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## **ADAPTING PAVEMENT MANAGEMENT TO ON-STREET BICYCLE NETWORKS: CASE STUDY OF PLATEAU-MONT-ROYAL, MONTRÉAL**

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**Abstract:** There are needs maintain on-street bicycle networks on optimal condition and to upgrade certain corridors to higher degrees of protection. This paper develops the foundation of such system for a case study of the Plateau-Mont-Royal borough in Montréal, QC. The case study borrows concepts of pavement management systems: historical data of pavement condition, at low-volume roads, and for the years 2010 and 2015, was used to construct deterioration curves for the bicycle network. The year 2017 was set as baseline and pavement's surface condition data collected using a mobile-phone application, for roads shared between bicycles and automobiles. A long-term plan was developed using a linear programming optimization approach over a span of 40 years. It was found that the optimal strategy allocates resources for the reconstruction of roads and on-street bikeways for the first 13 years, and recommends preventive maintenance thereafter. Future research will investigate the improvement of the degree of protection of on-street bicycle lanes.

### **1 INTRODUCTION**

#### **1.1 Bicycling as a Sustainable Mode of Transportation in Cities**

Health benefits of bicycling are significantly greater than its associated risks, by comparison with automobiles (de Hartog, Boogaard, Nijland, and Hoek, 2010). The society as a whole can experience even more benefits due to expected lower levels of air pollution and traffic accidents (de Hartog, Boogaard, Nijland, and Hoek, 2010). A growing body of research supports the advantages of active transportation (bicycling and walking) on individual health; reducing obesity rates, preventing cardiovascular diseases, and reducing Type 2 Diabetes (Shephard 2008; Rasmussen et al. 2016; Hamer and Chida 2008; Bassett et al. 2008; Huy et al. 2008). Bicycling also helps reduce traffic congestion (Transport 2004; OECD/International Transport Forum 2013).

For these reasons, many government agencies and municipalities around the world have started the implementation of long-term plans to encourage bicycling among individuals. This could be achieved by adopting a wide range of infrastructure, program and policy interventions to promote bicycling in cities. The infrastructure related interventions include; on-street bicycle lanes, off-street bicycle paths, shared bus/bicycle lanes, signed bicycle routes, colored lanes, bicycle boulevards, bicycle boxes (advanced stop lines), bicycle-phases traffic signals, improving quality of pavement, traffic calming zones, car-free zones and bicycle parking (Pucher, Dill, and Handy, 2010). Several studies found a positive relationship between bicycle lanes and bicycling levels (Pucher, Dill, and Handy 2010). A positive and significant correlation was also found for levels of bicycle infrastructure and commuting using bicycles (Dill and Carr, 2003; Nelson and Allen, 1997).

## 1.2 Pavement Management Systems

Pavement Management System (PMS) is an approach that incorporates the economic assessment of trade-offs between competing alternatives (Haas and Hudson, 1978; Hudson, Uddin, and Haas, 1997). PMS operates at two levels; project level (i.e. specific road) and network level. At both levels, field data collection is necessary to evaluate pavement performance to strengthen the decision-making process of appropriate maintenance, preservation and rehabilitation treatments, and priority planning and programming. Pavement performance is evaluated based on several measures: surface and structural. Pavement performance models are generally classified into two categories: deterministic and stochastic (Amador-Jiménez and Mrawira, 2009; George et al., 1989; Prozzi and Madanat, 2003). One of challenges in formulating these models is the lack of time-series data. (Amador-Jiménez and Mrawira, 2009) proposed an approach by which a pavement performance model can be formulated using as little as two time-series points.

