM-4 is recommended for roads carrying more than 200 vpd (Lebo & Schelling, 2001). As can be seen in the Figure above, one of the largest, most overlooked cost of a road investment are the M&R costs, which vary per pavement structure, notably with the pavement design and quality of the construction. In fact, if managed correctly, pavements can extend well beyond their intended design life with proper servicing. However, even more important than M&R costs are Vehicle operating cost (VOC) savings as a result of the M&R program. VOC savings are obtained by deducting the vehicle user costs between the do-nothing strategy and the more cost-effective M&R strategy that would improve the condition of the pavement surface and therefore reduce vehicle wear, oil and gas consumption, etc. as shown in green in Figure 1.30 above.

1.11.4 User Costs

User costs encompass: 1) vehicle operating costs, 2) time associated delay costs as a result of the deteriorated road surface and subsequent speed reduction, and 3) crash costs incurred by the users (Walls III & Smith, 1998).

Vehicle Operating Cost (VOC) encompasses costs from different vehicle classes due to their different operating characteristics and operating costs. Therefore, VOC shall be analyzed with at least three vehicle classes: Passenger Vehicles, Single-Unit Trucks, and Combination Trucks. Most research on VOC was conducted by the World Bank, where international roughness index (IRI) directly affects road users operating costs. The effect of roughness on user costs is shown in Figure 1.31.

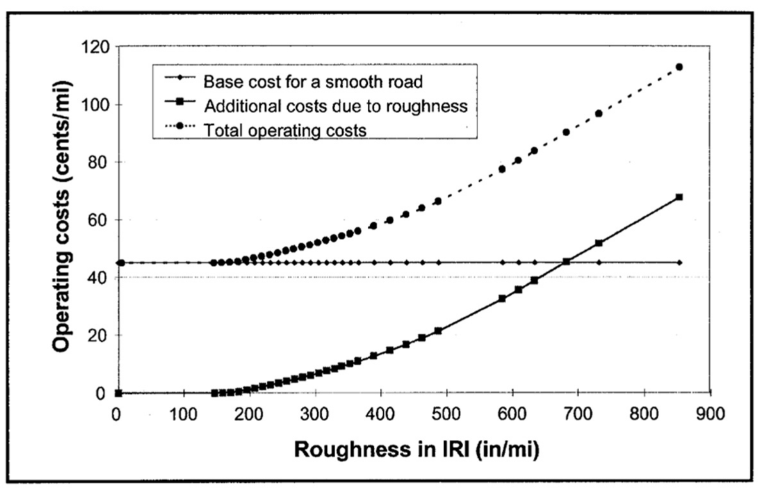


Figure 1.31 Effect of roughness on user costs
Taken from Walls III & Smith (1998)

The evolution of the IRI in time over the life of the pavement is embedded into the HDM-4 system based on pavement performance curves developed in many countries including those of the Long-Term Pavement Performance Program (LTPP) (Rohde et al., 1998) of the Strategic Highway Research Program (SHRP).

As such, each pavement structure has its own performance curve that shows pavement condition (IRI) deteriorating over time. Road maintenance interventions are also added in HDM-4 to show different costs for intervening at different times. For reference, the Figure 1.32 below shows a sample pavement curve with sample treatments at target intervention levels and sample intervention costs.

Obviously, municipalities can maximize consumer surplus *(resulting from improved pavement condition over time)* and lower overall agency costs with earlier maintenance interventions. A road maintenance strategy that intervenes earlier rather than later is a more efficient use of funds than rehabilitation and reconstruction.

Municipalities are a long way from marrying theory into practice, which is where a smart pavement management system can maximize each dollar spent in order to best serve its property taxpayers more efficiently. The subsequent section will go into more detail.

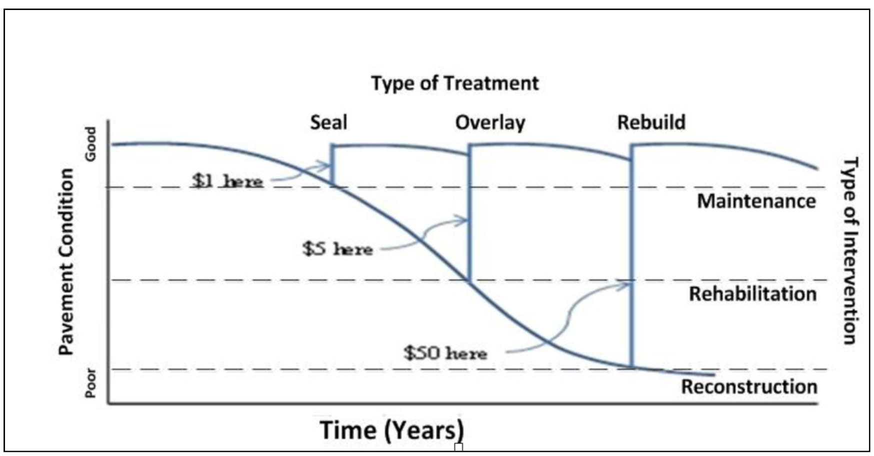


Figure 1.32 Pavement Condition Prediction with & without M&R
Taken from Assaf (2020)

1.12 Pavement Performance Dashboard

Dashboards are a common tool to summarize a situation in project management. Similarly, they can be very helpful to convey the present and the projected future condition of the road network in classes as shown below in Figure 1.33.

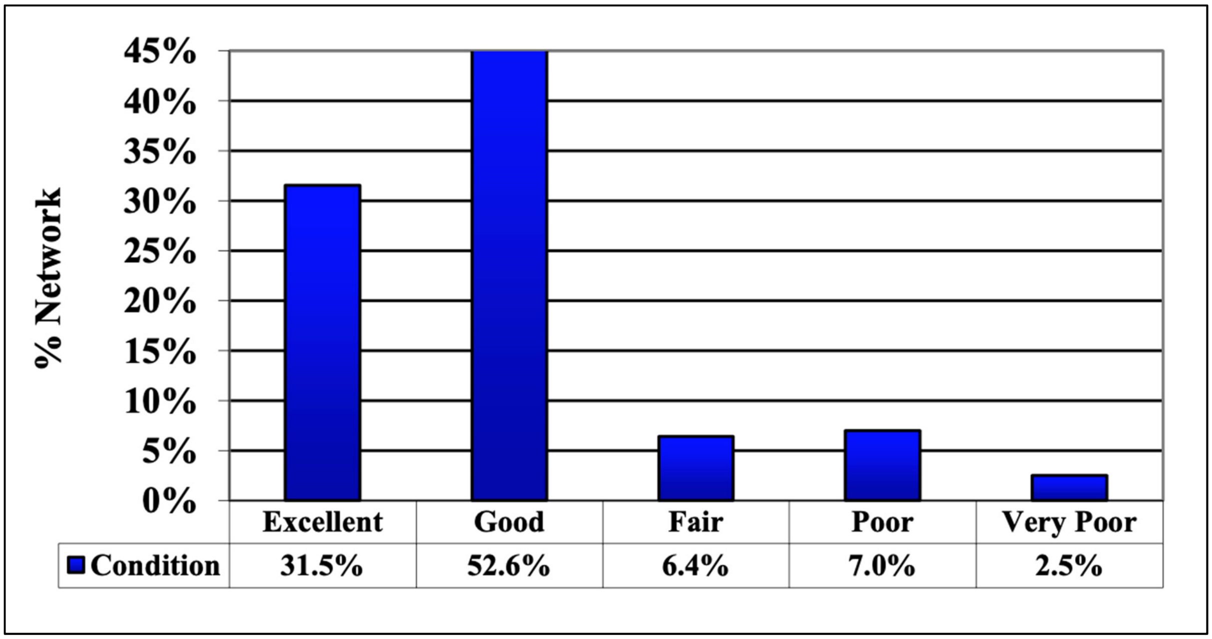
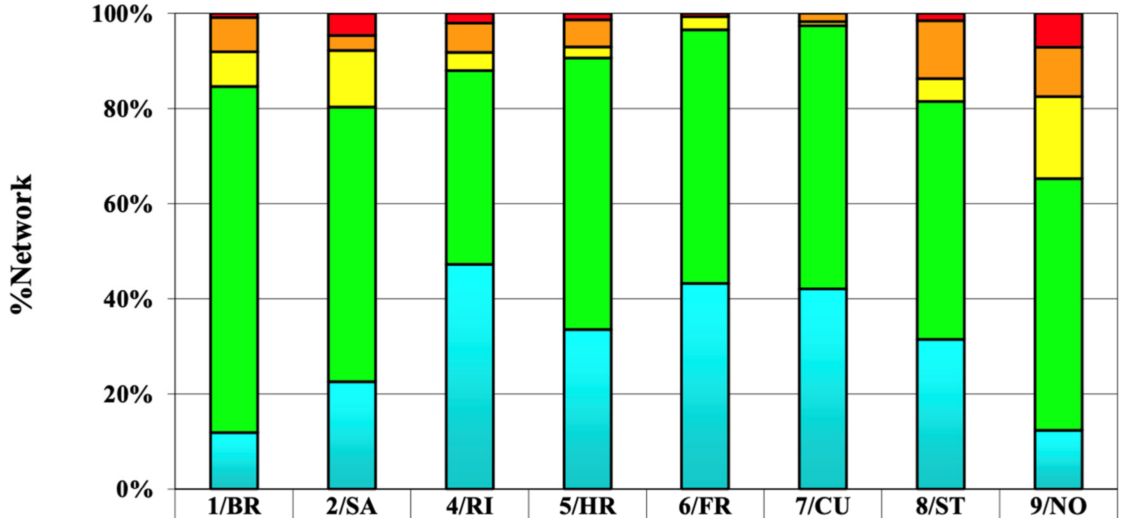


Figure 1.33 Pavement Condition - Interstate
Taken from Virginia Department of Transportation (2019)

A dashboard can also be very useful to convey the condition of each district of the network in order to identify the more needy sectors or boroughs as shown in Figure 1.34.



	1/BR	2/SA	4/RI	5/HR	6/FR	7/CU	8/ST	9/NO
Very Poor	0.9%	4.6%	2.1%	1.4%	0.7%	0.0%	1.5%	7.1%
Poor	7.2%	3.2%	6.1%	5.7%	0.0%	1.8%	12.2%	10.4%
Fair	7.3%	11.9%	3.8%	2.3%	2.8%	0.8%	4.8%	17.3%
Good	72.7%	57.7%	40.7%	57.0%	53.3%	55.3%	50.0%	52.8%
Excellent	11.9%	22.6%	47.3%	33.6%	43.2%	42.1%	31.5%	12.4%

Figure 1.34 Pavement Condition by District - Interstate
Taken from Virginia Department of Transportation (2019)

A geographic information system can also be associated to the dashboard as shown in Figures 1.35 and Figure 1.36.

