Development Practices for Municipal Pavement Management Systems Application

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Abstract

Pavement Management Systems (PMS) are widely used by transportation agencies to maintain safe, durable and economic road networks. There are many PMS software packages that have been developed over the past decades for provincial/state road agencies. However, sometimes due to lack of budget and experience, adopting the existing PMS for a road agency is not cost effective. Thus, it is important to introduce a simple, effective, and affordable PMS for a local agency and municipality.
This research is carried out in partnership between the City of Markham and the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo. For the purpose of developing a PMS for local agencies, an extensive literature review on PMS components was carried out, with emphasizing data inventory, data collection, and performance evaluation. In addition, the literature review also concentrated on the overall pavement condition assessment. In July 2011, a study on "Evaluation of Pavement Distress Measurement Survey" was conducted as a part of this research and was distributed to cities and municipalities across Canada. The study focused on the current state-of-the-practice in pavement distress and condition evaluation methods used by local agencies to compare the results from the literature review. The components of the proposed PMS framework are also developed based on the literature review with some modifications and technical requirements. The City of Markham is selected as a case study, since it represents a local agency and provides all the data, to illustrate the validation of the proposed PMS framework.

1.0 Introduction

1.1 Background

Pavement Management Systems (PMS) are widely used by transportation agencies to maintain safe, durable and economic road networks [1]. PMS prioritize the maintenance and rehabilitation of pavement sections by evaluating pavement performance at the network level [2]. There are many PMS software packages that have been developed over the past decades for provincial/state road agencies. However, sometimes due to lack of budget and experience, adopting the existing PMS for a road agency is not cost effective. Thus, it is important to introduce a simple, effective, and affordable PMS for a local agency and municipality.

1.2 Research Scope and Objectives

This research is carried out in partnership between the City of Markham and the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo.

The main objectives of the research project include defining:

- the inventory data required for the local agencies;
- the pavement performance data that should be collected during the condition survey by local agencies;
- the density levels and severity levels that should be used in assessment of pavement condition;
- the key steps required to implement a PMS.

In short, the research methodology includes development of a framework that can be utilized by the City of Markham and/or other cities and municipalities as a guideline for developing their own simple PMS.

2.0 Research Methodology

Inventory data, pavement condition assessment, establishing criteria, prediction models for pavement performance deterioration, rehabilitation and maintenance strategies, priority programming of rehabilitation and maintenance, economic evaluation of alternative pavement design strategies, and program implementation are the necessary components of a pavement management system. However, for the local agencies that have lower budget than the provincial/state agencies implementing such PMS is not cost effective

The intention of the proposed research methodology is to introduce a simple, effective, and affordable PMS for local road agencies. One of the main areas included in this research methodology is to discuss collection of pavement for local agencies. Thus, in 2011 the survey "Evaluation of Pavement Distress Measurement Survey" was developed and distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations.

Figure 1 represents the research methodology framework which consists of six main steps: referencing method, data inventory, evaluate current road network status, predict models for pavement performance deterioration, economic evaluation of rehabilitation and maintenance alternatives, and priority programming of rehabilitation and maintenance alternatives. The step related to evaluating current road network status contains three subsections, initially, it is essential for local agencies to evaluate the overall pavement condition of each road section. Then the local agencies should evaluate the overall road network condition and finally in the third subsection the local agency should divide the road network into homogeneous sections for analysis.