## 1.3 Measuring IRI Using Smartphones

One of the surface condition measures used in PMS is the IRI. The IRI was originally developed by World Bank to produce an objective indicator for road roughness that was time-stable, transportable, and reliable to values collected by practitioners regardless of their location (Sayers, Gillespie, and Queiroz, 1986). The roughness of a pavement is defined as the variations in the longitudinal surface profile that cause vibrations in traversing vehicles at a specific point of time (Sayers, Gillespie, and Queiroz 1986). The IRI summarizes the longitudinal surface profile in the wheel path and is computed from surface elevation data collected by either a topographic survey or a mechanical profilometer. IRI is typically expressed in vertical distance per horizontal distance of travel (mm/m, m/km, in/mi).

During last decade, researchers have been working on exploring the applicability of sensing capabilities of the smartphone to collect data on an objective performance measures for pavement surface (Aksamit and Szmechta, 2011; Byrne, Parry, Isola, and Dawson, 2013; Mednis, Strazdins, Zviedris, Kanonirs, and Selavo, 2011; Perttunen *et al.*, 2011; Strutu, Stamatescu, and Popescu, 2013). In particular the potential of using the output of smartphone sensors in determining IRI for pavement was studied (Douangphachanh and Oneyama, 2013, 2014; Du, Liu, Wu, and Jiang, 2014; Hanson *et al.*, 2014; Islam, Buttlar, Aldunate, and Vavrik, 2014). IRI has become an international standard for road roughness since its beginning (Tighe 2013; Hanson, Cameron, and Hildebrand 2014). In Canada, IRI was the most widely used pavement performance index by provincial, federal, and territorial agencies in Canada, with 85% of the 14 agencies surveyed reported using it (Tighe 2013).

## 2 Objective

The main objective of this paper is to develop a PMS for an on-street bicycle network in an urban context. The bike network of *Plateau-Mont-Royal* was used to assess the condition and available implementation of interventions, with goals to developing investment plans. The paper also discusses the advantages of adopting PMS to bicycle lanes as well as the limitation and drawbacks of low-cost data collection approaches. Finally, the study concludes with the potential future work in this research area.

## 3 Methodology

The size of bicycle network in the City of Montréal is approximately 748 km, of which 214 km and 181 km are on-street bicycle lanes, and roads shared by cars and bicycles, respectively (Vélo Québec 2015). The City of Montréal is ranked 2nd across Canada after Calgary's network, 1032 km (Vélo Québec 2015). Plateau-Mont-Royal region itself has 46.3km of bicycle lanes, of which 40.6km are on shared roads which makes it the densest borough for bicycle lanes in the City of Montréal (Vélo Québec 2015). Furthermore, Plateau-Mont-Royal has the highest bicycle mode share (percentage of trips made by travelers using a particular type of transportation); 10.8% versus 2.5% across the Island of Montréal (Vélo Québec 2015). For these reasons, Plateau-Mont-Royal was selected as a case study in this paper. The following steps were followed to accomplish the main objective: first, to create pavement deterioration curves for based on data collected in 2010 and 2015 for the road network in Montréal. Second, to collect pavement roughness

condition data for the Plateau-Mont Royal borough for 2017. Third, to prepare a decision support model based on an optimization framework to forecast budget allocation for different interventions over a period of 40 years. Figure 1 illustrated these steps as well as the required data.