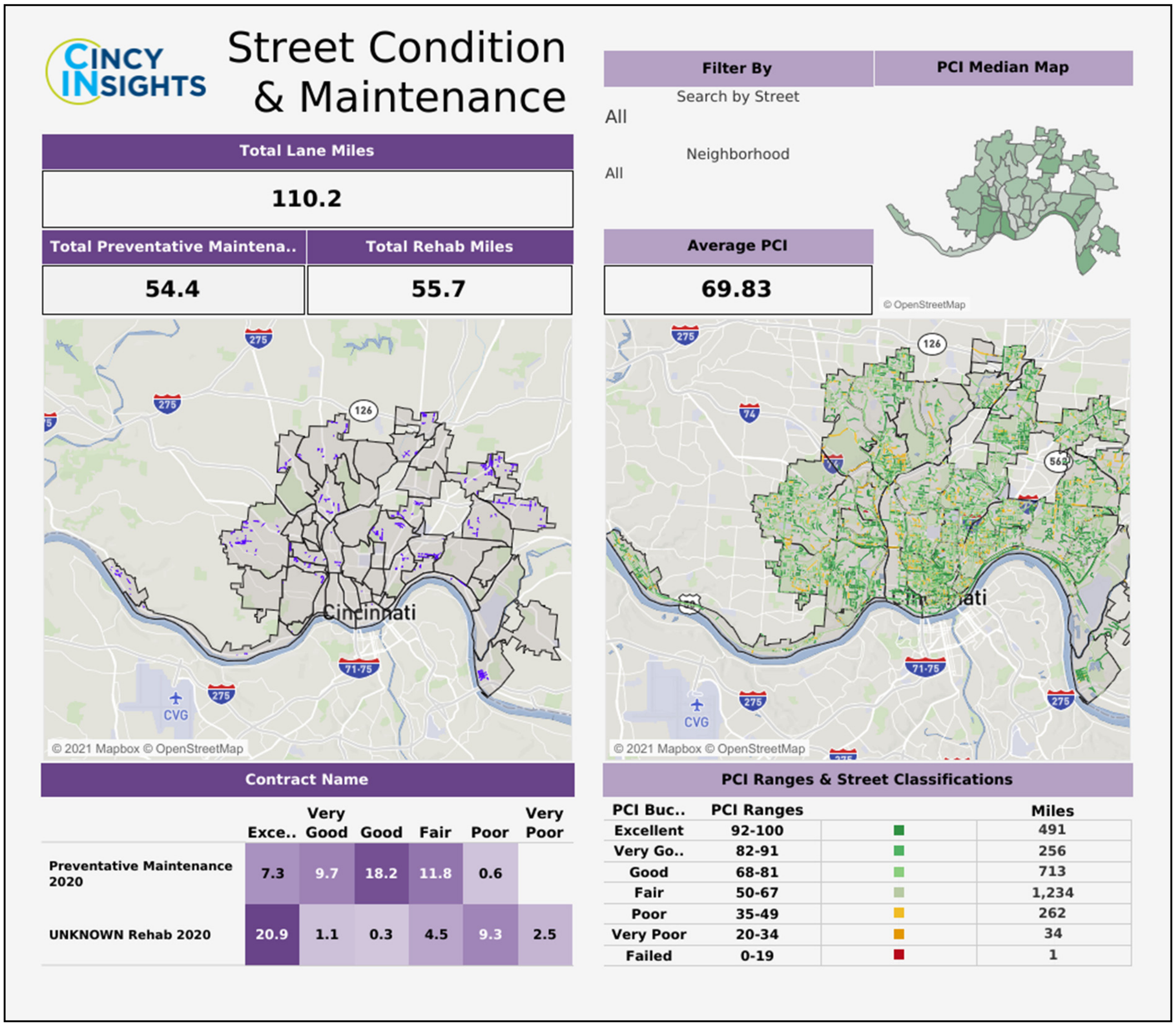


Figure 1.35 Integration of a Dashboard in a GIS platform (I)
Taken from https://cagismaps.hamilton-co.org/cincistreetscap (Accessed June 2021)

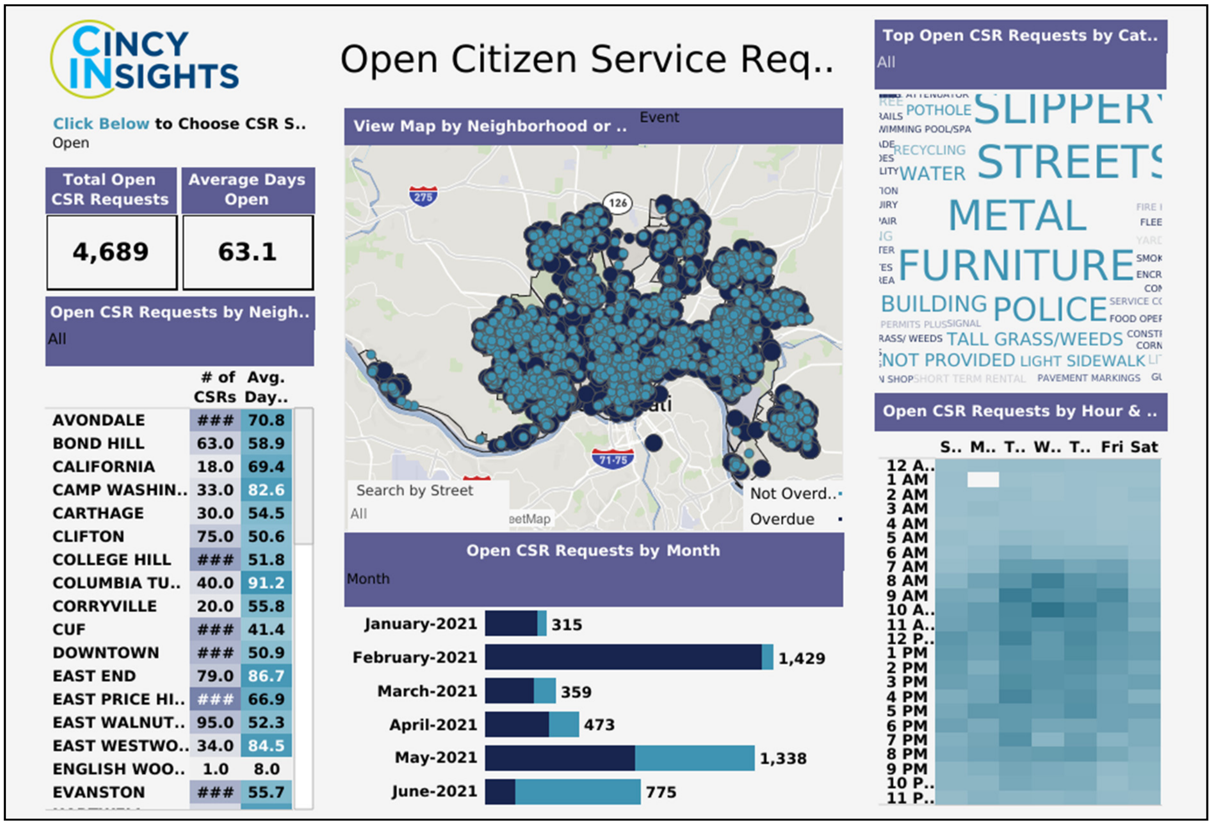


Figure 1.36 Integration of a Dashboard in a GIS platform (II)
Taken from https://insights.cincinnati-oh.gov/stories/s/ve9a-xare (Accessed June 2021)

CHAPTER 2

RESEARCH METHODOLOGY

2.1 Introduction

This chapter describes the different tools used, adapted from the literature summarized in Chapter 1, and in some instances specifically developed in this study.

The chapter also explains how these tools were directly used in the evaluation of the present surface condition, the projection of the future condition, and the assessment of the present and future needs over a ten-year horizon.

The first tool used in this study is the Location Referencing System (LRS) whereby every section of the road network of a City is referenced by its name and intersecting roads. As an example, the attached MS Excel file titled "*Châteauguay - Evaluation Sommaire, Diagnostic Préliminaire, Caractérisation Requise, Intervention et Horizon*" segments the road network of the City of Chateauguay in 1,550 road sections. For reference, the road database is provided in sheet titled "*Évaluation Réseau".*

Section referencing is followed with a Detailed Visual Assessment of the distress observed on the road sections by type, severity and distress, followed by a video of the road with a conventional, geo-referenced and high-resolution video-camera, and a PASER distress-identification is performed in a way that is compatible with the determination of the cause of deterioration.

For reference, examples of the videos are available on this link:
https://91800060qi.securevdr.com/d-sd43bec56849145d194205d69ec81ce92

The chapter then provides a comprehensive and key tabulated synthesis, which integrates all types of surface distress common to asphalt pavements along with: a) their potential causes, b) relevant diagnostic tests that need to be performed to confirm these causes, and c) the list of potential treatments to address the aforementioned pavement distress and their causes so that any intervention is sustainable, i.e. that it addresses the cause of failure so that the pavement does not fail again, and the intervention is a waste.

The following section of this chapter provides a structural design performed with the Quebec DOT design software covering the reconstruction option. The designs are performed for three (3) classes of soils, i.e. from the weakest silty clay to the strongest granular, and three (3) classes of traffic (*residential, commercial/residential collector and industrial).* These 3 X 3 pavement design cases correspond to the layer thickness requirements for each of these three types of soils and three types of road classification (residential, commercial or industrial) or traffic levels. They apply to the reconstruction scenario.

The chapter then provides the equations to obtain the projected Vehicle Operating Costs (VOC) depending on the International Roughness Index (IRI) or pavement surface distortion and calculates the life cycle costs of every intervention compared to the life cycle costs of the do-nothing strategy.

As a direct application of the tabulated synthesis, all the distress present on the roads of the City of Chateauguay (City) were assessed on the whole road network by type of distress, severity of the distress and extent or amount of coverage of the distress.

The list of distress observed on all the sections of the City are compiled in the aforementioned sheet titled "*Évaluation du réseau*," columns L to AA.

