Influence of pavement maintenance strategy on road traffic social and environmental impacts and associated costs

Luc Pellecuer, Eng., Ph.D.
École de technologie supérieure, Montréal

Paper prepared for presentation
at the Sustainability and Climate Change Considerations in Pavements Session

of the 2016 Conference of the
Transportation Association of Canada
Toronto, ON

The author gratefully acknowledges the MTQ (ministère des transports du Québec) for providing the data used in this study. This study was supported by a fellowship from the FRQNT (Fonds de recherche du Québec – Nature et technologies).

Influence of pavement maintenance strategy on road traffic social and environmental impacts and associated costs

Abstract

To achieve sustainable road networks, long-term social and environmental costs and benefits related to traffic emissions should be recognized and considered in the decision-making process of pavement management units. PEIM, a new tool designed to monetize and incorporate social and environmental impacts in decision-making processes, was used to assess the life cycle social and environmental benefit, related to traffic emissions (noise, air pollutants, and greenhouse gases), that is provided by pavement management. A case study regarding a 1 km long section of an urban collector road located in Montreal is presented in this paper. The results show that pavement surface maintenance provided an estimated social and environmental benefit ranging from $700 000 to $18 100 000 over a 40 year analysis period, depending on the maintenance treatment applied and the discount rate. Despite uncertainties, the results unambiguously show that this benefit was the same order of magnitude as the maintenance costs. As such, this benefit deserves to be incorporated in the life cycle assessment of pavement maintenance strategies. Whatever the maintenance strategy, most of the social and environmental benefit was associated with noise, while those associated with greenhouse gases were minimal. Preventive maintenance was found clearly more sustainable than corrective maintenance. The study also points out the necessity to take into account the influence of the discounting method when assessing the social and environmental benefit.

Keys-words: pavement maintenance, road traffic emissions, life cycle cost analysis, social impacts, environmental impacts.

Résumé

Afin de développer de façon durable les réseaux routiers, les unités de gestion des chaussées devraient incorporer dans leur processus de prise de décision les coûts et bénéfices sociaux et environnementaux encourus sur le long terme qui sont liés aux émissions routières. PEIM, un nouvel outil destiné à monétiser les impacts sociaux et environnementaux afin de les incorporer dans les processus de prise de décision, est utilisé dans le but d'estimer, sur le cycle de vie de la chaussée, les bénéfices liés aux émissions routières (bruit, pollution atmosphérique, et gaz à effet de serre) qu'offre la gestion des chaussées. Les résultats d'une étude de cas réalisée sur un tronçon d'un kilomètre d'une collectrice en milieu urbain, à Montréal, montrent que l'entretien de la surface de roulement induit, sur 40 ans, des bénéfices sociaux et environnementaux d'un montant estimé entre 700 000 à 18 100 000 $ selon le type d'entretien et le taux d'escompte considérés. Malgré les incertitudes liées à ces estimations, les résultats montrent de façon claire que les bénéfices liés aux émissions routières sont du même ordre de grandeur que les coûts d'entretien. Ces bénéfices méritent donc d'être incorporés dans l'évaluation sur le cycle de vie des stratégies d'entretien des chaussées. Indépendamment de la stratégie d'entretien considérée, la majeure partie des bénéfices sociaux et environnementaux sont associés au bruit tandis que ceux associés aux gaz à effet de serre restent minimaux. La maintenance préventive est clairement plus durable que la maintenance corrective. Par ailleurs, l'étude souligne la nécessité de prendre en compte l'influence de la méthode d'actualisation des coûts lors de l'estimation des bénéfices sociaux et environnementaux.

Mots-clés: gestion de la chaussée, émissions routières, analyse des coûts sur le cycle de vie, impacts sociaux, impacts environnementaux.

1. Introduction

Road traffic is recognized to adversely impact society and the environment. The interaction between the road and the vehicles causes various environmental nuisances (such as noise and air pollution). The scope and intensity of these nuisances can greatly vary according to the driver, vehicle, traffic, and road characteristics that affect the motion of the vehicles. In particular, pavement characteristics and condition are expected to significantly influence the emission of environmental nuisances (Akbarian, Moeini-Ardakani, Ulm, & Nazzal, 2012). For example, pavement surface characteristics and condition affect the power required by the vehicle to move and, in turn, the associated fuel consumption. As a result, they affect the exhaust emissions from the traffic (Gillespie and McGhee, 2007). Choosing the right pavement maintenance strategy may thus help limit emissions from traffic during the use phase of the pavement life cycle and associated social and environmental impacts. From a sustainability perspective, it is important to include those impacts in the decision-making process of road agencies and pavement management units (Haas, 1997). However, those impacts occurring during the use phase are often omitted by road agencies (Santero et al., 2011).