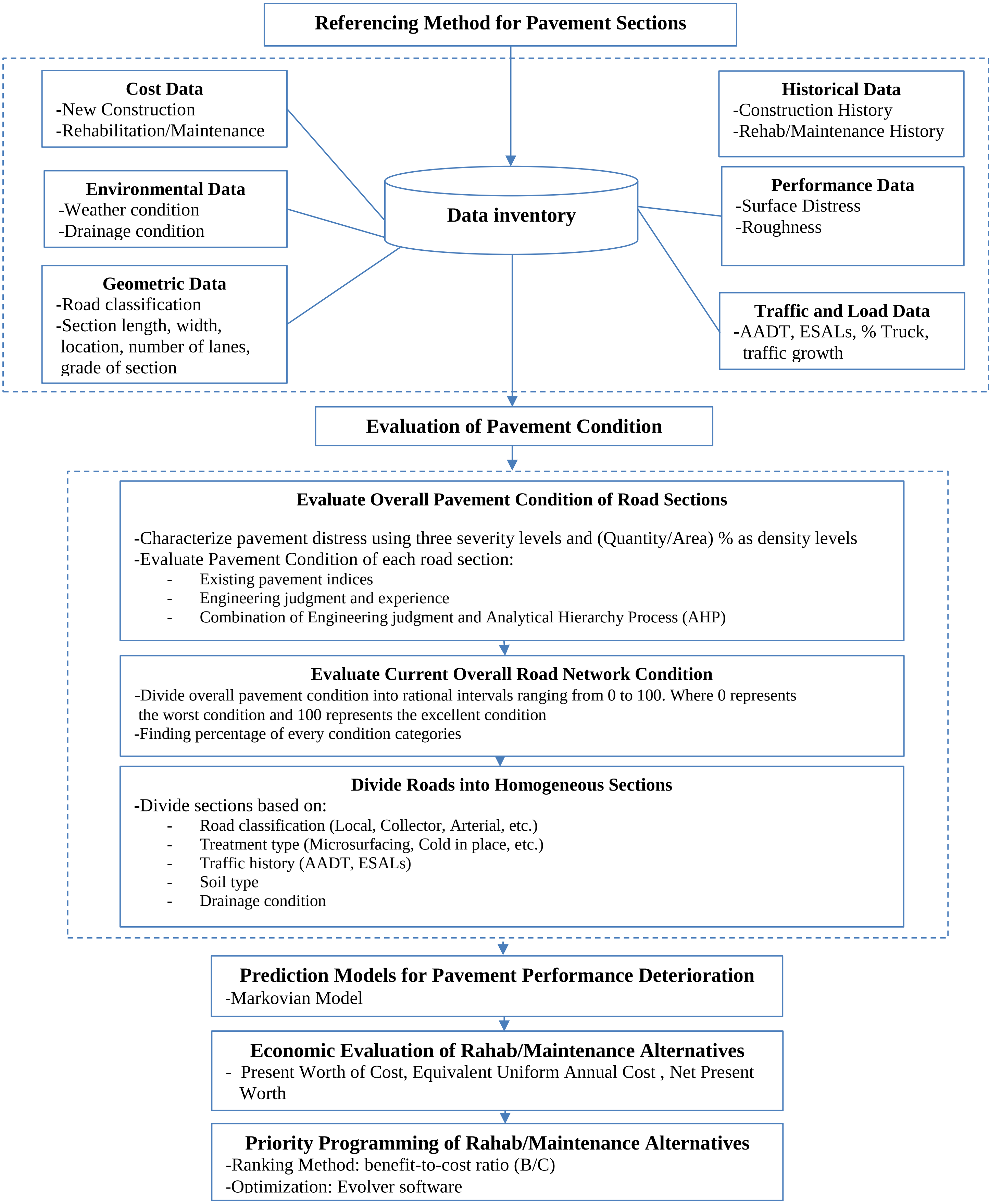

Figure 1: Research Methodology Framework

2.1 Referencing Method

The first step is to develop a method of referencing for pavement sections. The basic method for referencing pavement sections includes node-link, branch-sectioning, route-km post, and Geographic Information Systems (GIS). GIS is one of the referencing methods that have the capability of defining pavement sections by integrating data (condition, history, etc…), and generating maps for pavement management reports. Most agencies in Canada including the Ministry of Transportation of Ontario and Alberta Transportation are implementing GIS [1]. Moreover, at the municipal level, agencies such as Calgary, Edmonton, and Montreal, etc. are rapidly implementing GIS for their road network [1],[3].Thus, GIS is set as the best practice for referencing pavement sections.

2.2 Data Inventory

The next step involved obtaining various types of inventory data such as performance data, historic data, policy data, geometric data, environment, traffic and load data, and cost related data. Due to the limited budget, cities and municipalities cannot afford to obtain and collect all the necessary data; however, the following data is the key to obtaining an efficient and effective pavement management system.

2.2.1 Historical Data

Historical data can be categorized as to construction-related (the year and type of the initial construction), and treatment-related (any rehabilitation or maintenance treatment and the year at which these treatments are applied after the initial construction).

2.2.2 Traffic and Load Data

The proper use and collection of traffic and load data, such as Average Annual Daily Traffic (AADT), percent trucks, traffic growth, and annual Equivalent Single Axle Loads (ESALs), are highly important in a PMS.

2.2.3 Performance Data

Performance data is also necessary and should be obtained by the local agencies for the pavement management system. The performance data is collected, depending on the agency's available budget, usually every two to five years for the road network using manual, semi-automated tools, automated tools, or two or more of the three. The survey can be conducted on every 30 m, 50 m, 100 m, etc. intervals. Many provincial/states agencies collect one or more of the surface distress, friction, roughness, and structural adequacy as their performance data. Local agencies; on the other hand, due to different traffic volume, budget limit, speed limit, and user expectation, should collect fewer and specific types of pavement performance data. Thus, a survey was developed in 2011 and distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations. A total of nine surveys were completed including seven cities (Edmonton, Hamilton, Moncton, Saskatoon, Victoria, Calgary, and Niagara Region) and two consultants (Golder Associates Ltd. and Applied Research Associates (ARA))..

Figure 2 shows the percentage of agencies that collect the different types of pavement distresses to evaluate flexible pavement of their overall road networks.

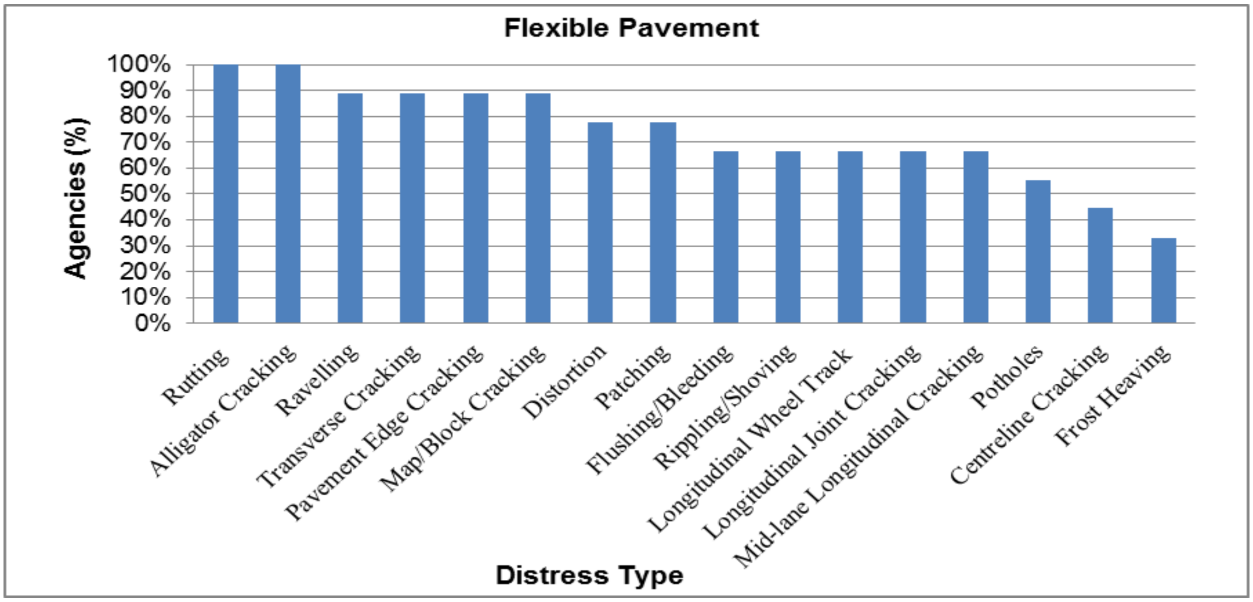

Figure 2: Percentage of Agencies Collecting Flexible Pavement distresses

As noted in Figure 2, rutting, alligator cracking, ravelling, transverse cracking, pavement edge cracking, map/block cracking, distortion, and patching are the dominant distresses that are collected by local agencies in evaluation of their road networks. Figure 2 also indicates that centreline cracking and frost heaving are the least commonly collected pavement distress for flexible pavements. In addition, the survey results indicate 67% of agencies collect the International Roughness Index (IRI) and no agencies collect structural adequacy data or friction data for their road networks.