Causes were identified based on the aforementioned tabulated synthesis *(Line 3 of sheet)*, and tests to perform to confirm the causes were indicated *(column AB)* with appropriate treatment options *(column AC)* and time horizon *(column AD)* for their implementation.

Unit cost for the technically justified solution is provided in column AN and the cost per lane is provided in column AO.

Total annual vehicle user cost (VOC) before the intervention, based on the present condition is provided in column AP and the same VOC post-intervention is provided in column AQ. The differential saving during the first-year post-intervention is provided in column AS. The internal rate of return is shown in column AR.

2.2 Proposed Location Referencing System

The Location Referencing Systems (LRS) provides the integration and visualization of information and data from many sources to a specific location. Such referenced information is crucial in any management system in areas with geographical diversity. In management of a pavement network, LRS provides a means to link specific roadway attributes and conditions to a location where it can provide a visual display of information and data for analysis and reporting (Flintsch & McGhee, 2009).

2.2.1 Type of Referencing Method Selected

While geo-referenced GPS coordinates are very useful to locate and position rural roads, the conventional, location referencing methods (LRM) are more appropriate in an urban environment for their easiness and practical requirements. Conventional LRM usually contains four (4) main points, namely (i) route-mile (km), (ii) route-reference post, (iii) link-node, (iv) and route-street reference. The four points mentioned are all appropriate methods for managing data in the context of roadway network. The basic methods and key aspects are shown in Table 2.1.

The features in a road network are linear in nature and the most common location referencing methods are route-mile (km), route-reference post, link-node, and route-street reference.

The reference method used for this project is the route-street reference as shown in Table 2.1, with key aspects as described below (TAC, 2012; FHWA, 2013):

- Local streets are used to identify roadway features;
- Feature is recorded on one street at a specified distance and direction from another street.

Table 2.1 Location referencing method key aspects
Taken from Haas & Canada (1997); Smith et al. (2001)

Location Referencing Method	Key Aspects
Route-mile (km) point (see figure 2.1)	- Each route is assigned a unique name or value. - The beginning of the route is defined. - Distance is measured from a given or known point to the referenced location. - Route-mile (km) posts are not physically identified in the field.
Route-reference post (see figure 2.2)	- Uses signs posted in the field to indicate known locations. - Benefit over the route-mile (km) post is the elimination of problems associated with change in route length (e.g., due to realignment).
Link-node (see figure 2.3)	- Specific physical features are identified as nodes (e.g., intersections, cross streets). - Each node is assigned a unique identifier or number. - Links are defined as the length between nodes.
Route-street reference (see figure 2.4)	- Local streets are used to identify roadway features. - Feature is recorded on one street at a specified distance and direction from another street.

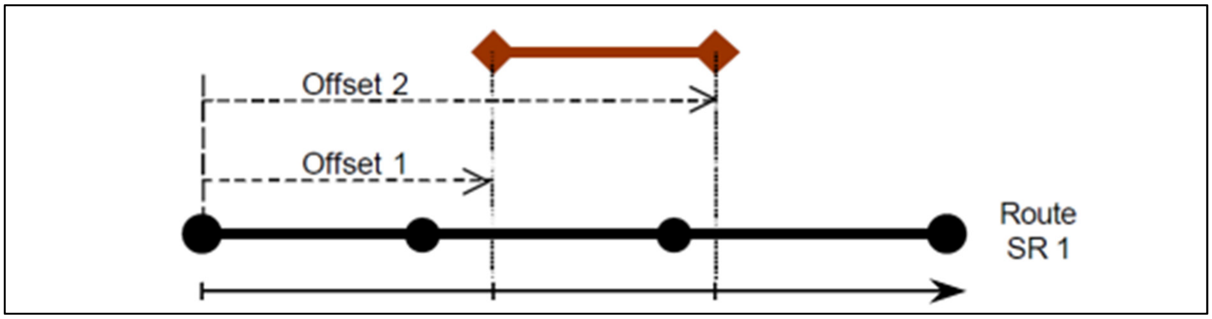


Figure 2.1 Route-mile point
Taken from Smith et al. (2001)

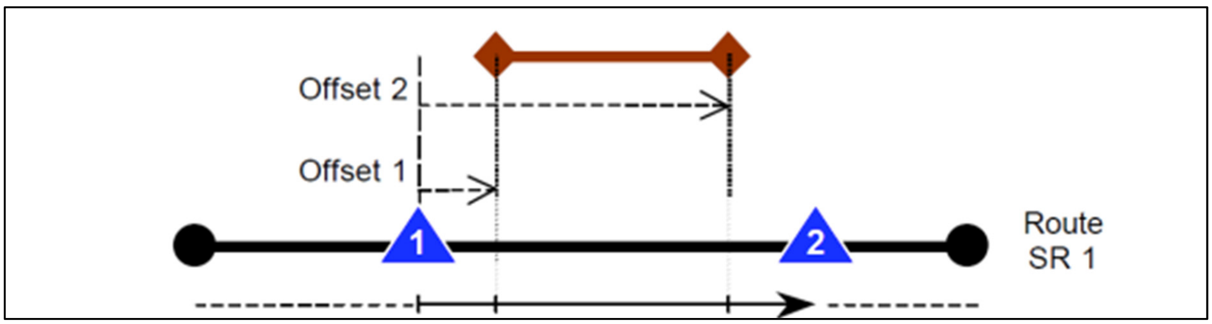


Figure 2.2 Route-reference post
Taken from Smith et al. (2001)

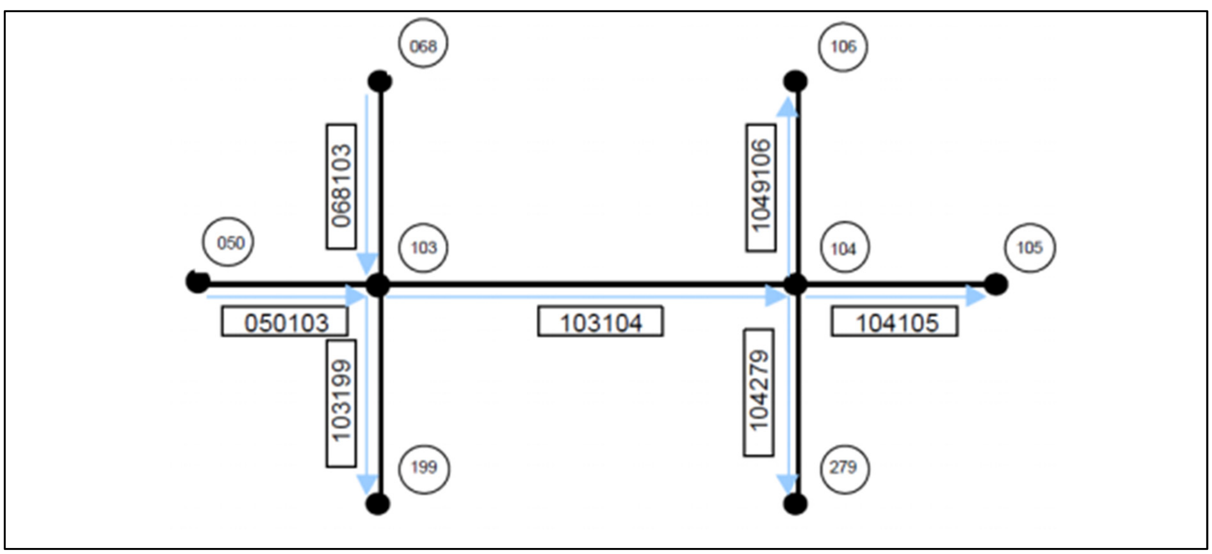


Figure 2.3 Link-node
Taken from Smith et al. (2001)

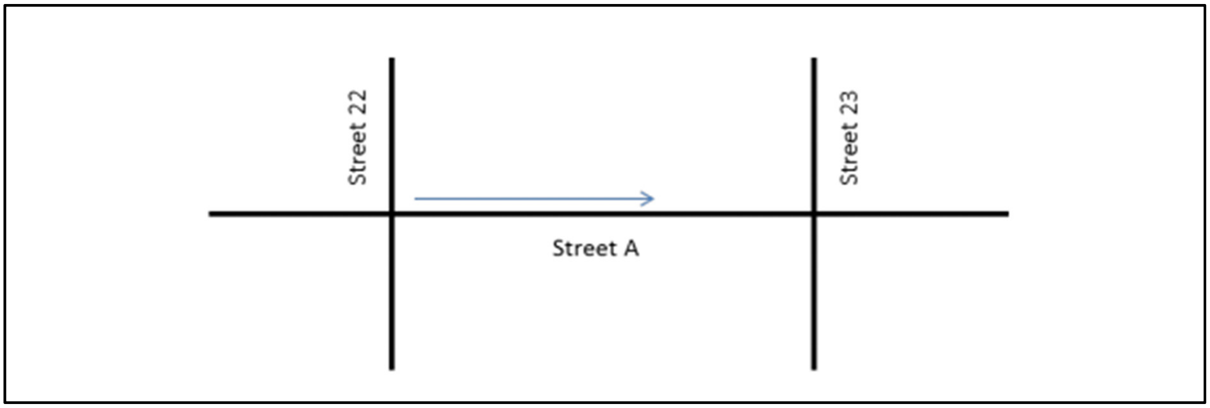


Figure 2.4 Route-street reference
Taken from Smith et al. (2001)

2.3 Proposed Distress survey and network segmentation

In Quebec, distress surveys of road networks (MTQ, 2002) are mostly conducted as early as spring, after the thawing of the pavement structure and terminates before the first frosts (MTQ, 2007).

Prior to conducting a survey, it is important to divide the road network into road portions which can be easily identifiable in the field. Road intersections as well as bridges, viaducts, railroad tracks and sector boundaries are used to create segmented portion for survey (MTQ, 2007). In this project, the city's road network was segmented into road portions based on the geographical map received from Mr. Jasmin Fournier, *Chef de la Division Génie et bureau de projets*. The segmented road sections and intersections (cross streets) in the database were defined by road names and/or boulevards. The activity prior to the evaluation consisted of regrouping the segmented sections of the network into an Excel database where a complete list of the road portions was entered into an Excel spreadsheet for each type of road class, in order to evaluate the overall-long-term economic efficiency between alternative investment options by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs (FHWA, 1998).