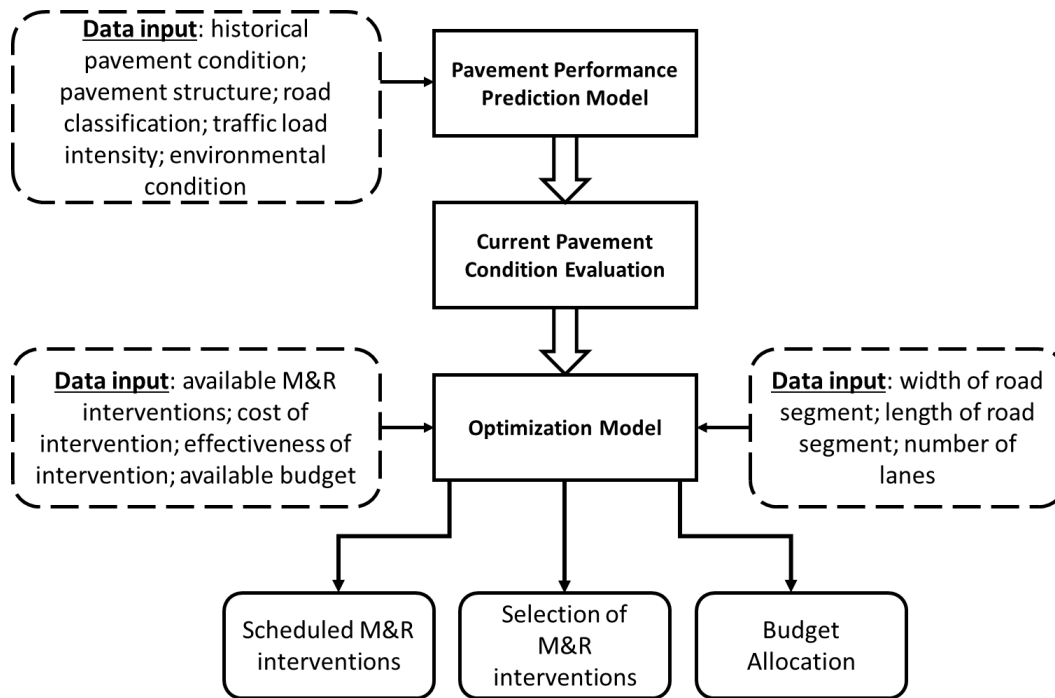


Figure 1: The proposed methodology for decision-making support model.

### 3.1 Pavement Deterioration curves

The pavement deterioration curves were developed based on a dataset that contains road surface condition in terms of IRI for two years, 2010 and 2015. This dataset is provided by City of *Montréal*. Deterioration curves were developed for road segments with low volume of vehicles, since on-street bicycle lanes are impacted by minimal loads. It is expected that the environmental freeze-thaw cycle is the dominating criterion in the deterioration process of bicycle lanes where the environment is expected to be the main factor. Low-traffic-volume was set for Equivalent Single Axle Load (ESAL) values below 3,739,185; the 33<sup>rd</sup> percentile threshold within the whole island.

Road segments were categorized into four homogeneous groups of similar characteristics those have an effect on the performance model such as pavement structure, as-built quality, environmental exposure, traffic loading, and maintenance practice. This step is helpful in developing performance models for network-level long-term planning (Amador-Jiménez and Mrawira, 2009; Butt, Shahin, Feighan, and Carpenter, 1987; Pedigo, Hudson, and Roberts, 1981). This resulted in four homogeneous groups: arterial roads made of flexible pavement, local roads made of flexible pavement, arterial roads made of rigid pavement, and local roads made of rigid pavement, all of them have low traffic volumes. Table 1 presents a summary of the groups along with average IRI and ESALs values for each group.

The performance curves for these homogeneous groups were developed using the approach proposed by (Amador-Jiménez and Mrawira, 2009); by which a pavement performance model can be formulated using as little as two time-series data for a large cross-sectional sample (whole network of roads) on condition and traffic data. Figure 2 shows the developed deterioration curves for homogeneous groups. As noticed in Figure 2, the four homogeneous groups have similar behaviour in terms of deterioration, thus, an overall performance curve was considered for all groups with a best-fitted linear equation.

Table 1 Summary of database, low-traffic-volume roads

Pavement Type	Flexible Pavement		Rigid Pavement	
Road Classification	Arterial	Local	Arterial	Local
Average ESALs	2,078,553	1,983,417	1,986,362	2,457,579
Average IRI 2010	3.66	4.33	3.92	4.84
Average IRI 2015	4.72	5.37	4.98	5.87
Number of segments	541	2066	1933	1045