As noted in Figure 3, the Ministry of Transportation Ontario (MTO) protocols and the American Society for Testing and Materials (ASTM) protocols are the most utilized protocols by the Canadian cities and municipalities as guidelines to collect pavement distress.

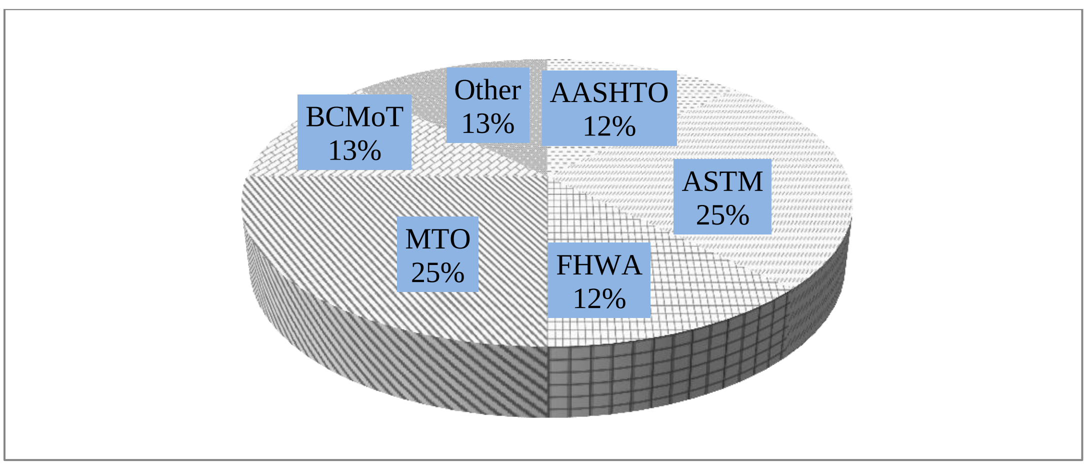

Figure 3: Percentage of Protocols Utilize by Canadian Agencies for Collecting Pavement Distress

Table 1 illustrates the number of agencies that use different severity levels and density levels to characterize each type of collected data for the flexible pavement.

Table 1: Number of agencies that Use Different Severity Levels and Density Levels for Flexible Pavement

	Severity Levels (# of agencies)		Density Levels (# of agencies)			
Data Type	**Three Severity Level**	**Five Severity Level**	**Three Density Level**	**Five Density Level**	**Quantity/Area**	**Others**
Ravelling	3	3	0	2	4	
Flushing/Bleeding	2	2	0	2	2	
Rippling/Shoving	2	2	0	2	2	
Rutting	4	2	0	2	3	% Length
Distortion	3	2	0	2	3	
Longitudinal Wheel Track Cracking	3	2	0	2	2	Length
Longitudinal Joint Cracking	3	0	0	1	2	Length
Alligator Cracking	5	2	0	2	4	AREA LINEAR SPACING AREA LINEAR
Meander and mid-lane Longitudinal Cracking	4	1	0	2	2	Length
Transverse Cracking	4	2	0	2	2	AREA LINEAR SPACING AREA LINEAR, Length
Centreline Cracking	2	1	0	2	1	
Pavement Edge Cracking	4	2	0	2	2	AREA LINEAR SPACING AREA LINEAR, %Length
Map/Block Cracking	4	2	0	2	3	AREA LINEAR SPACING AREA LINEAR
Patching	3	2	0	2	3	
Potholes	2	2	0	2	0	Count
Frost Heaving	0	0	0	0	0	
Excessive Crown	2	0	0	0	0	% length
Coarse Aggregate Loss	1	0	0	0	1	
Structural Integrity	1	0	0	0	1	
Drainage	1	0	0	0	1	

It can be concluded from Table 1 that most agencies use three severity levels and percentage of the affected area as the density levels (area of each distress over the area of inspected pavement section) to identify the pavement distress.

2.2.4 Geometric Data

The local agency should also obtain geometric data. The geometric data defines the physical characteristics and features of the pavement sections such as location, length, width, number of lanes, shoulder type and width, classification (local, collector, arterial, etc.) and, grade of the section [4]

2.2.5 Environmental Data

The environmental conditions such as maximum and minimum temperatures, freeze thaw cycles, precipitation, and drainage conditions have an important impact on the pavement deterioration rate, and the associated selection of proper rehabilitation and maintenance alternatives by local agencies. Thus, this data should also be included.

2.2.6 Cost Data

The cost of new construction, maintenance and rehabilitation should also be maintained since it is useful for the economic analysis, prioritization, and project selection process.

2.3 Evaluation of Pavement Condition

The first step in evaluating the current road network status is to quantify the overall pavement condition for each pavement section. Agencies, after identifying the pavement distress and evaluating each distress condition based on its severity levels and density levels, could calculate the overall pavement condition of each road by the three different methods. The first method is to adapt the current well developed pavement indices such as MTO index (PCI_{MTO}). The second method is to use the engineering judgement and experience. The third method, which is the emphasis of this research, is to use both the engineering judgement and the Analytical Hierarchy Process (AHP) to assign weights for each pavement performance data. AHP is a theory of relative measurements of intangible criteria [5]. AHP is based on eigenvector methods that are usually applied to establish the relative weights for different criteria [5]. The AHP determines the weights for each criterion indirectly by relative importance score between criteria [5]. The final weighting is then normalized by the maximum eigenvalue for the matrix to minimize the impact of inconsistencies in the ratios. The method is illustrated in the following steps [6].

Let C = $\{C_1, C_2, C_3, \ldots, C_n\}$ be the (n) pavement performance data identified to be assigned weights.
Let A = (a_{ij}) be a square matrix where a_{ij} presents the relative importance between pairs (C_i,C_j) as shown in the following matrix:

$$\mathbf{A}=\begin{bmatrix} a_{11} a_{12} \ldots & a_{1n} \\ a_{21} a_{22} \ldots & a_{2n} \\ a_{n1} a_{n2} \ldots & a_{nn} \end{bmatrix}$$

where:

$$a_{ij} = \frac{1}{a_{ji}}, \text{ for all } i,j = 1,2,3,\ldots n \qquad \text{(Equation 1)}$$

The term a_{ij} assumes a value of relative importance between C_i and C_j in a scale from 1-9 as shown in Table 2.
The matrix A should be filled based on the engineering judgment and experience.