2.4 Proposed Equipment and Data Collection Method

2.4.1 Proposed Equipment

A comprehensive network level survey may be conducted in a slow-moving vehicle (MTQ, 2002). With a complete database of the road network, the distress data was collected via a low speed visual windshield survey, as well as a recorded right-of-way with dash cam video camera Azdome 4k model GS63H. Shown in Figure 2.5 is the video camera used to record distresses.

Figure 2.5 Video camera Azdome 4k model GS63H

2.4.2 Proposed PASER System

The Pavement Surface Evaluation and Rating (PASER) system was used to conduct pavement condition, the segments were visually examined and rated on a scale of 1 (failed pavement) to 10 (excellent pavement). A rating was assigned to the common pavement distress such as surface defects, surface deformation, cracks, as well as patches and potholes, where variables such as raveling severity, cracks opening and spacing, patching, as well as density of block and fatigue cracking were considered. The PASER manual provides pictures and descriptions of all distress types and varying severity levels (Transportation Information Center, 2002). Shown in Figure 2.6 is the PASER Asphalt Roads Manual.

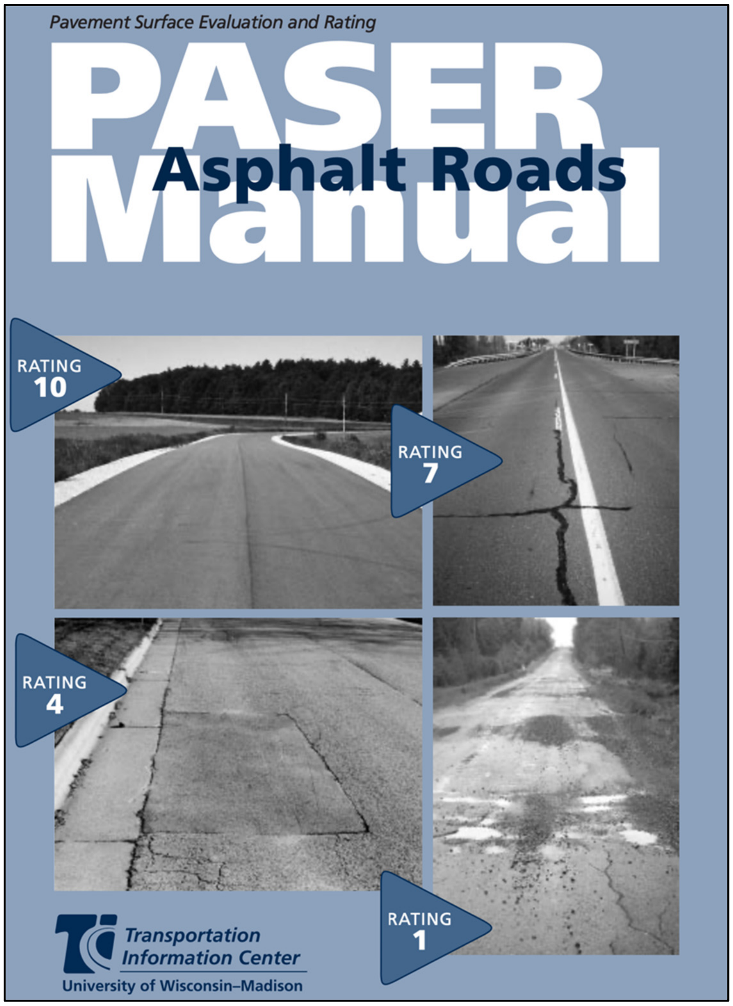


Figure 2.6 PASER Asphalt Roads Manual
Taken from Transportation Information Center (2002)

2.4.3 Proposed Road Roughness Measurement

The Present Serviceability Rating (PSR) is a **subjective** ride comfort assessment, developed in the 1960s at the AASHO Road Test, where a panel rated the drive quality of pavement segments on a serviceability scale. The numerical rating is a measure of ride quality of a pavement segment to serve traffic and is based on the ride quality as experienced by a panel of observers riding in a vehicle. The pavement segments are rated from 0 to 5, where 0 value is very poor, and 5 is very good (Watson et al., 2007; Haas et al., 2015).

The ride comfort assessment used in this project is similar to the Present Serviceability Rating, where a subjective ride comfort assessment was conducted on the road network and rated according to three subjective modalities: **Poor, Average and Good**, as perceived by the user, for which an IRI of 3, 5 and 7 m/km was respectively assigned.

2.5 Data Collection

This section on distress and comfort data collection, determination of the cause of deterioration and potential tests to perform the cause and the treatment to consider, is written in French as it is specifically addressed to French-speaking municipalities in Quebec.

2.5.1 Scope of Data Collection

This report provides a visual assessment of the surface defects of the City's pavements based on a simplified approach of the MTQ's guides for recording distresses in asphalt.

A preliminary diagnosis as to the cause of deterioration of each section is provided according to the surface defects observed, followed by the level of the layers to be characterized by confirmatory tests, according to the causes of deterioration previously identified.

All data and analyses are provided in the Excel file attached.

2.5.2 Description of the steps

2.5.2.1 Getting Started

The first step is to segment the road network and evaluate the surface defects and ride comfort of all pavements. The following section details the two distress and comfort surveys and the resulting aggregate ratings that summarize the overall condition and ride comfort of each section.

2.5.2.2 Network Segmentation and Database Development

The pre-evaluation activity is the creation of a computerized Excel database of all sections of the network.

This database is generated from a map of the City. The list of all the sections of the road network is then entered into an Excel sheet, which could later be exported to the computer platform in use within the Public Works Department or the City's IT department.

As such, this database could also be populated with all the information available in the reports and plans available to the City, in order to list the physical characteristics and properties of each section of the network. This would centralize the information scattered in the documents, reports and plans and make it easily accessible to engineers.

The first step in the constitution of the database is the division of the road network into sections. The nomenclature followed for this purpose is that each section is delimited by the two sections that intercept it in accordance with the segmentation policy of the National Road Network database. Each section is therefore simply referenced as follows:

- By a spreadsheet line number to identify and distinguish each roadway section;
- By the name of the street, road or boulevard;
- By the name of the adjacent cross streets or the geographical limit of the City.

2.5.2.3 Faults, Diagnosis, Quality Rating and Comfort Rating

The evaluation of the road network is essential in order to obtain an overview of the current state of the network, to make a preliminary diagnosis of the cause of deterioration and to locate the tests to be considered, to determine the required interventions and finally to rationally optimize the intervention program in the short, medium and long terms.

The content of the Excel database, which includes the reference number of each street, road or boulevard, its name as well as the name of the cross streets, is completed by the various pavement evaluations: the surveys of the defects and of the rolling comfort.

The defect survey is based on a simplified approach of the MTQ's guides for distress surveys of asphalt pavements (MTQ, 2002) and rigid overlay pavements (MTQ, 1997). These evaluations include the recording of various types of cracks, deformations, disintegrations and holes as well as an assessment of ride comfort. The following subsections present each of these defects, how to identify them and judge their severity, and the most likely cause of deterioration that explains its occurrence. It also explains the principle of aggregating the defects into a single deterioration rating on a 0-100 scale.

2.5.2.4 Transverse cracks

Transverse cracks are recorded according to their spacing in metres. An average equivalent spacing of transverse cracks is determined visually and approximately.

The severity is rated according to two modalities: P for not very severe, indicating cracks with an opening of the order of 5mm or less and no loss of material, spalling or spalling of the cracks. Otherwise, the severity is rated T for very severe.

The underlying causes for the presence of transverse cracks are generally:

- Rise (reflection) of cracks from the underlying cement concrete or asphalt pavement to the surface course;
- Thermal cracking of the surface asphalt due to cold weather in winter.

2.5.2.5 Alligator cracks

Alligator cracks are shaped like an alligator skin and are graded according to the percentage of the total section area covered by them.

The severity is rated in two ways: P for mild, indicating cracks with an opening of 5mm or less and no loss of material, spalling or spalling of the cracks. Otherwise, the severity is rated T for very severe.

The underlying causes for the presence of alligator cracks are generally:

- Oxidation (attachment of oxygen molecules to those of the bitumen, removing its malleability and its ability to deform without breaking) or aging (evaporation of solvents) of the first +/- 25 mm of the asphalt wearing course;
- Structural fatigue, a cause excluded because: 1) the majority of pavements have a concrete base, 2) the number of heavy vehicle passages is relatively low on the vast majority of the pavements in the network.

2.5.2.6 Edge cracks

Edge cracks are longitudinal cracks, in the direction of the traffic or cracks in mesh (crocodile skin) located on the sides of the pavement. They are noted according to the percentage of the surface of the section which is covered by them.

The severity is rated according to two modalities: P for not very severe, indicating cracks with an opening of about 5 mm or less and no loss of material, spalling or spalling of the cracks. Otherwise, the severity is rated T for very severe.

The underlying causes for the presence of edge cracks are generally:

- A deficiency in lateral drainage, allowing water stagnation in the edges and localized weakening in the edges resulting in premature structural failure;
- Poor compaction of the foundation's edges, resulting in settlement of the sides and subsequent longitudinal cracking.

2.5.2.7 Longitudinal cracks

Longitudinal cracks are parallel to the direction of traffic. They are recorded according to the percentage of the section area covered by them.

The severity is rated in two ways: P for mild, indicating cracks with an opening of about 5 mm or less and no loss of material, spalling or spalling of cracks. Otherwise, the severity is rated T for very severe.

The underlying causes for the presence of longitudinal cracks are generally:

- A discontinuity in the pavement construction joint resulting from cooling of one spread asphalt span before the second span was laid;
- Cuts to access or repair utilities.

2.5.2.8 Uplift and Settlement

Uplift and settlement are vertical deformations of a portion of the section upwards or downwards. They are recorded according to the percentage of the total area of the section covered by them.

The severity is rated according to two modalities: P for not very severe, indicating uplifts that do not intuitively force the slowing of traffic. Otherwise, the severity is rated T for very severe.

The underlying causes of heave or settlement are generally vertical movement of a soil or foundation of varying frost susceptibility causing differential heave (otherwise heave is not noticeable).

2.5.2.9 Ripples

Ripples are deformation movements in small successive waves perpendicular to the direction of traffic. Ruts are localized settlements in wheel-paths.

They are rated according to the percentage of the section area that is covered by them.