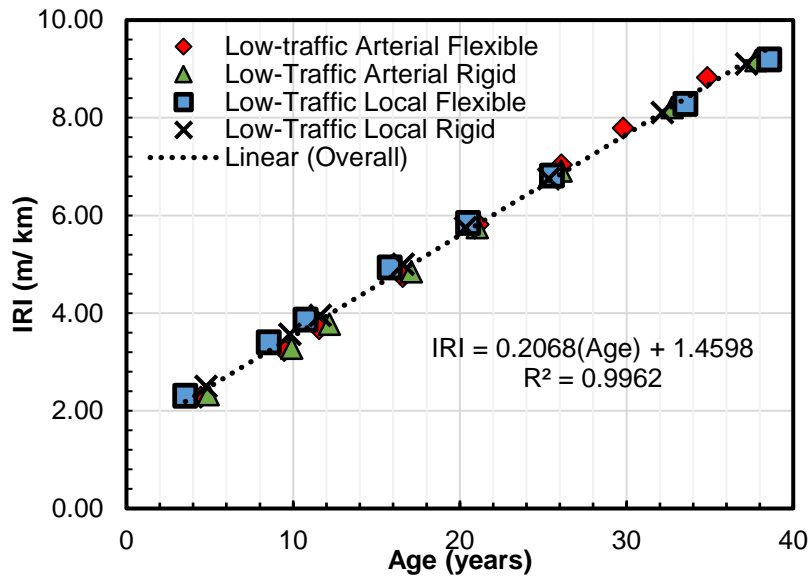


Figure 2: Deterioration curves developed for homogeneous groups

### 3.2 Estimating Roughness Index (RI)

Data was collected using the Android-based application, *ANDROSENSOR* (<https://play.google.com/store/apps/details?id=com.fivasim.androsensorandhl=en>), using two separate smartphones on January 21<sup>st</sup> 2017 and January 28<sup>th</sup>, 2017, between 10:00AM-3:00PM in order to validate observed values. Values of acceleration and speed were logged every 0.25 seconds. The type of smartphone might have an impact on the data collection process. However, this does not significantly affect the data collected for long-term planning purposes at a network-level scale. For instance, the highest percent of difference between the estimated IRI values using smartphones and those measured by Class 1 profiler was 5.4% (Hanson, Cameron, and Hildebrand 2014). In the second session, data collection was done every 0.02 seconds, which represented 50 data points collected per second. Both of these data collection files are presented in Figure 3. For both surveys, data was collected using the same automobile and the same driver to minimize the effect of the damping system in the vehicle, and to some extent, the driver’s behaviour. The smartphones were left to rest on the floor of the vehicle in two different locations. The latter was assumed not to cause discrepancies in the data since it was concluded that smartphone applications, the type of the device, and the location of the smartphone inside the vehicle have insignificant impact on the observed vertical accelerations (Al-Dabbagh 2014). Variability in the speed of the vehicle is a factor that could affect data collected, because the car reacts differently at high speeds versus low speeds and the driver generally drives at a speed suitable to the road surface condition (the driver will slow down to avoid violent movements which cause discomfort and vehicle damage on the poor-condition road). Thus,

data collection initiated well before the initial and final locations of each road segment to remove the effect of acceleration and deceleration. In addition observed vertical accelerations were normalized by speed (1/s) and speed was kept constant as previously suggested (Al-Dabbagh 2014). Extreme values caused by the presence of speed bumps were eliminated from the data collected.