Table 2: Comparison Scale [5]

Intensity of importance	Definition
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2,4,6,8	Intermediate values between adjacent scale values

Let $w = \sum \{w_1, w_2, w_3 \ldots w_n\} = 1$ be the weights for each pavement performance data. The weight can be obtained as follow:

$$W_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{(\sum_{k=1}^{n} a_{kj})} \qquad \text{for i,k = 1,2,…..n} \qquad \text{(Equation 2)}$$

The eigenvalue (λ_{max}) is obtained as follows:

The sum of the resultant vector of (A*w/w) divided by number of pavement performance data (n) where: w = Weight vector.

$$\text{The Consistency Index (C.I.)} = \frac{((\lambda_{max}) - n)}{(n-1)} \qquad \text{(Equation 3)}$$

$$\text{The Consistency Ratio (C.R.)} = \frac{C.I}{\text{Random Index (R.I)}} \qquad \text{(Equation 4)}$$

where:

Random Index (R.I.) is a constant that depends on the pavement performance data (n) as shown in Table 3 In addition, a consistency ratio less than 0.1 indicates consistent pairwise comparison.

Table 3: Random Index [5]

n = 2	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9	n = 10
R.I = 0.00	R.I = 0.59	R.I = 0.90	R.I = 1.12	R.I = 1.24	R.I = 1.32	R.I = 1.41	R.I = 1.45	R.I = 1.49

After determining weights for each pavement performance data, the overall pavement condition (OPC) is calculated by:

$$OPC = \sum_{i=1}^{n}(C1 * W1 + C2 * W2 + \cdots Cn * Wn) \qquad \text{(Equation 5)}$$

where,

OPC = Overall Pavement Condition;
C_i = Pavement performance data;
W_i = Calculated weight associated to each pavement performance data.

The next step after calculating the overall pavement condition for each section is to find the current overall road network condition by finding the percentage of different OPC categories. Table 4 is an example of OPC categories.

Table 4: Example of OPC Categories

OPC (Overall Pavement Condition) Classification	**Condition**
OPC (100-85)	Excellent
OPC (85-70)	Very Good
OPC (70-55)	Good
OPC (55-40)	Fair
OPC (40-0)	Poor

To have a better understanding of current road network condition, each class of road (local, collector, arterial, etc.) should be examined separately by dividing each road class into homogenous sections. Each road class should further divide into subsections based on the common rehabilitation/maintenance type, same range of traffic volume and ESALs, same soil type, and drainage condition for the analysis purposes.

2.4 Prediction Models for Pavement Performance Deterioration

Transportation agencies should use a deterioration model to predict the future condition of a pavement so that proper rehabilitation/preservation decisions can be made. Markovian models are the most common stochastic techniques and have been widely used due to their less need for data [7]. This research used the Markovian model to predict pavement performance deterioration for all the road classes based on the specific treatment type.

The first step for the Markov chain model involved constructing a Transition Probability Matrix (TPM) which predicts change over a period of time. TPM is a matrix of order (n x n), where n is the number of possible condition states. TPM shows the probability of going from one candidate stage to another over a period of time as shown in Figure 4. For example, there is a 35% probability of staying in condition state 2 after one year of service and a 65% probability of moving from state 2 to state 3.

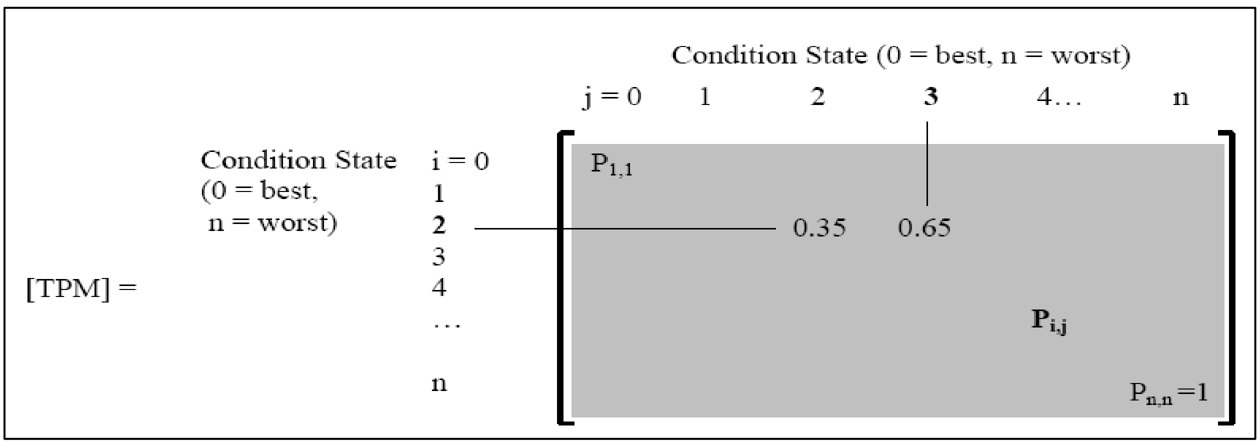

Figure 4: Transition Probability Matrix [7]

Where $P_{i,j}$ represents the probability of deterioration from state i to state j over a specific time period called the transition period t.

To estimate the future-state vector $[FP_t]$, the initial probabilty vector IP_o , the state of new asset at t = 0, is multiplied by the TPM matrix [7].

State: 0 = best, 1, 2,………n=worst
IP_o = [1, 0, 0………0] at t=0

Therefore, FP_t can be calculated as [7]:

$$[FP_t]_{1\times n} = [IP_o]_{1\times n} \cdot [TPM]^{t}_{n\times n} \qquad \text{(Equation 6)}$$

Figure 5 shows a sample transition probability matrix with state transition matrix.