The severity is rated in two ways: P for not very severe, indicating deformations that do not intuitively force the slowing down of traffic. Otherwise, the severity is rated T for very severe. The underlying causes of rutting or undulations are generally:

- Thawing and weakening of the bearing capacity (unlikely given the concrete base);
- Vertical movement of poorly compacted layers (idem);
- Overly rounded asphalt aggregates - not very angular (unlikely due to light traffic);
- Wear of the mix (unlikely due to light traffic);
- Bitumen too soft in summer (possible);
- Deficient bitumen proportioning (possible but not observed);
- Excessive voids in the mix (possible);
- Overdosing of bitumen (possible).

2.5.2.10 Disintegration and potholes

Disintegrations and holes are defects characterized by the loss of cohesion of the asphalt wearing course. They are graded according to the percentage of the section area covered by them.

The severity is rated according to two methods: P for not very severe, indicating defects that do not intuitively force traffic to slow down. Otherwise, the severity is rated T for very severe.

The underlying causes for the presence of disintegrations and holes are generally:

- Thawing and weakening of the bearing capacity (unlikely given the concrete base);
- Suction of water from the soil into the structure (unlikely due to the concrete base);
- Fatigue failure of the asphalt mix (unlikely due to the concrete base);
- Water infiltration through cracks (possible);
- Oxidation and natural aging of the bitumen (possible);
- Deficient bitumen dosage (possible);
- Overheating of the bitumen during spreading (possible);
- Chemical incompatibility and separation of bitumen and aggregates (possible).

2.5.3 Quality Rating (Q)

The quality rating (Q) of each section, expressed on a scale of 0 (poor) to 100 (excellent), is calculated from the penalties assigned to each type of defect according to its severity and extent.

A penalty is deducted cumulatively for each defect present according to the maximum percentage of the extents of the defects present on the section, which is increased by a factor of 2 when the defect is rated " Very Severe (T) ".

An additional increase of a factor of 2 is also applied for Lift and Settle defects due to their negative impact on the road condition.

An additional surcharge of a factor of 3 is also applied for Disintegration/Holes defects due to their significant impact on the road condition.

For transverse cracks, a 20% penalty is applied when they are rated "Very Severe".

Provided the City has a geomatics module for its road network, it may be possible to graphically display the aggregate condition of the road network on a map using an appropriate colour scale for each 20 points Quality rating.

2.5.3.1 Rolling Comfort Rating

A subjective assessment of ride comfort is also established according to three levels: Poor corresponding to an IRI of 7 m/km, Average corresponding to an IRI of 5 m/km and Good corresponding to an IRI of 3 m/km.

Comfort is rated according to these three levels, as perceived by the user, and an IRI estimate is associated with each of these three levels.

2.5.3.2 PASER Rating

PASER was developed by the University of Wisconsin-Madison Transportation Information Center. It uses visual inspection to evaluate pavement surface conditions and linking them to a cause. Understanding the cause of current conditions is extremely important in selecting an appropriate maintenance or rehabilitation technique. There are four major categories of common asphalt pavement surface distress: Surface defects Raveling, flushing, polishing. Surface deformation Rutting, distortion—rippling and shoving, settling, frost heave. Cracks Transverse, reflection, slippage, longitudinal, block, and alligator cracks. Patches and potholes Deterioration have two general causes: environmental due to weathering and aging, and structural caused by repeated traffic loadings. Shown in Table 2.2 below is how the PASER rating was developed.

Table 2.2 PASER rating system
Taken from Transportation Information Center (2002)

Rating system

Surface rating	Visible distress*	General condition/ treatment measures
10 Excellent	None.	New construction.
9 Excellent	None.	Recent overlay. Like new.
8 Very Good	No longitudinal cracks except reflection of paving joints. Occasional transverse cracks, widely spaced (40′ or greater). All cracks sealed or tight (open less than ¼″).	Recent sealcoat or new cold mix. Little or no maintenance required.
7 Good	Very slight or no raveling, surface shows some traffic wear. Longitudinal cracks (open ¼″) due to reflection or paving joints. Transverse cracks (open ¼″) spaced 10′ or more apart, little or slight crack raveling. No patching or very few patches in excellent condition.	First signs of aging. Maintain with routine crack filling.
6 Good	Slight raveling (loss of fines) and traffic wear. Longitudinal cracks (open ¼″–½″), some spaced less than 10′. First sign of block cracking. Sight to moderate flushing or polishing. Occasional patching in good condition.	Shows signs of aging. Sound structural condition. Could extend life with sealcoat.
5 Fair	Moderate to severe raveling (loss of fine and coarse aggregate). Longitudinal and transverse cracks (open ½″) show first signs of slight raveling and secondary cracks. First signs of longitudinal cracks near pavement edge. Block cracking up to 50% of surface. Extensive to severe flushing or polishing. Some patching or edge wedging in good condition.	Surface aging. Sound structural condition. Needs sealcoat or thin non-structural overlay (less than 2″)
4 Fair	Severe surface raveling. Multiple longitudinal and transverse cracking with slight raveling. Longitudinal cracking in wheel path. Block cracking (over 50% of surface). Patching in fair condition. Slight rutting or distortions (½″ deep or less).	Significant aging and first signs of need for strengthening. Would benefit from a structural overlay (2″ or more).
3 Poor	Closely spaced longitudinal and transverse cracks often showing raveling and crack erosion. Severe block cracking. Some alligator cracking (less than 25% of surface). Patches in fair to poor condition. Moderate rutting or distortion (1″ or 2″ deep). Occasional potholes.	Needs patching and repair prior to major overlay. Milling and removal of deterioration extends the life of overlay.
2 Very Poor	Alligator cracking (over 25% of surface). Severe distortions (over 2″ deep) Extensive patching in poor condition. Potholes.	Severe deterioration. Needs reconstruction with extensive base repair. Pulverization of old pavement is effective.
1 Failed	Severe distress with extensive loss of surface integrity.	Failed. Needs total reconstruction.

2.5.3.3 Analyses of Distress Evaluation Data

A visual assessment was performed on all the sections comprising the network of the city of Chateauguay between March and July 2021 to identify the following distress:

1. Transverse cracking;
2. Longitudinal cracking;
3. Alligator cracking;
4. Wheel path cracking;
5. Edge cracking;
6. Upheaving;
7. Settlement;

8. Rutting;
9. Undulations;
10. Bleeding;
11. Stagnant water;
12. Potholes and disintegration;
13. Peeling.

2.5.3.4 Preliminary diagnosis and Identification of layers to be characterized

Based on the synthesis of distresses, causes and treatments tabulated in section 2.5, the following association was developed to provide a preliminary diagnosis of the most likely cause of deterioration, whereby per Figure 2.7:

1. A diagnosis of “Asphalt retraction and reflective cracking” is established if transverse cracks are observed;
2. A diagnosis of “Asphalt Oxidation retraction and reflective cracking” is established if alligator cracks are observed;
3. A diagnosis of “Drainage / Lateral support failure” is established if edge cracks are observed;
4. A diagnosis of “Poor construction joint or Accelerated Utility-cuts related Deterioration” is established if longitudinal cracks are observed;
5. A diagnosis of “Frost associated deterioration” is established if upheaving or settlement or both are observed;
6. A diagnosis of “Asphalt mix design related deterioration” is established if either undulations or rutting or both are observed;
7. A diagnosis of “Oxidation or thaw cycles related deterioration” is established if disintegration or potholes are observed.

R: RETRAIT/REMONTÉE		O: OXYDATION		DS: DRAINAGE/SUPPORT		CJ: COUPES/JOINT		G: GÉLIVITÉ				SE: ENROBÉ		OD: OXYDATION/DÉGEL	
Fissures Tranvsersales		Fissures en Mailles		Fissures en Rives		Fiss. Longitudinales		Soulèvements		Tassements		Ondulations/Ornières		**Desintégrations/Trous**	
Espacem. (m)	Sév (P,T)	% surface	Sév (P,T)	% surface	Sév (P,T)	% de long.	Sév (P,T	% surface	Sév (P,T)	% surface	Sév (P,T	% surface	Sév (P,T	% surface	Sév (P,T)

Figure 2.7 Summary Evaluation, Preliminary Diagnosis, Required Characterization, Intervention and Horizon

Confirmation testing associated to the preliminary diagnosis, namely whether the tests should focus on the asphalt layer or the granular base course are based on whether there are any upheaving or settlements or more than 5% alligator cracking, undulations or rutting observed in which case the granular based require an investigation to determine its characteristics (sieve, water content, water-table level,...). Shown in Figure 2.8 is the decision-making rule used to determine which layer is affected and to be tested.

Règle de décision pour l'obtention des essais de CARACTÉRISATION			
Si Soulèvements ou Tassements >	0%	alors	Fondation (granulaire/eau)
Si Fis.Mailles ou Ondulations/Ornières >	5%	alors	Fondation (granulaire/eau)
Autrement		alors	Enrobé

Figure 2.8 Summary Evaluation, Preliminary Diagnosis, Required Characterization, Intervention and Horizon

If the section shows heave or settlement, there is automatically a foundation problem, in which case it is important to consider performing a characterization of the underlying foundation before deciding on the appropriate rehabilitation technique.

If the foundation has a high level of fine material, it will be necessary to reduce this level below 7-10% by adding net stone during rehabilitation in order to conform with the general technical specifications for roads (CCDG) of the Ministry of Transport of Quebec (MTQ).

If this is not economical or possible, consider maintaining an average fine material content of less than 14% (as practised by the City of Montreal) and stabilize the granular base. Otherwise, the granular base should be replaced.

If the section shows alligator cracks or corrugations, then it is plausible to assume that the problem is strictly in the wearing course or asphalt base course. It would then be necessary to characterize the asphalt mixes in order to locate the exact cause and to remedy it preferably by an appropriate recycling which would address the cause of deterioration (excess of voids, too soft bitumen, too rounded aggregates, ...).

Any other combination of deterioration would exclude both the foundation (absence of deformation movements in the foundation) and the asphalt alone and would require an investigation of both the asphalt and the underlying cement concrete layer.

2.5.3.5 Choice of interventions

All the information collected in the previous steps is collated and analyzed to determine the rehabilitation needs, which can be of two types: 1) pulverization and stabilization or 2) planning and resurfacing.

The analysis is performed using the standard pavement management principles co-authored in the Transportation Association of Canada's "Pavement Design and Management Guide" and taught in the course entitled "Pavement Evaluation" offered annually at the École de Technologie Supérieure.

As such, pavement management at the network level is satisfied with less detailed and less precise data and analysis than that required at the project level, the latter being more oriented towards the detailed design of rehabilitation, which is not the object of this mandate.