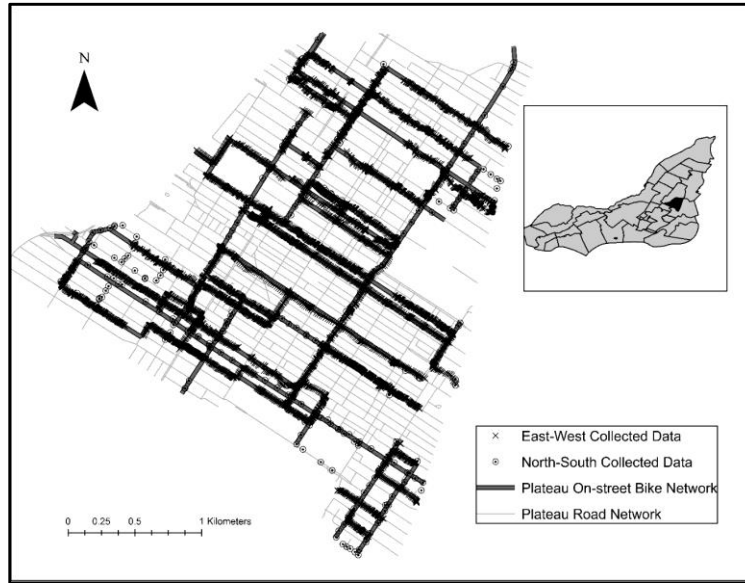


Figure 3: Collected data in the Plateau-Mont-Royal

Several studies have verified that Z-axis acceleration obtained from smartphones can be used as an effective and reliable signal estimation of road surface condition (Amador-Jimenez and Matout, 2014; Hanson, Cameron, and Hildebrand, 2014; Li and Goldberg, 2018). Based on the recorded data by *ANDROSENSOR*, Root Mean Square (RMS) was used to capture variation on cyclical responses of sinusoidal form. The following equations were generated based on (Al-Dabbagh, 2014, Amador-Jiménez and Matout, 2014; Li and Goldberg, 2018), and were used to estimate Roughness Index (RI):

Standard deviation of the vertical component of acceleration ( $\sigma_z$ ):

$$[1] \sigma_z = \sqrt{\frac{1}{N} \sum_{i=1}^N (a_{zi} - \bar{a}_z)^2}$$

Speed-normalized standard deviation of the vertical component of acceleration:

$$[2] \frac{\sigma_z}{v_{yi}} = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (a_{zi} - \bar{a}_z)^2}}{v_{yi}}$$

Roughness Index:

$$[3] RI = \frac{\sigma_z}{v_{yi}} \times 100$$

where  $a_{z_i}$  is the vertical component of acceleration,  $\bar{a}_z$  is the mean,  $N$  is the total number of recorded values,  $v_{y_i}$  is the vehicle's speed.

### 3.3 Optimal Allocation of Budget

Dynamic integer linear programming (ILP) was applied to achieve the optimal pavement roughness condition (Amin and Amador-Jiménez, 2015). The identification of the sequence of interventions through time is further detailed by Equation 6. This identification relies on a time transfer function that connects all periods of time. A typical application of the optimization process seeks maximizing the aggregated network pavement condition subject to a given budget per a planning period ( $B_t$ ). The mathematical formulation to minimize the network-level  $RI$  index is synthesized by the following equations:

Minimize:

$$[4] Z = \sum_{t=1}^T \sum_{i=1}^a L_i RI_{it}$$

Subject to:

$$[5] \sum_{t=1}^T \sum_{i=1}^a \sum_{j=1}^k C_{ij} x_{ijt} L_i \leq B_t$$

$$[6] IRI_{ijt} = x_{ijt} (IRI_{(t-1)ij} - E_{ij}) + (1 - x_{ijt}) (IRI_{(t-1)ij} - D_{it})$$

$$x_{ijt} \in [0, 1]$$

where  $x_{ijt}$  is 1 if treatment  $j$  is applied on road segment  $i$  at year  $t$ , zero otherwise;  $RI_{it}$  is condition Index for road segment  $i$  at year  $t$ ;  $RI_{ijt}$  is condition index of road segment  $i$  at year  $t$  for intervention  $j$ ;  $RI_{(t-1)ij}$  is condition Index of road segment  $i$  at year  $(t-1)$  for intervention  $j$ ;  $C_{ij}$  is cost (\$) of intervention  $j$  at year  $t$ ;  $L_i$  is length of road (km) for road segment  $i$ ;  $E_{ij}$  is improvement in terms of  $RI$  reduction on road segment  $i$  from intervention  $j$ ;  $D_{it}$  is deterioration on road segment  $i$  at time  $t$ ;  $B_t$  is the budget at year  $t$ .