Transition Probability Matrix (TPM)
From one condition to another

	10	9	8	7	6	5	4	3	2	1	0	States	
10	0.7	0.3	0	0	0	0	0	0	0	0	0	10	New
9	0	0.4	0.6	0	0	0	0	0	0	0	0	9	
8	0	0	0.5	0.5	0	0	0	0	0	0	0	8	
7	0	0	0	0.2	0.8	0	0	0	0	0	0	7	
6	0	0	0	0	0.2	0.8	0	0	0	0	0	6	
5	0	0	0	0	0	0.2	0.8	0	0	0	0	5	
4	0	0	0	0	0	0	0.1	0.9	0	0	0	4	
3	0	0	0	0	0	0	0	0.1	0.9	0	0	3	
2	0	0	0	0	0	0	0	0	0.1	0.9	0	2	
1	0	0	0	0	0	0	0	0	0	0.1	0.9	1	
0	0	0	0	0	0	0	0	0	0	0	0.1	0	Critical

State Transitions: **LIFE EXPECTANCY (YEARS)** 15

Condition State

Age	0	1	2	3	4	5	6	7	8	9	10	
0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	New
1	0.70	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.49	0.33	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
3	0.34	0.28	0.29	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4	0.24	0.21	0.31	0.16	0.07	0.00	0.00	0.00	0.00	0.00	0.00	
5	0.17	0.16	0.28	0.19	0.14	0.06	0.00	0.00	0.00	0.00	0.00	
6	0.12	0.11	0.24	0.18	0.18	0.13	0.05	0.00	0.00	0.00	0.00	
7	0.08	0.08	0.19	0.15	0.18	0.17	0.11	0.04	0.00	0.00	0.00	
8	0.06	0.06	0.14	0.12	0.16	0.18	0.15	0.10	0.04	0.00	0.00	
9	0.04	0.04	0.11	0.10	0.13	0.16	0.16	0.14	0.09	0.03	0.00	
10	0.03	0.03	0.08	0.07	0.10	0.14	0.15	0.16	0.14	0.09	0.03	
11	0.02	0.02	0.06	0.05	0.08	0.11	0.12	0.15	0.15	0.13	0.08	
12	0.01	0.01	0.04	0.04	0.06	0.08	0.10	0.13	0.15	0.15	0.13	
13	0.01	0.01	0.03	0.03	0.04	0.06	0.08	0.10	0.13	0.15	0.15	
14	0.01	0.01	0.02	0.02	0.03	0.05	0.06	0.08	0.11	0.13	0.15	
15	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.06	0.08	0.11	0.13	

Figure 5: TPM and State Transition Matrix

2.5 Economic Evaluation of Rehabilitation and Maintenance Alternatives

The economic evaluation is commonly used in the selection of maintenance and rehabilitation strategies for the pavement segments. The present worth (PW), net present worth (NPW), and the equivalent uniform annual cost (EUAC) are the common methods that are being used by agencies to properly evaluate competing alternatives [1]. The PW represents the equivalent dollars at the beginning of the analysis period [1],[8].

$$PW = C * [1 / (1 + i_{Discount})]^n \qquad \text{(Equation 7)}$$

where:

PW = Present Worth ($);

C = Future Cost ($);

$i_{Discount}$ = Discount rate (e.g. 4% = 0.04);

n = Period in years between future expenditure and present.

The NPW represents the total dollars that needed for the analysis period.

$$NPW = IC * \sum_{j=1}^{k}(M\&R_j * [1/(1 + i_{Discount})])^{nj} - SV * [1/ (1 + i_{Discount})]^{AP} \qquad \text{(Equation 8)}$$

where:

NPW = Net Present Worth ($);
IC = Initial Cost ($);
K = Number of future maintenance, preservation and rehabilitation activities;
$M\&R_j$ = Cost of j^{th} future maintenance, preservation and rehabilitation activity ($);
$i_{Discount}$ = Discount rate;
n_j = Number of years from the present of the j^{th} future maintenance, preservation or rehabilitation treatment
SV = Salvage Value ($)
AP = Number of years in analysis period

The EUAC presents the dollars needed for every year to pay for the project [1].

$$EUAC = NPW * [(i_{Discount} * (1 + i_{Discount})^{AP}) / ((1 + i_{Discount})^{AP} - 1)] \qquad \text{(Equation 9)}$$

where:

EUAC = Equivalent Uniform Annual Cost ($);
NPW = Net Present Worth ($);
$i_{Discount}$ = Discount rate;
AP = Number of years in analysis period

2.6 Priority Programing of Rehabilitation and Maintenance Alternatives

Local agencies should prioritize the road sections need and select the appropriate rehabilitation and maintenance alternatives using either the ranking method or optimization method. Road sections are prioritized in the ranking method based on the descending order of the benefit-to-cost ratio (B/C). The drawback with the ranking method is that it fails to consider alternative funding levels [9]. The other approach to prioritizing the road sections is optimization. Optimization is the most complex method of priority programming. The optimization method can give the optimal solution based on various objective functions (e.g.. maximize pavement condition, minimum budget, etc.) while considering various constraints. Since the optimization method is very complex to develop, the local agencies could use the already developed optimization software such as Evolver [10] to prioritize their road network level.

3.0 Case Study

The analysis is based on the data which are provided by the City of Markham engineering staff.

3.1 Referencing Method

The City of Markham uses a Geographic Information System (GIS) as a referencing method to represent the pavement sections. The GIS is used to generate maps for the road network in terms of pavement condition and road classification.

3.2 Data Inventory

There are five sets of data provided by the City of Markham. The first set of data is composed of the surface distress condition survey that was collected in 2008 and 2011 for the roads in the City of Markham. This data includes the road section unique ID, surface distress (patching, rutting, mapping, longitudinal cracking, alligator cracking, edge cracking, and transverse cracking) and roughness (IRI) condition for every 30m section of the road segment and the length of each segment and the total length of the segment. Sections at the end of the segments may be less than 30m. The second set of data includes the rehabilitation/maintenance history that includes, road segment ID, treatment strategy type, year of treatment and street name. The third set of data contains the AADT data that includes road segment ID, the AADT history for some of the road, the year that the AADT was collected, and the name of the road. The fourth set of data road includes the road segment ID, rehabilitation/maintenance year, road installation year, road classification, road length and width, and number of lanes. The fifth set is the ArcGIS file that only the road segment ID and the corresponded road speed limit is used.