Being widely used to assess the long-term economic cost-effectiveness of maintenance alternatives, the life cycle cost analysis (LCCA) is an appropriate tool to incorporate social and environmental costs and benefits, most of which being long-term by nature. Some recent studies relied on LCCA to incorporate the use phase environmental impacts in pavement management (see Lidicker et al. 2013; Zhang et al. 2013). In particular, Pellecuer et al. (2014a) developed the Pavement Environmental Impact Model (PEIM) to assess the annual cost of the social and environmental impacts associated with pavement condition. This tool is useful to establish the life-cycle social and environmental benefit of pavement surface maintenance. Providing an order of magnitude of this benefit is essential to promote, justify and ensure the sustainability of road networks. It also helps quantify the social and environmental consequences of alternative pavement management strategies.

Based on the results of Pellecuer et al. (2014b), the main objective of this paper is to explore and assess the influence of pavement management decisions on the social and environmental impacts of the road traffic and the associated costs. This paper focuses in particular on the influence of maintenance strategies on these impacts and costs. It also aims to show that, while not considering the cost of those impacts along with usual agency costs, pavement management units make decisions that may be unsustainable and non-optimal from society's perspective.

2. Methods

This study relied on the comparison of three different maintenance strategies and their associated social and environmental benefits. The annual social and environmental benefit of a pavement maintenance strategy was calculated as the difference between the cost associated with a "do nothing" base scenario versus the cost associated with the maintenance strategy in question. The next two sections present the approach and tool used to assess the social and environmental costs, and the characteristics of the case study.

2.1 Assessment of impacts

The impact pathway approach (IPA) is a bottom-up approach that determines the economic cost of adverse social and environmental impacts by following the pathway of emissions from their source to their impacts on receptors and ultimately to the costs incurred to prevent or repair those impacts (Bickel et al. 2006). Using the IPA approach, Pellecuer et al. (2016) explored the relationship between pavement surface condition, traffic emissions, their impacts on society and the environment, and the associated costs. They developed a conceptual model supporting the incorporation of traffic emissions in the decision-making process of pavement management units. The following emissions were considered:

- noise;
- air pollutant;
- greenhouse gases;
- leachate and runoff water;
- vibrations.

Based on that model, the Pavement Environmental Impact Model (PEIM) is the first tool to adapt the Impact Pathway Approach to assess the emission, dispersion, and impact of traffic emissions, so that social and environmental impacts can be included in the economic models of pavement management units (Pellecuer et al., 2014a). Figure 1 presents the schematic architecture of PEIM, designed to assign an economic value to the impacts associated with three kinds of emission: noise, air pollutants, and greenhouse gases. Leachate and runoff water, and vibrations are not included in the tool because of the lack of knowledge about their impacts and costs. The models underlying PEIM require 15 input variables related to the receptors affected by those emissions and to the traffic, road, and climate. The receptor data include the distance from the receptor to the road and the linear population density along the road section. The traffic data comprise the annual average daily traffic, the percentage of heavy vehicle and the average vehicle speed. The road data encompass geometric data (the length of the road section as well as the width and the number of traffic lanes) and pavement characteristics (the pavement roughness, the surface texture, and the structural deflection). The climate data are limited to the average wind velocity and direction.

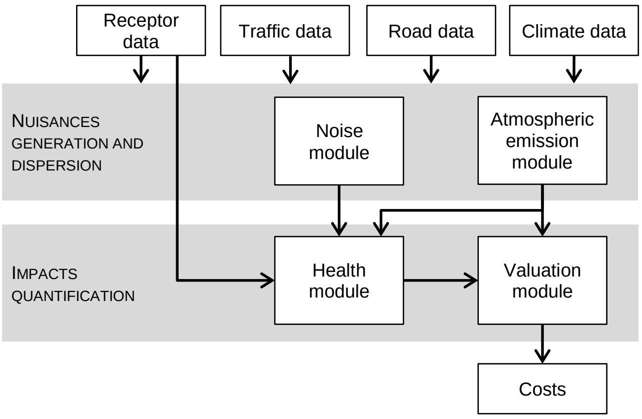

Figure 1. Schematic architecture of PEIM with arrows representing the links between inputs, modules and outputs (adapted from Pellecuer et al., 2014b).