Table 2 presents the operational window of each treatment, lower and upper ranges for each applicable treatment along with the service life extension, values were provided by practitioners and local engineers in *Montréal*. This study qualitatively grouped pavement condition in terms of  $RI$  into three groups: good ( $RI \leq 2.49$ ), fair ( $2.5 < RI \leq 3.54$ ), and poor ( $RI > 3.54$ ).

Table 2: Service life, cost and operational window for each treatment

Treatment	Treatment service life (Years)	Treatment cost (US\$/m <sup>2</sup> )	Operational Window
Micro-surfacing	4	6.74	$RI \leq 2.49$
Mill and Overlay	8	25	$RI \leq 3.53$
Reconstruction	Brand New	42	$RI > 3.54$

The above optimization problem was solved over a 40-year period of time using a Commercial package: *Remsoft® Spatial Planning System 4.0*. The solution was expressed in terms of the application of the most cost-effective intervention at the most suitable period of time to each road segment within the inventory.

## 4 Results

The optimization algorithm identifies the optimal set of pavement treatments for the network in the study area during the analysis period within a complex structure with time dependencies that link the consequences of decisions through time. The aggregate condition of bicycle lanes in terms of RI was minimized given an annual budget of \$200,200 over a 40 year-period.

The pavement surface condition of bicycle lanes in the network was maximized with an annual budget of \$200,000 over a 40 year-period. The average RI obtained for each year due to treatment actions is illustrated in Figure 4. The RI value decreased over the first 15 years until reaching a minimum value representing a very good average surface condition for the bicycle network. Figure 5 shows the distribution of expenditure per year for each pavement treatment. During the first 11 years, reconstruction is the dominant choice, however, for the remaining 29 years, mill and overlay and micro-surfacing are the appropriate solutions to sustain the good condition on the bicycle network (Figure 5). Figure 6 illustrates the percentage of road segments according to their surface condition. The percentage of segments with poor surface condition is decreasing over the first 11 years. After 13<sup>th</sup> year, all segments in the network become at good condition; this phase can be described as stable and sustainable.