This being said, although the City of Chateauguay pavement management proposed in the attached Excel file represents a network-level system, it proposes rehabilitation interventions that are sufficiently detailed to guide the design and execution of the work.

Also, in the same spirit as for the identification of the layers to be characterized, the choice of interventions is based on the following principle:
If the pavement shows more than 5% heaving or settlement on the surface, then it will be necessary to intervene on the subgrade and consider pulverizing the surface layers, recycling some of them and/or correcting their grading, consider cement stabilization to reduce or even eliminate deformation movements, and cover the whole with a new asphalt wearing course.

In the contrary case (heave and settlement of less than 5%), the pavement does not present any visible problems at the level of its foundations and levelling up to the base of the cracks is recommended, followed by partial recycling of the removed layers and a new asphalt wearing course. Shown in Figure 2.9 is the decision-making rule used to determine which rehabilitation treatment to be used.

Règle de décision pour l'obtention des INTERVENTIONS:			
Si Soulèvements ou Tassements > ou =	5%	alors	Pulvo-Stabilisation
Autrement			Planage/Resurfaçage

Figure 2.9 Summary Evaluation, Preliminary Diagnosis, Required Characterization, Intervention and Horizon

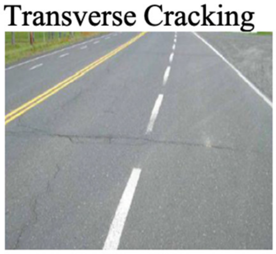
2.6 Relationships between Distress, Cause, Test and Treatment

Based on the literature review conducted in Chapter 1, Table 2.3 compiles the different types of distress, a brief description, the potential problems, and underlying causes of deterioration and relevant tests. Potential interventions or treatments that should be considered, because they specifically address the causes of deterioration, are also provided. Table 2.3 is continued in Annex 1.

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments

Types of Distress	Description	Cause of deterioration/testing	Treatment solutions
Wheel Path Cracking 		Fatigue rupture due to cumulated excess permanent tensile strain on the bottom of the asphalt concrete mix.	Addition of an asphalt concrete overlay, with or without previous milling of 25 mm of the older asphalt if the existing cracks are superficial, otherwise removal and recycling of the existing asphalt concrete with an additional overlay thickness as required following the structural pavement design. Another solution when height constraints exists (in urban areas) is to also pulverize part of the base, mix with the asphalt concrete and stabilize the combined material. By increasing the rigidity of the base, a thinner asphalt concrete is required.

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

Edge Cracking 	Cracking localized on the edges of the pavement.	Lateral shear failure on the edges due to :1) narrow driving lane resulting in repetitive localized heavy loads on the edges in the same path, 2) inadequate side slope, 3) poor compaction on the edges, or 4) lack of re-gravelling of the shoulders, 5) poor drainage of the surface water accumulating on the edges.	If 1) road widening if the driving lane is too narrow, followed by an overlay on the whole pavement. If 2) adjustment of the side slope to avoid lateral failure, or geo-grid reinforcement. If 3) remove asphalt, compact and replace recycled asphalt with additional material If 4) correct deficiencies and pave shoulders If 5) restore defects, add levelling course and overlay
Transverse Cracking 	Cracks perpendicular to the pavements centerline, usually thermally induced. Allows moisture infiltration and affects roughness	Asphalt shrinkage and daily temperature cycling. Typically caused by an inability of asphalt binder to expand and contract with temperature cycles because of: 1) Asphalt binder aging, 2) Poor choice of asphalt binder in the mix design Impossible to distinguish from reflective cracking unless cores are taken and cracks checked for reflection or not.	Options depend on severity & extent of block cracking: Low severity cracks (< 1/2 inch wide) require crack sealing to prevent (1) entry of moisture into subgrade through cracks and (2) further raveling of crack edges. HMA can provide years of good service after developing small cracks if they are sealed. High severity cracks (> 1/2 inch wide and cracks with raveled edges) require removal and recycling of cracked pavement layer by adding rejuvenating agent followed by overlay.

The segmented network of a small to mid-sized city should then be classified per functional class, based on the concept of equivalent single axle loads. The concept refers to the number of 8-ton axle loads expected on each section on a representative day of the year, commonly referred to as the Design Traffic Number (DTN) (Asphalt Institute, 2021). It is basically obtained by multiplying the average annual daily number of vehicles per day (AADT), by the percentage of trucks (% trucks), by the truck factor or coefficient of aggressivity (Average equivalent 8-ton axle load per truck).

The truck factor refers to the average amount of single 8-ton axle loads per truck. The DTN is increased to account for traffic growth over the next 20 years.

$$\text{DTN} = \text{AADT} \times \text{TKS} \times \text{TF} \times \text{G} \qquad (2.1)$$

Where: AADT, Average annual daily traffic
TKS, Percentage of trucks (%)
TF, Average truck factor (coefficient of aggressivity)
G, Annual Traffic growth factor (%)

Based on the aforementioned criterion for classification in functional classes, the city streets should be grouped in three (3) categories: 1) local residential; 2) residential collector or commercial; 3) industrial. These classes are based on traffic type, percentage of trucks, truck factor, and number of lanes, and AADT. Expanding further with three (3) classes of soils, one could consider nine (9) families or roads in a city.

A Life-Cycle Cost Analysis (LCCA) compiling the structural design required to withstand the DTN of each of the three functional classes was conducted with the software developed by the Ministry of Transport of Quebec, Chaussee 2 (Agal, 2005).

The results are compiled in the Table 2.4 below for nine (9) family types, namely for traffic levels T1 corresponding to local residential streets, T2 for residential collector streets and T3 for main arterials and industrial streets; and subgrade S1 corresponding to sandy and/or gravelly soils, S2 for silty or clayey sand or gravel and S3 corresponding to predominantly silty or clayey soils.

Every flexible pavement section in the city of Chateauguay should have layer thicknesses complying with the below indicated values in mm. Base and subbase courses can be either granular (FGP) or stabilized (FS).

Table 2.4 Typical structures for flexible pavements
Adapted from Catalogue of flexible pavements Agal (2005); Assaf (2020)

Traffic and Soil		**S1**	**S2**	**S3**
T1	Local residential streets	95 mm EB 400 mm FGP	95 mm EB 400 mm FGP	95 mm EB 400 mm FGP
T2	Collector residential and commercial streets	130 EB 400 mm FGP	130 EB 400 mm FGP	Option 1 130 mm EB 420 mm FGP Option 2 140 mm EB 400 mm FGP
T3	Arterials and Industrial streets	Option 1 190 mm EB 300 mm FGP Option 2 175 mm EB 175 mm FS 300 mm FGP	Option 1 200 mm EB 450 mm FGP Option 2 175 mm EB 175 mm FS 300 mm FGP	Option 1 215 mm EB 500 mm FGP Option 2 180 mm EB 200 mm FS 400 mm FGP

Where: EB refers to asphalt concrete in mm
FGP refers to granular base course (new or recycled MG-20)
FS: refers to cement and/or bitumen stabilized material, either new or reclaimed.

2.7 Economic analysis

Roy (2009) adapted the HDM-4 to the environmental conditions and the vehicle fleet prevailing in Quebec and produced the relationships between the IRI and vehicle user costs expressed in \$/km.

Table 2.5 below provides the standard equation between the VOC expressed as CEV (Coûts d'exploitation des véhicules) and the IRI for different speeds and vehicle type, namely:

$$CEV_{jk}\ (\$/km) = a0_{jk} + a1_{jk}\,(IRI) + a2_{jk}\,(IRI)^2 + a3_{jk}\,(IRI)^3 \qquad (2.2)$$

Where:	CEV_{jk}	cost of operating vehicle k on a road type j, expressed in dollars in 2006.
	IRI	international roughness index (m/km)
	$a0_{jk}$, $a1_{jk}$, $a2_{jk}$, $a3_{jk}$	coefficients of the polynomial model for vehicle k on road j.

Walls III and Smith (1998) developed the same for the Federal Highway Administration (FHWA) for state highway agencies (SHA) as illustrated in Table 2.5.

Table 2.5 Vehicle Operating Costs as a function of the IRI for different vehicles
Taken from Roy (2009)

			CEV ($) en fonction de l'IRI (m/km)			
			CEV = a0 + a1*IRI + a2*IRI2 + a3*IRI3			
			a0	a1	a2	a3
Rural	100 km/h	Automobiles	0,38116166	-0,00725084	0,00282656	-5,6107E-05
		Camions	1,09481970	-0,01818232	0,00690888	-0,00014385
	90 km/h	Automobiles	0,39847694	-0,00987906	0,00295441	-5,8112E-05
		Camions	1,03940909	-0,01214377	0,00635551	-0,00013296
	70 km/h	Automobiles	0,46361587	-0,01772901	0,00322846	-6,0538E-05
		Camions	1,05711194	-0,01299434	0,00629732	-0,00013029
	50 km/h	Automobiles	0,57494727	-0,01997400	0,00262338	-3,9241E-05
		Camions	1,19698460	-0,02345263	0,00625101	-0,00012006
Urbain	100 km/h	Automobiles	0,38116166	-0,00725084	0,00282656	-5,6107E-05
		Camions	1,05057101	-0,01611689	0,00664246	-0,00013941
	90 km/h	Automobiles	0,39847694	-0,00987906	0,00295441	-5,8112E-05
		Camions	0,99710537	-0,01079008	0,00613602	-0,00012957
	70 km/h	Automobiles	0,46361587	-0,01772901	0,00322846	-6,0538E-05
		Camions	1,01939420	-0,01211682	0,00609061	-0,00012693
	50 km/h	Automobiles	0,57494727	-0,01997400	0,00262338	-3,9241E-05
		Camions	1,15727548	-0,02089767	0,00590255	-0,00011356

Shown in Figure 2.10 is vehicle operating costs as a function of the IRI for different vehicles.