The study presented in this paper considered the following impacts:

- the impacts of noise on human health (e.g. myocardial infarction) and annoyance (e.g. loss of productivity);
- the impacts of air pollutants on human health (e.g. respiratory disease), ecosystems biodiversity (e.g. loss of biodiversity), and building facades and materials (e.g. facade degradation);
- the impacts of greenhouse gases (via climate change) on human welfare, ecosystems, crops, and buildings and infrastructures.

The assessment of the social and environmental costs associated with air pollution was performed with PEIM. PEIM computes the annual traffic noise levels and emissions of air pollutant and greenhouse gases through the analysis period. Then, it estimates the social and environmental impacts and the associated costs for each year.

To compute the effects on human health, PEIM 1) estimates the noise level and the concentration of PM10 and PM2.5 at the receptors' locations, 2) determines the nature and severity of the impacts with concentration-response functions that provide the number of the different health cases, and 3) assigns an appropriate economic value (corresponding to the treatment costs) to each health case. The health outcomes related to air pollution include:

- mortality;
- respiratory hospital admission and emergency visit;
- cardiac hospital admission and emergency visit;
- restricted activity day,
- asthma symptom day;
- acute respiratory symptom day;
- bronchitis.

The health outcomes related to noise include:

- myocardial infarction;
- angina pectoris;
- hypertension;
- sleep disturbance.

On the other hand, to compute the costs related to the impacts on biodiversity and buildings, PEIM directly applies exposure-cost functions to the amount of chemicals released into the atmosphere. The exposure-cost function for biodiversity is based on the restoration costs of the ecosystem affected by the emissions of SO_2 and NO_X from road traffic. The exposure-cost function for buildings impacted by particulate matter is inferred from the observed cleaning and renovation expenditures.

Finally, PEIM estimates the costs related to climate change through exposure-cost functions based on the social cost of carbon (see Ackerman and Stanton, 2012). For more details about the assessment of social and environmental impacts, the reader can refer to Pellecuer et al. (2014a).

2.2 Case study

To explore the effect of pavement management practices on society and the environment, PEIM was used in a case study about a 1 km long section of a typical urban collector road (50 km/h speed limit) in a densely populated neighborhood of Montreal, Canada (see Figure 2). The linear population density was 260 people/km. The road section had two traffic lanes each 3.5 m wide and two parking lanes each 2.5 m wide. The house rows were located 2 m away from the road right-of-way. The average daily traffic on this road section was 5 000 vehicle/day, with an annual growth rate of 1.3%, and it included 5% of heavy vehicles.

We performed an assessment of the life cycle social and environmental benefit of three different maintenance strategies over a base scenario consisting in letting the road surface deteriorates without any maintenance operation. Based on the practices of the Ministry of Transport of Quebec (MTQ), the analysis covered a period of 40 years, and all costs and benefits were discounted to present at a 6.5% rate.

Based on the practices of MTQ, the pavement condition is characterized by roughness, rutting and cracking performance indexes. This case study focused on the maintenance triggered by pavement roughness, which have been shown to significantly influence traffic emissions (Pellecuer et al., 2014a). Thus, rutting and cracking were considered to require no maintenance treatment except when affecting pavement roughness. In addition, the pavement structure was assumed to remain acceptable over the analysis period. Therefore, the variation of the pavement surface condition was assumed to be well described by the variation of its roughness only. The surface maintenance was assumed to be the only maintenance required. The pavement surface condition was described by a roughness performance index (RPI) based on a 0-100 scale (0 for the poorest condition and 100 for a new construction)[1]. For the road section at study, RPI was estimated based on pavement age with Equation 1:

$$RPI = 100 - \propto * \text{ pavement age} \quad (1)$$

where $\propto$ is the deterioration rate.

The three alternative maintenance strategies were as follow:

- two corrective strategies (A and B), with the same maintenance treatment, but with a different intervention trigger, implying one and two interventions respectively;
- one preventive strategy, characterized by a less deep maintenance treatment, implying three interventions.

Figure 2. Typical section of Notre-Dame street, Montreal (source: Gene Arboit).

Table 1 details the key characteristics of each maintenance strategy and Figure 3 shows the variation of the pavement surface condition over the analysis period for the base scenario and for the three maintenance strategies. In particular, it shows that the pavement condition deteriorated at a different rate depending on the maintenance treatment applied.