3.3 Evaluate Current Road Network Status

To evaluate the current road network status the overall condition of each road is determined using the existing method that the City of Markham is adopted. This method is based on the engineering judgment and experience. In addition, the roads' conditions are also calculated using the MTO's condition index and the AHP method. The City of Markham uses an overall pavement performance index called the Overall Condition Index (OCI) which is a function of Surface Condition Index (SCI) and Roughness Condition Index (RCI) to evaluate the road condition.

The OCI for each section is calculated by taking the minimum value among the collected surface distress multiply by 0.8 plus the roughness for each section multiply by 0.2.

$$OCI_{Section} = (\mathrm{Min} \sum_{i=1}^{7} i) * 0.8 + RCI * 0.2 \qquad \text{(Equation 10)}$$

where:

$OCI_{Section}$ = Overall Condition Index of each section, ranging from 0 to100;

i = Surface Distress (Alligator cracking, edge cracking, transverse cracking, patching, rutting, longitudinal cracking, and mapping);

RCI = Roughness Condition Index.

The Overall Condition Index (OCI) of each road is calculated as follow:

$$OCI = \sum_{i=1}^{n} (OCI\ i * Length\ i) \ / \ \sum_{i=1}^{n} Length\ i \qquad \text{(Equation 11)}$$

Where:

i	=	Number of road segment with the same Unit ID1 and Unit ID2;
OCI	=	Overall Condition Index for each road segment, ranging from 0 to100;
Length	=	Inspected length for each road segment.

The OCI for the roads, as it is mentioned earlier, is also calculated based on the AHP method. Table 5 represents the AHP table that was provided to the City of Markham for incorporating their engineering judgment and experience in the AHP method. This is necessary to identify the relative importance factor of each of the collected pavement performance data as compared to the other factors. The response from the various City of Markham engineering staff is shown in Table 6. This is then used to determine weights for each pavement performance data.

Table 5: AHP Table Provided to the City of Markham

	Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting
Edge Cracking	1.00							
Transverse Cracking		1.00						
Longitudinal Cracking			1.00					
Alligator Cracking				1.00				
Map Cracking					1.00			
Patching						1.00		
Roughness							1.00	
Rutting								1.00

Table 6: Response from the City of Markham

	Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting
Edge Cracking	1.00	0.20	0.20	0.14	0.14	3.00	0.33	0.20
Transverse Cracking	5.00	1.00	1.00	0.33	0.33	3.00	1.00	1.00
Longitudinal Cracking	5.00	1.00	1.00	0.33	0.33	3.00	1.00	1.00
Alligator Cracking	7.00	3.03	3.03	1.00	1.00	5.00	3.00	3.00
Map Cracking	7.00	3.03	3.03	1.00	1.00	5.00	3.00	3.00
Patching	0.33	0.33	3.00	0.20	0.20	1.00	0.33	0.33
Roughness	3.03	1.00	1.00	0.33	0.33	3.03	1.00	1.00
Rutting	5.00	1.00	1.00	0.33	3.03	3.03	1.00	1.00

Table 7 shows the calculations that are required for evaluating the pavement performance weights and verifying the consistency in the data pair-wise comparison.

Table 7: AHP Process to Calculate Weights for All the Pavement Performance Data

	A	B	C	D	E	F	G	H	I	J	K	L
1		Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting	Sum	Calcuted Weights	CI
2	Edge Cracking	1.00	0.20	0.20	0.14	0.14	3.00	0.33	0.20	5.21	0.05	7.94
3	Transverse Cracking	5.00	1.00	1.00	0.33	0.33	3.00	1.00	1.00	12.66	0.11	8.84
4	Longitudinal Cracking	5.00	1.00	1.00	0.33	0.33	3.00	1.00	1.00	12.66	0.11	8.84
5	Alligator Cracking	7.00	3.03	3.03	1.00	1.00	5.00	3.00	3.00	26.06	0.23	10.45
6	Map Cracking	7.00	3.03	3.03	1.00	1.00	5.00	3.00	3.00	26.06	0.23	10.45
7	Patching	0.33	0.33	3.00	0.20	0.20	1.00	0.33	0.33	5.73	0.05	12.00
8	Roughness	3.03	1.00	1.00	0.33	0.33	3.03	1.00	1.00	10.73	0.09	9.50
9	Rutting	5.00	1.00	1.00	0.33	3.03	3.03	1.00	1.00	15.39	0.13	11.86
10									Total	114.50	Sum	79.87
12											C.I	0.28
13											R.I	1.41
14											C.R	0.20

= Sum (B2:I2)

= (J2/$J$10)

=MMULT (B4:I4,$K$2:$K$9)/K4

= Sum (J2:J9)

=Sum (L2:L9)

The Consistency Index (C.I.) is calculated based on Equation 3. Since there are 8 pavement performance data the C.I = ((Sum (C.I) /8) – 8) / (8 – 1) = (79.87/8 – 8) / 7 = 0.28.The Random Index (R.I) based on Table 3 is 1.41. The Consistency Ratio (C.R) based on Equation 4 is calculated to be 0.2. Table 8 shows the weighting factors that are obtained for each pavement performance data using the AHP method.

Table 8: Weighting Factors for Pavement Performance Data Using AHP Method

Edge Cracking	5%
Transverse Cracking	11%
Longitudinal Cracking	11%
Alligator Cracking	23%
Map Cracking	23%
Patching	5%
Roughness	9%
Rutting	13%

In addition to the AHP method and the City of Markham existing method, the MTO's pavement condition index was used as a third method to calculate the OCI for the road network. Based on Table 9, it can be concluded that the results from the AHP method is very close to the City of Markham method.

Table 9: Comparing Different Methods

Methods	Mean	Variance	Standard Deviation
City of Markham	83.1	93.2	9.6
AHP	83.1	88.9	9.4
MTO	79.1	88.4	9.4

3.3.1 Current Pavement Condition for Each Road Classification

After calculating the OCI for each road, the next step involved dividing the roads into homogenous sections based on the road classification, treatment type, and AADT. After analyzing all the available data, a total of 643 road segments were utilized to analyze the network. The 643 road segments are classified according to the road classification and treatment type as summarized in Table 10.