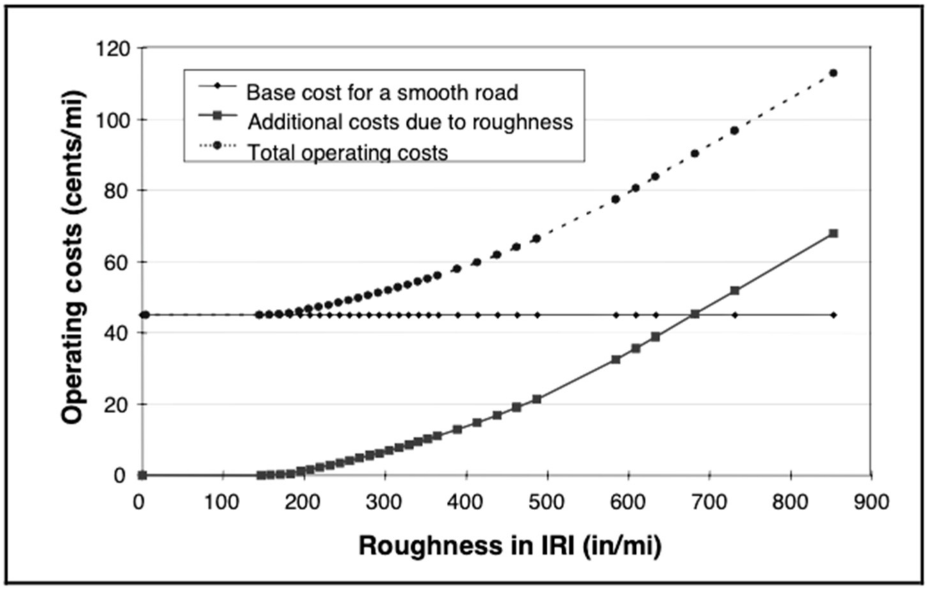


Figure 2.10 Vehicle Operating Costs as a function of the IRI for different vehicles
Taken from Walls III & Smith (1998)

2.7.1.1 Vehicle Operating Cost Savings

The savings in vehicle operating costs (VOC) are calculated from the adaptation to the Quebec context of the World Road Association (PIARC) HDM-4 model.

The equations linking the VOCs to the IRI for each vehicle representative of each class of vehicle in Quebec were developed as part of the mandate given to ETS by the Ministry of Transport (Roy, 2009). Thus, a calculation of the reduction in VOC is obtained based on the IRI reduction to a post-intervention reference value of 1.5 m/km. It should be noted that the Ministry of Transportation's performance specifications require an IRI of less than 1.2 m/km to qualify for a bonus on the pavement installed, and an escalating penalty applies when the post-intervention IRI is between 1.2 m/km and 1.7 m/km with no payment for the wearing course when the post-intervention IRI is greater than 1.7 m/km. Therefore, while demanding, the 1.5 m/km limit is not too ambitious, but realistic given that these are not projects on freeways or national roads.

2.7.1.2 Cost of the intervention

The costs of the interventions were obtained for 2021 from "La Compagnie Meloche Inc.” (Meloche), "Carrière et Pavage Saint-Eustache Ltée" (Mathers) and “Carrière St-Jacques” (Demix) as well as the compilation obtained from the Ministry of Transport's website of contracts signed in 2020. Shown in Table 2.6 are prices from three different quarries.

Table 2.6 Cost of stone from quarries

Quarry	Location	MG20	MG56	MG112	Redevance	Transport
Meloche	Coteau-du-Lac	13.65	13.30	12.90	0.61	8.10
Mather	Saint-Eustache	14.75	14.50	N/D	0.61	7.33
Demix	Saint-Jacques	15.30	15.10	13.75	0.61	9.89

Reconciliations with the bitumen prices posted on the Bitumen Quebec website were also performed and illustrated in Table 2.7.

Table 2.7 2021 Bitumen prices
Taken from Bitume Québec (2021)

GRADES	PRIX (tonne métrique)	DATE EFFECTIVE D'ENTRÉE EN VIGUEUR DU PRIX
PG 58S-28	576,69 $	1er mars 2021
PG 58H-34	668,82 $	1er mars 2021
PG 58H-34 T	702,95 $	1er mars 2021
PG 58H-34 THRD	586,93 $	1er mars 2021
PG 58H-34 HRD	689,30 $	1er mars 2021
PG 52V-40 THRD	730,25 $	1er mars 2021
PG 52V-40 HRD	716,60 $	1er mars 2021
PG 58E-34	702,95 $	1er mars 2021
PG 58E-34 T	737,07 $	1er mars 2021
PG 58E-34 THRD	737,07 $	1er mars 2021
PG 58E-34 HRD	723,42 $	1er mars 2021
PG 64H-28	-	-
PG 64E-28	-	-
PG 64E-28 $Jnr_{3,2} \leq 0{,}15$ kPa^{-1}	-	-
PG 64E-34 $Jnr_{3,2} \leq 0{,}15$ kPa^{-1}	-	-

Table 2.8 illustrates the list and prices of transport infrastructure work.

Table 2.8 List and prices of transport infrastructure work
Taken from MTQ (2019-2020)

LISTE ET PRIX DES OUVRAGES D'INFRASTRUCTURES DE TRANSPORT

CATÉGORIE **13** **Revêtement de chaussée en enrobé**
SOUS-CATÉGORIE

RÉFÉRENCE CCDG	CODE	UNITÉ	DÉSIGNATION DE L'OUVRAG	VARIABLE 1	VARIABLE 2	VARIABLE 3	2017 Qté prévue / Qté exéc.	2017 Prix moyen / Coût moyen	2018 Qté prévue / Qté exéc.	2018 Prix moyen / Coût moyen	2019 Qté prévue / Qté exéc.	2019 Prix moyen / Coût moyen
13.3.5.4	613205	t	Couche de surface, enrobé									
				autre enrobé								
					PG 58-28							
						transport total inclus (rural)						
						transport total inclus (urbain)						
					PG 58-34		**595**	**201,96$**	**156**	**95,35$**		
							584	159,08$	177	217,41$		
						transport total inclus (rural)	**595**	**201,96$**	**156**	**95,35$**		
							584	159,08$	177	217,41$		
						transport total inclus (urbain)						
					PG 58-34HRD				**230**	**100,31$**		
									186	120,00$		
						transport total inclus (rural)			**230**	**100,31$**		
									186	120,00$		
						transport total inclus (urbain)						
					PG 64-28		**600**	**120,00$**	**80**	**200,00$**	**60**	**300,00$**
							167	83,01$	102	78,87$		
						transport total inclus (rural)	**600**	**120,00$**	**80**	**200,00$**	**60**	**300,00$**
							167	83,01$	102	78,87$		
						transport total inclus (urbain)						

2.7.1.3 Maintenance frequencies

Standard maintenance tasks are applied post-rehabilitation and have been considered in determining the required maintenance interventions. Unit costs are based on MTQ costs adjusted to an annual inflation rate of 2%. Table 2.9 illustrates maintenance schedule and cost for a 25-year lifecycle.

Table 2.9 Maintenance schedule and cost for a 25-year lifecycle
Adapted from LCCA (MTQ 2007; Course notes Assaf 2020)

An		coûts		
		$/m^2	$/m^3	$/t
0	reconstruction complète			
0	MG-112		21.00	
0	MG-20		24.20	
0	Asphalte		350.00	156.25
0	Marquage époxy	0.74		
4	Rafraichissement marquage époxy BB	0.46		
7	Rafraichissement marquage époxy BB	0.46		
10	Rafraichissement marquage alkyde BB	0.04		
11	Rafraichissement marquage alkyde BB	0.04		
12	Rafraichissement marquage alkyde BB	0.04		
13	Rafraichissement marquage alkyde BB	0.04		
14	Planage 100%(40mm) resurfaçage (100 kg)	17.39		
14	Marquage époxy	0.74		
18	Rafraichissement marquage époxy BB	0.46		
21	Rafraichissement marquage époxy BB	0.46		
24	Rafraichissement marquage alkyde BB	0.04		
25	Rafraichissement marquage alkyde BB	0.04		
26	Rafraichissement marquage alkyde BB	0.04		

2.7.1.4 Internal rate of return on intervention

The internal rate of return for each proposed rehabilitation intervention is calculated based on annual CEV savings and takes into consideration post-rehabilitation maintenance costs.

$$\sum_{i=0}^{n-1} \frac{b_i - c_i}{\left(1+\left(\frac{r}{100}\right)\right)^i} = 0 \Rightarrow \sum_{i=0}^{n-1} \frac{b_i}{\left(1+\left(\frac{r}{100}\right)\right)^i} - \sum_{i=0}^{n-1} \frac{c_i}{\left(1+\left(\frac{r}{100}\right)\right)^i} = 0 \qquad (2.3)$$

Where: b= benefits

c_i= cost

r = discount rate

i = time period

2.7.1.5 Intervention Horizon

The intervention horizon is established according to (3) three different time periods, namely:

- Short-term, from 2021 to 2025 inclusive, when comfort is rated "POOR" or when the QUALITY rating is less than 20% in 2021. Nearly 9% of the network is in this class.

- In the medium term, from 2026 to 2030 inclusive, when comfort is rated "AVERAGE" or when the QUALITY rating is between 20% and 60% in 2021. Nearly 44% of the network is in this class.

- In the long term, beyond 2030 (more than 10 years), when comfort is rated as "GOOD" or when the QUALITY rating is above 60% in 2021. Nearly 47% of the network is in this class.

2.7.1.6 Costs, benefits and Internal rate of return

The VOCs are provided for: 1º) the do-nothing option (except routine maintenance) over the next 25 years, 2º) 50-mm milling and 50 mm resurfacing, 3º) full-depth asphalt-and-base-course reclamation and 4º) resurfacing and reconstruction over the next 25 years.

The savings generated by each of the three (3) interventions are calculated as:

a. the differential VOC of milling and resurfacing versus VOC of the do-nothing over the life cycle of 25 years;
b. the differential VOC of pulverization and stabilization versus VOC of the do-nothing over the life cycle of 25 years;
c. the differential VOC of reconstruction versus VOC of the do-nothing over the life cycle of 25 years.

The VOC - IRI equations were obtained from an application of the HDM-4 pavement performance and works-effect models adapted for Quebec conditions based on previous work undertaken at ETS by Jean-Philippe Roy (2009).

These polynomial equations provide the VOC savings resulting for each of the three (3) traffic classes, on poor soils only, as a result of the intervention.

Detailed cost estimates of each intervention and the type and frequency of maintenance requirements, for each of the three (3) types of traffic over a period of 26 years are then provided in order to perform a life-cycle cost analysis (LCCA). The differential monetary flows between each intervention and the do-nothing option are calculated.

The differential LCCA for the three aforementioned options (A, B, C) represents the benefits.