Table 1. Characteristics of the maintenance strategies (Pellecuer et al., 2014b).

Scenario	Maintenance trigger level	Maintenance treatment	Treatment cost ($/1000 m^2)	RPI improvement per treatment	RPI deterioration rate (per year)
Base	-	-	-	-	2.23
Corrective A	RPI under 33	Mill and overlay	15,000	100	2.90
Corrective B	RPI under 58	Mill and overlay	15,000	100	2.90
Preventive	Pavement surface age is 10	Seal coat	5,000	20	2.23

---

[1] MTQ, 2013. Personnal communication.

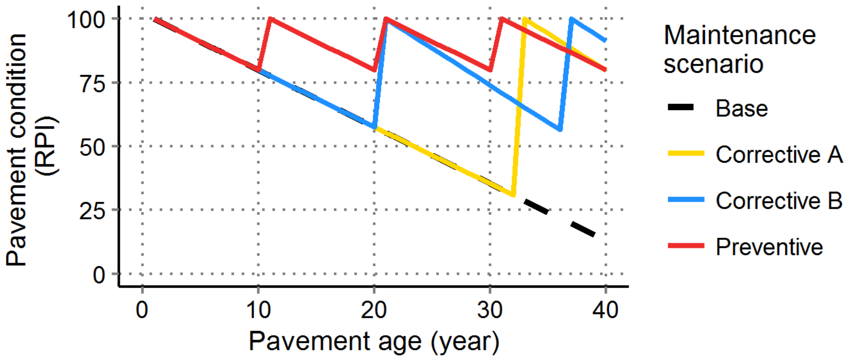

Figure 3. Pavement surface condition of the base and alternative scenarios over the analysis period (adapted from Pellecuer et al., 2014b).

3. Results

The valuation of the social and environmental impacts related to traffic emissions is affected by uncertainties that prevented us from estimating the precise absolute values of the costs associated with each maintenance strategy (see Section 3 for a discussion of the uncertainties). However, the estimation of the relative costs and benefits are suitable to compare the performance of the maintenance strategies. Thus, the social and environmental benefit over the base scenario was assessed for the three alternative maintenance strategies presented above. Figure 4 shows the variation of the expected annual benefit provided by each strategy through the analysis period.

In general, the three alternative maintenance strategies provided constantly increasing social and environmental benefit with pavement age. Most of the increase resulted from the change in pavement condition due to each maintenance treatment. This is illustrated in Figure 4 by the visible steps. In addition, the traffic growth tended to accentuate the benefit resulting from the maintenance treatments. Indeed, this benefit was all the more important as the maintenance impacted more vehicles. The annual increase of benefits associated with the traffic growth is particularly noticeable in Figure 4 for the preventive strategy. An exception arose for the corrective strategy B between the years 21 and 36 while the decrease of the benefit associated with the deterioration of the pavement condition was exceeding the increase of the benefit related to the traffic growth.

The preventive strategy presented an exceptional annual benefit for the year 11 (around $3 200 000). This high value was due to a threshold effect in the noise impact assessment. The health effects due to noise do not include hospital admissions unless the noise level is above 70 dBA. Because of the deterioration of the pavement surface and because of the traffic growth, the noise level exceeded 70 dBA at year 11 for the base scenario, while the noise level exceeded this threshold only at year 12 for the preventive strategy. This resulted in a delay between the occurrence of the hospital admissions in the base scenario and in the preventive strategy that in turn caused the exceptional benefit of the preventive scenario for the year 11.

Figure 4 shows that, whatever the maintenance strategy, most of the social and environmental benefit provided by the pavement surface maintenance was related to noise and air pollution. Only around 2% of this benefit was associated with the impacts of greenhouse gases. An exception was the year 11 of the preventive strategy for which, as explained above, a threshold effect caused noise to represent almost 98% of the social and environmental benefit.