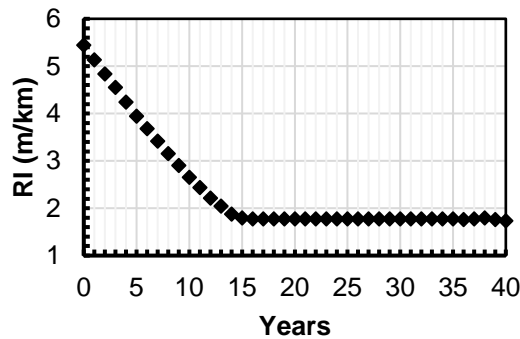


Figure 4: Network-level average RI of on-street bicycle lanes

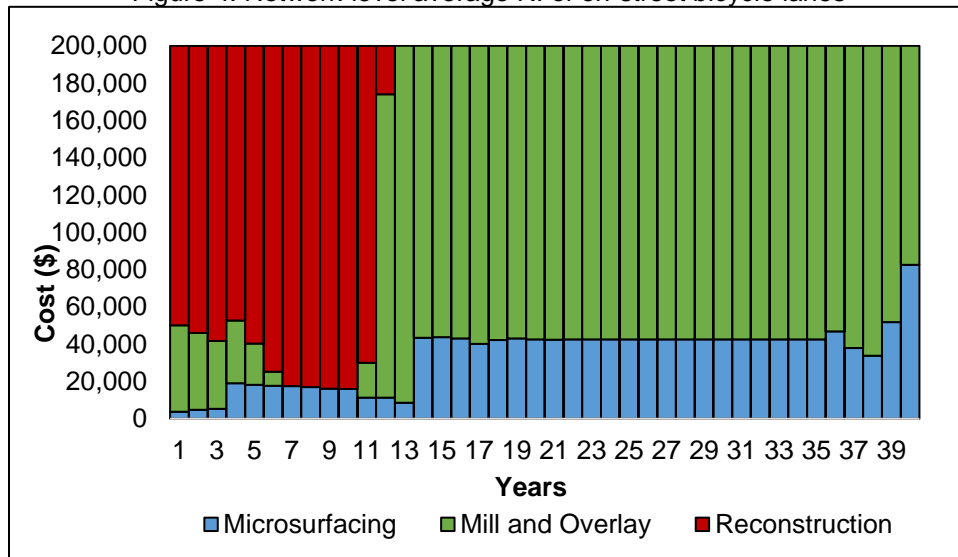


Figure 5: Expenditure according to applied treatment actions

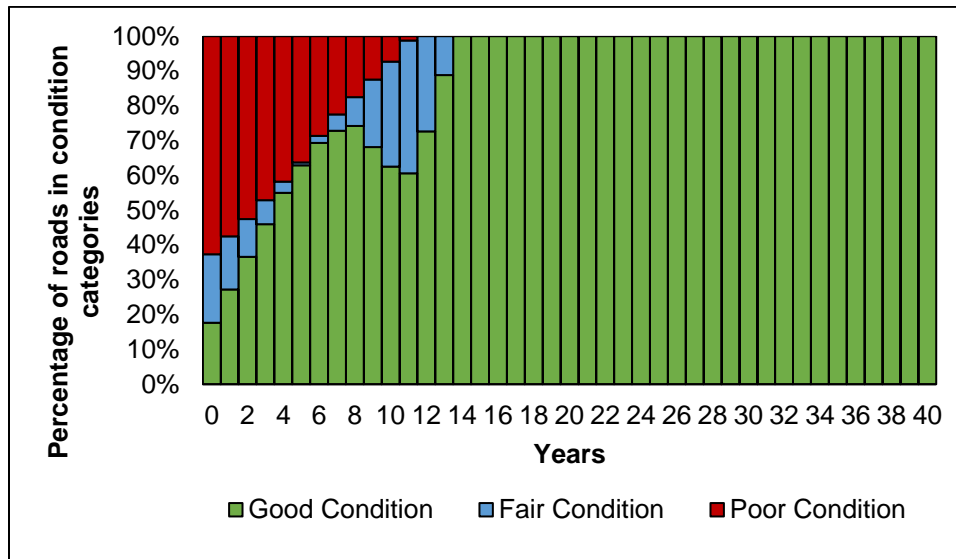


Figure 6: Surface condition of on-street bicycle lanes

## 5 Conclusion

Pavement management systems can be applied to bicycle lanes given the set of tools that allows keeping the pavement at a predetermined level of service while applying certain budget limitations. This case study adopted the concepts of pavement management systems. Historical data of pavement condition (IRI) for low-volume roads in Montréal was used to develop deterioration curves transferable to bicycle networks along with a dataset of current surface condition that were collected using a smartphone. This resulted in developing an optimal long-term plan over a span of 40 years. This allows selecting the most cost-effective treatment alternative among several Maintenance and Repair actions and contributes in establishing long-term strategies, and maximizes the operational efficiency. The results of this study show that an annual budget of around \$200,000 is appropriate to improve the surface condition of on-street bicycle lanes in the study area up to a good level and then to sustain that level of the segments in the network. This annual amount is allocated for 43.89 km of bike lanes. As a quick approximation, it costs \$4557 per km, which sums up to \$3.41 million as an annual operating budget to cover the whole bicycle network in Montreal. This amount represents 2.47% of the annual operating budget for road repairs allocated by the City of Montreal allocated in 2016 (City of Montreal, 2016). This procedure, that adopts the principles of PMS can be a powerful tool that helps practitioners, planners, policy makers and government agencies to set the optimal annual operating budget to achieve their strategic objectives.

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