Table 10: Distribution of Road Classification and Treatment Type

	Treatment Type						
Road Classification	**Shave and Pave**	**Expanded Asphalt**	**Cold in Place Recycling**	**Micro-surfacing**	**Chip Seal**	**Fog Seal**	**Total**
Laneway					17		17
Local	197	90	4	13	2	21	327
Collector	49	56		19			124
Minor Arterial	20	49	14	39			122
Major Arterial	6	16		31			53
Total	272	211	18	102	19	21	643

In the case of available AADT information, roads were further classified based on the AADT. Figures 5 shows the OCI plotted against the age of the pavement with the specific AADT range for the local road classification corresponding to the shave and pave treatment.

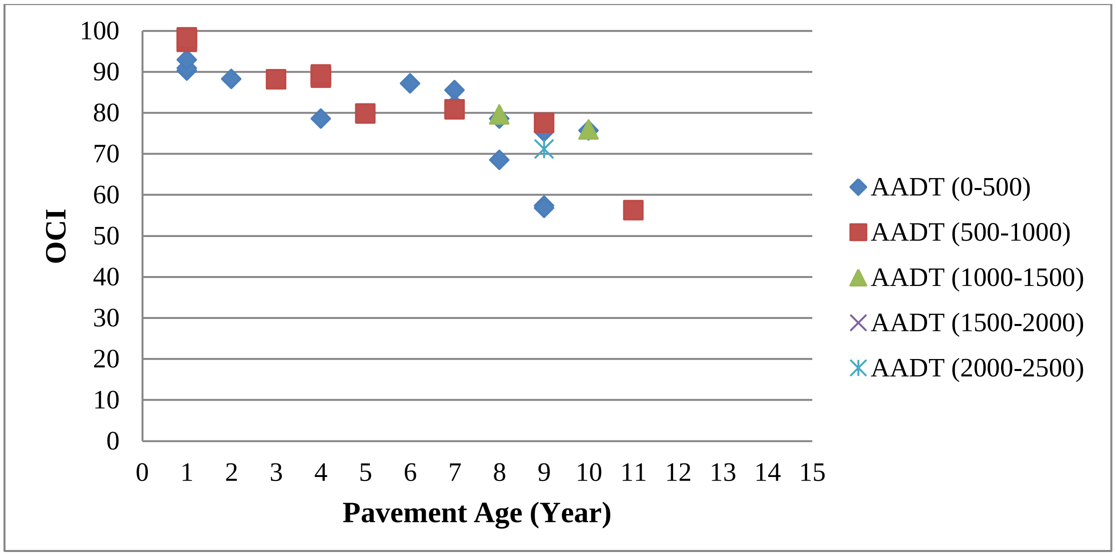

Figure 0: Local Roads with Shave and Pave Treatment for Different AADT

3.4 Prediction Model for Pavement Performance Deterioration

After calculating the OCI for each road section the Markov model is used to predict the pavement performance deterioration for various road classifications corresponding to each treatment strategy for the road network. The performance models were developed for a 20 year period and considered an OCI of 50 as the minimum accepted service life for the roads. Figure 6 illustrates the pavement performance prediction models using the Markov chain methods for the three different methods for the local roads with the microsurfacing treatment. The pavement performance prediction models are drawn up to the minimum acceptable service life which is 50.

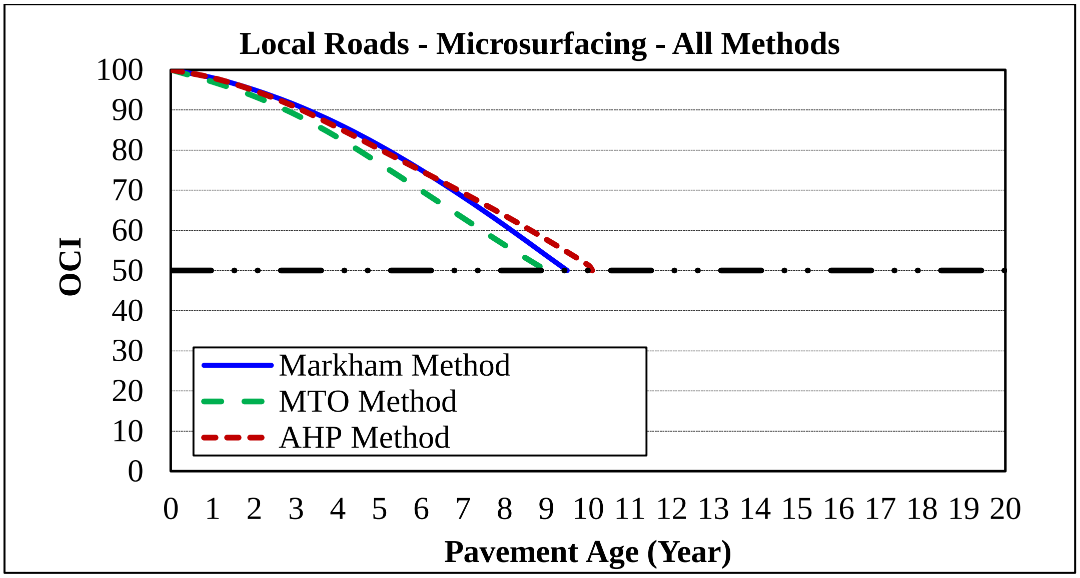

Figure 6: Pavement Performance Prediction Model for Local Roads with the Microsurfacing Treatment

3.5 Economic Evaluation of Rehabilitation and Maintenance Alternatives

The present worth (PW) was used for the case study to evaluate the cost for each rehabilitation and maintenance alternative. To use the PW formula, the analysis period was considered to be five years with the discount rate of 4% (0.04). The future cost (C) for each treatment type was calculated by multiplying the length and width of each road by the unit costs of selected alternative.

3.6 Priority Programing of Rehabilitation and Maintenance Alternatives

The City of Markham's main objective for selecting road and treatment type is to maintain the OCI of 50 or higher for each road within the five year period. The ranking method and optimization method were used for this case study to prioritize the road sections need. The budget limit for each year for the next five years was considered to be $5,100,000 / year.