These benefits are provided in the attached MS Excel file titled "*Châteauguay - Evaluation Sommaire, Diagnostic Préliminaire, Caractérisation Requise, Intervention et Horizon*", namely in sheets titled:

- LCCA *Planage resurfacage;*
- LCCA *Pulvo stabilisation;*
- LCCA *Reconstruction.*

The Internal Rate of Return (IRR) is then provided, for each of the three (3) classes of roads, based on: 1) the cost of rehabilitation, 2) the cost of the maintenance alternatives envisaged for each traffic class and 3) the VOC reduction savings or benefits obtained from the HDM-4 application to Quebec conditions.

CONCLUSIONS AND RECOMMENDATIONS

The thesis provided a literature survey of common road management practices in North America, based on which it developed a simplified framework for managing roads at the municipal level.

The thesis then provided an application on the road network of the City of Chateauguay, Quebec, Canada. This application relies first on a visual assessment of the surface defects of the City's pavements based on a simplified approach to the MTQ's guides for recording distress in asphalt and rigid overlay pavements, as well as a subjective assessment of ride comfort based on three ratings: Poor, Fair and Good, which were related to pavement roughness.

It then makes a preliminary diagnosis of the cause of deterioration of each section according to the surface defects observed.

It identifies the level of the layers to be characterized by confirmatory tests, according to the causes of deterioration previously identified, determines the technically justified intervention needs in terms of rehabilitation and prioritizes those needs according to three periods 0-5 years, 6-10 years and more than 10 years.

It assesses the costs of the interventions and their associated maintenance needs over the next 25 years, and the vehicle user cost savings that result from the intervention, over the 25-year cycle. The resulting internal rate of return is also provided as a result.

In conclusion, this approach is a significant and modern improvement in municipal asset management based on the principle that the only way to optimize interventions is to invest in technically justified interventions. To this end, a pavement intervention plan is based on an assessment of the actual current condition of pavements and their current and future technical needs.

As a cautionary note on the limitations of this thesis, it is worthy to stress that a preliminary network-level intervention plan does not, however, constitute a project-level rehabilitation design for each deteriorated section.

It does, however, answer the following questions in a preliminary and executive manner: Where, why, how and when to intervene? by providing a practical, simple and easily accessible dashboard for engineers, administrators and municipal councillor.

ANNEX I

DESCRIPTION, PROBLEMS, MECHANISMS, CAUSES OF DETERIORATION AND TREATMENTS

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments

Types of Distress	Description	Cause of deterioration/Tests	Treatment solutions
Polygonal or Alligator Cracking 	Series of interconnected cracks caused by: A) oxidation and hardening of asphalts, or B) fatigue failure of the HMA surface (or stabilized base) under repeated traffic loading. Indicator of either A) oxidation and hardening or B) structural failure, cracks allow moisture infiltration. Roughness, may further deteriorate to a pothole.	A-Fixation with time of oxygen molecules conjugated with the evaporation of solvents resulting in both cases in a hardened asphalt. Cracking initiates top down and is usually superficial (first 25 mm). B- Fatigue rupture due to cumulated excess permanent tensile strain on the bottom of the asphalt concrete mix. Cracking initiates at the bottom of the HMA layer where the tensile stress is the highest then propagates to the surface as one or more longitudinal cracks. This is commonly referred to as “bottom-up” or “classical” fatigue cracking. After repeated loading, the longitudinal cracks connect forming - sided sharp-angled pieces that develop into a pattern resembling an alligator skin.	A-Recycling of the first 25 mm of the asphalt concrete with the addition of a rejuvenating agent, followed by another thin layer of new asphalt concrete. B1) Overlay with or without milling or, preferably to address the drainability issue, pulverize asphalt and mix with base for a total of 300 mm, then stabilize with bitumen and/or cement (preferably both, respectively 3% and 1%), and cover with 50 mm of HMA. A LCCA will determine cheapest option on yearly basis as the latter option will last 15 years versus 7-8 for an overlay. B2, B3 and B4) Overlay with thickness as needed with or without milling. B5) Pulverize asphalt and mix with base for a total of 300 mm, then stabilize with bitumen and/or cement (preferably both, respectively 3% and 1%), and cover with 50 mm of HMA.

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

		These types of failures are often the result of insufficient support in the underlying base structure due to either insufficient design, non-conforming thicknesses or water penetration that weakens the base. Inadequate structural support, can be caused by a myriad of things: B1) Decrease in pavement load supporting characteristics such as Loss of base, subbase or subgrade support (e.g., poor drainage or spring thaw resulting in a less stiff base). B2) Stripping on the bottom of the HMA layer (the stripped portion contributes little to pavement strength so the effective HMA thickness decreases) B3) Increase in loading (e.g., more or heavier loads than anticipated in design) B4) Inadequate structural design B5) Poor construction.	

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

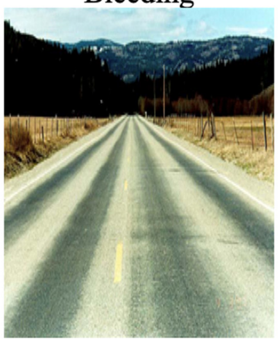
Bleeding 	A film of asphalt binder on the pavement surface. It usually creates a shiny, glass-like reflecting surface (as in the photo) that can become quite sticky. Sometimes referred to as "flushing". Reduces skid resistance.	Bleeding occurs when asphalt binder fills the aggregate voids during hot weather and then expands onto the pavement surface. Since bleeding is not reversible during cold weather, asphalt binder will accumulate on the pavement surface over time. This can be caused by one or a combination of the following: Excessive asphalt binder in the HMA (either due to mix design or manufacturing); Excessive application of asphalt binder during BST application (as in the above figures); Low HMA air void content (e.g., not enough room for the asphalt to expand into during hot weather); A bitumen that is too soft for the climatic conditions which flows away; A bitumen that is too temperature susceptible.	The following repair measures may eliminate or reduce the asphalt binder film on the pavement's surface but may not correct the underlying problem that caused the bleeding: Minor bleeding can often be corrected by applying coarse sand to blot up the excess asphalt binder. Major bleeding can be corrected by cutting off excess asphalt with a motor grader or removing it with a heater planer. If the resulting surface is excessively rough, resurfacing may be necessary. A common solution for this is to recycle the existing asphalt by adjusting the mix design, in accordance with the cause as per the column on the left. If the problem is excessive binder, then the mix design will provide more filler, if the problem is low voids content, then the mix design will provide angular aggregates resulting in less final compaction, if the problem in a soft bitumen, then the milling and heating processes should harden the old bitumen, if the bitumen is too temperature susceptible, then a modified bitumen with a lower temperature susceptibility may be used.

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

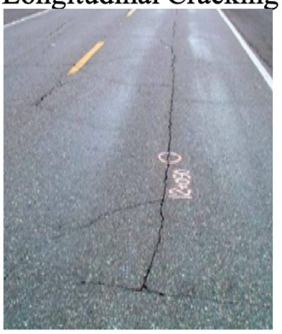
Longitudinal Cracking 	Cracks parallel to the pavement's centerline or laydown direction. Can be a type of fatigue (alligator or polygonal) cracking or top-down cracking. Allows moisture infiltration, roughness, and it may indicate the possible onset of alligator cracking and structural failure.	Poor joint construction or location. Joints are generally the least dense areas of a pavement. Therefore, they should be constructed outside of the wheelpath so that they are only infrequently loaded. Joints in the wheelpath like those shown in third through fifth figures above, will general fail prematurely. A reflective crack from an underlying layer (not including joint reflection cracking) HMA fatigue (indicates the onset of future alligator cracking) top-down cracking.	Strategies depend upon the severity and extent of the cracking: Low severity cracks (< 1/2 inch wide and infrequent cracks). Crack seal to prevent (1) entry of moisture into the subgrade through the cracks and (2) further raveling of the crack edges. HMA can provide years of satisfactory service after developing small cracks if they are kept sealed. High severity cracks (> 1/2 inch wide and numerous cracks). Remove and replace the cracked pavement layer with an overlay

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

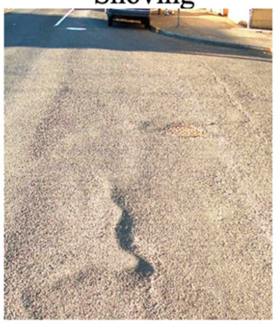
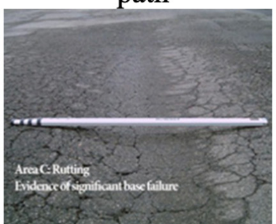
Shoving 	A form of plastic movement typified by ripples (corrugation) or an abrupt wave (shoving) across the pavement surface. The distortion is perpendicular to the traffic direction. Usually occurs at points where traffic starts and stops (corrugation) or areas where HMA abuts a rigid object (shoving).	These types of failures present bumps or corrugations where the surface asphalt has been "shoved" or bunched up. This is most often the result of extreme horizontal stress caused where heavy traffic loads typically stop or start.	The most common repair for these areas is to perform full-depth repair. This exposes the base, allowing for any base weaknesses to be repaired.

Table 2.3 Description, problems, mechanisms, causes of deterioration and treatments (cont'd)

Rutting in the wheel path  	Surface depression in the wheelpath. Pavement uplift (shearing) may occur along the sides of the rut. Ruts are particularly evident after a rain when they are filled with water. Ruts filled with water can cause vehicle hydroplaning, can be hazardous because ruts tend to pull a vehicle towards the rut path as it is steered across the rut.	There are two basic types of rutting: A) mix rutting, and B) subgrade rutting. A-Mix rutting due to lateral shear failure of the asphalt concrete, occurs when the subgrade does not rut yet the pavement surface exhibits wheelpath depressions as a result of: A1) Poor compaction of the asphalt concrete, A2) Excessive voids, A3) rounded aggregates (not angular enough), A4) A bitumen that is too soft, A5) A bitumen that is too temperature susceptible, A6) A high bitumen content., A7) Wearing of the asphalt, A8) thawing of the base course when not drainable. B-Subgrade rutting due to structural failure occurs when the subgrade exhibits wheelpath depressions due to loading. In this case, the pavement settles into the subgrade ruts causing surface depressions in the wheelpath. This is due to cumulated excess permanent compression strain on the top of the soil or the subbase.	A heavily rutted pavement should be investigated to determine the root cause of failure (e.g. insufficient compaction, subgrade rutting, poor mix design or studded tire wear). Slight ruts (< 1/3 inch deep) can generally be left untreated. Pavement with deeper ruts should be leveled and overlayed.

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