3.6.1 Do Nothing Option

The do nothing option is carried out as part of this analysis to evaluate the condition of the road network over the next five years if there is no treatment. To determine the condition of each road over the next five years, the equation obtained from each Markov model was used.

3.6.2 Simple Ranking Method

The simple ranking method was the first method used to prioritize the road sections needs and used to select the appropriate rehabilitation and maintenance alternatives for this case study. The road network was ranked based on the Benefit Cost ratio (B/C) where benefit is the sum of the average condition of each road for the next five years after applying any treatment and the cost is the PW value of each treatment in the first year. A budget limit of $5.1 million per year within a five year period was enforced. The road network was then ranked based on the descending order of the B/C ratio.

3.6.3 Optimization Method

The Evolver software (Evolver 2012) is employed for optimization purposes. Table 11 shows the two objective functions and the constraints which were used for the optimization method.

Table 11: Objective Functions and Constraints for Optimization Method

Objective Functions	Constraints
Minimize the total cost within a five year period	Minimum acceptable level of an OCI=50 for each section of the road network within a five year period
Maximize the average road network condition within a five year period	Budget limit of $5.1 million per year within a five year period

3.6.3.1 Results Comparison from Priority program

Tables 12 and 13 show the cost and condition obtained using the simple ranking method and optimization method for the road network within a five year period, respectively.

Table 12: Road Network Cost Comparison for all Options

Scenario	Year 2012	Year 2013	Year 2014	Year 2015	Year 2016	Total Cost
Maximize Average Condition	$5,096,338.46	$5,098,631.32	$5,098,317.10	$5,045,781.13	$5,079,865.31	**$25,418,933.32**
Minimize Total Cost	$10,205,389.49	$6,680,036.52	$5,575,354.35	$3,194,177.59	$5,267,622.47	**$30,922,580.42**
Simple Ranking	$5,059,888.58	$5,077,115.38	$5,013,868.34	$5,027,725.74	$5,064,846.34	**$25,243,444.39**

Table 13: Road Network Condition Comparison for all Options

Scenario	Year 2012	Year 2013	Year 2014	Year 2015	Year 2016	Average Condition
Maximize Average Condition	84	83	82	81	83	**83**
Minimize Total Cost	87	87	88	87	88	**88**
Simple Ranking	84	84	84	85	85	**84**

Based on the results from Tables 12 and 13, even though the minimum cost scenario provided the best average road network condition within a five year period, it does not satisfy the budget limit and it is over by 30,922,580.42 – (5*5,100,000) = $5,422,580.42. Thus, the minimize total cost scenario should be eliminated for further analysis. Figure 7 shows the percentage of sections of the road network that are below the minimum acceptable level (OCI = 50) within a period of five years. Based on the results from Figure 7, it can be concluded that maximizing the average condition scenario provides a lower percentage of sections with the OCI below 50.

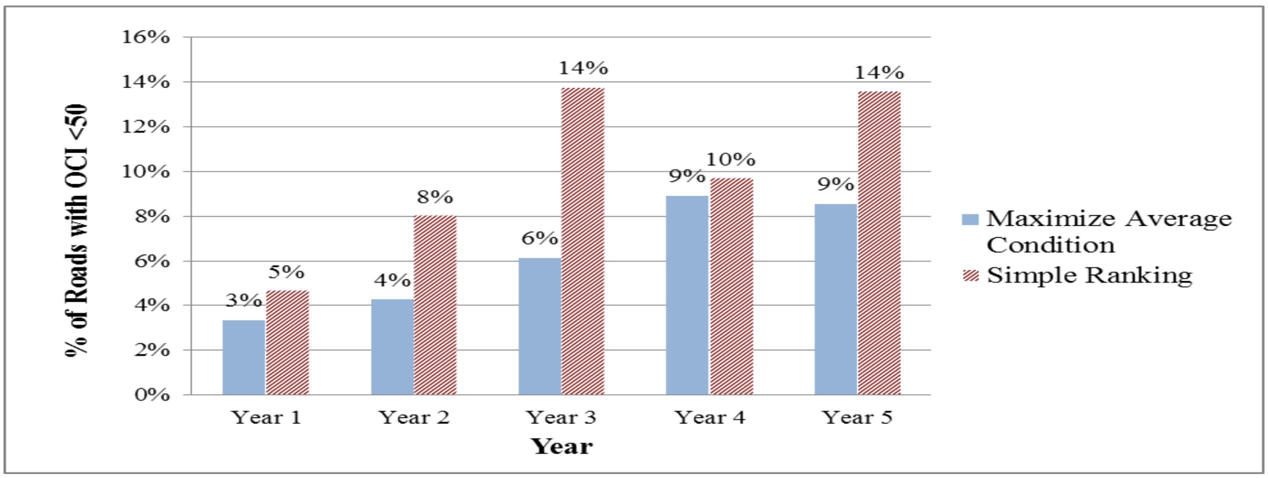

Figure 7: Percentage of Roads with OCI < 50 Using Simple Ranking and Evolver

Therefore, it can be concluded that the optimization method provides the ability to produce better results than the simple ranking method.

Conclusions

The City of Markham's overall road network condition was calculated based on the three methods, engineering judgement and experience, a combination of AHP method and engineering judgement and experience, and the existing well developed pavement indices. After calculating the OCI, roads were divided into homogenous sections based on the road classification, treatment type, and AADT for analysis. Markov modeling was used to develop a prediction model for the pavement performance deterioration. The PW value was used for the economic evaluation and the discount rate was considered to be 4%. The simple ranking and Evolver software were used for the prioritization purpose. After comparing the results from the simple ranking and the optimization method, it can be concluded that the optimization method provides the ability to produce better results than the simple ranking method. The overall results from the case study indicated that the steps and requirements which are explained in the research methodology are appropriate for implementation in a local agency.

Future Work

Further studies are required to be conducted to explain how local agencies should consider, identify, and incorporate the distresses associated particularly to the utility cuts such as manholes, catchbasins, and valve boxes, curb and gutter, and rail road crossing on the pavement while collecting performance data.
Further studies need to be done to compare different optimization software in terms of advantages and disadvantages, pricing, and the inputs required from a local agency to be able to adapt the software.

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