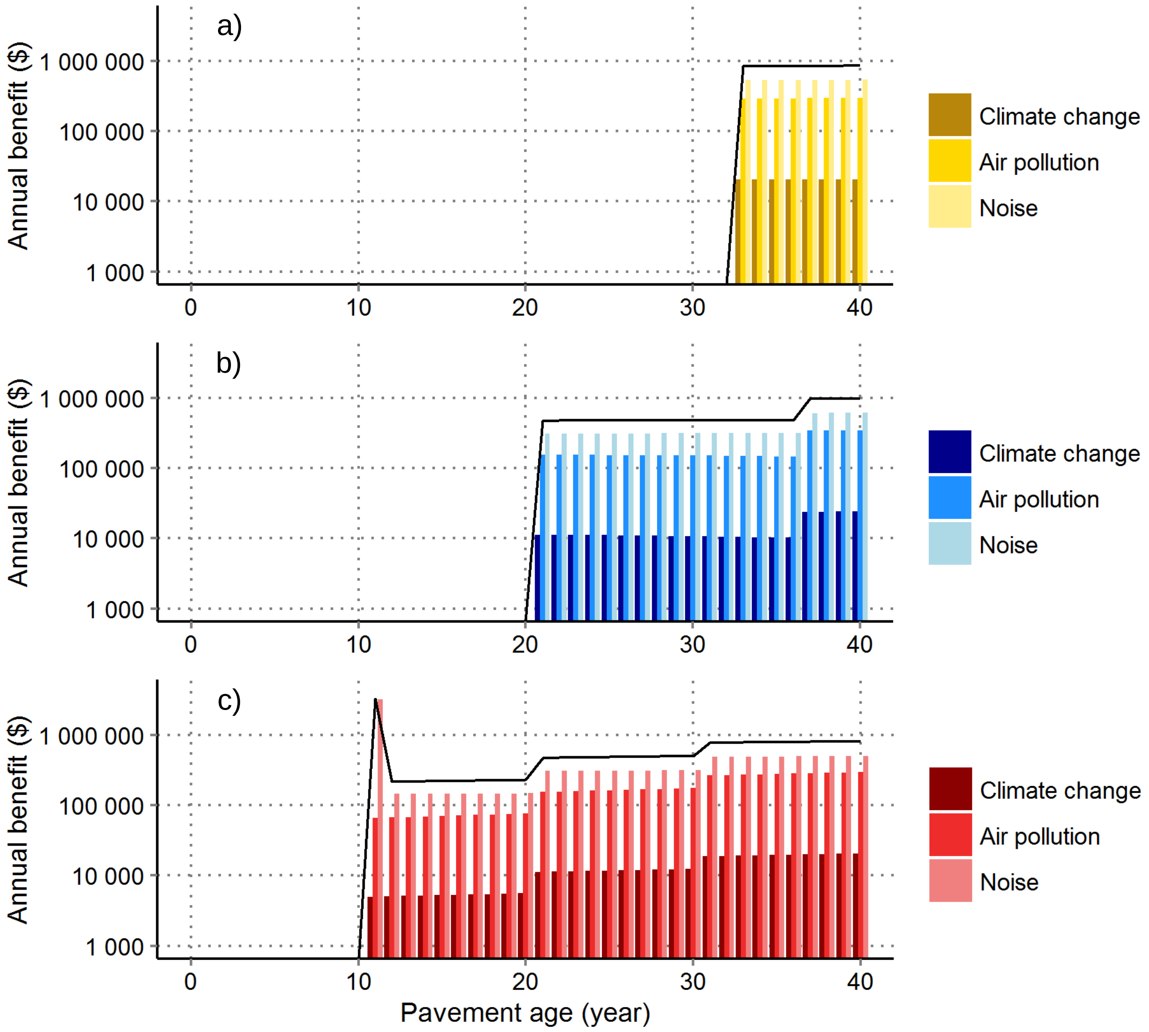

Figure 4. Central estimates of undiscounted annual social and environmental benefits of the (a) corrective strategy A, (b) corrective strategy B and (c) preventive strategy. The black line represents the sum of the annual benefits related to noise, air pollution and greenhouse gases.

Comparison of pavement maintenance strategies usually relies on the pavement life cycle costs and benefits incurred during the analysis period, discounted to present. Figure 5 presents, for the three alternative maintenance strategies, the life cycle social and environmental benefit calculated with two different discount rates: the discount rate usually applied by the MTQ (6.5%), and a zero discount rate to better apprehend the intrinsic value of the life cycle benefit. The error bars shown in Figure 5 illustrate the uncertainty pertaining to the quantification and monetization of health effects and climate change impacts (Section 3 for a discussion of the uncertainties). These error bars were calculated with the lowest and highest estimates of the parameters involved in the quantification and valuation processes. Therefore, they represent the low and high estimates of the life cycle benefit.

The results reveal that, over the 40 year analysis period, pavement surface maintenance provided a central estimate of social and environmental benefit ranging from $6 860 000 to $18 100 000, depending on the maintenance strategy and the discount rate (from $370 000 to $11 200 000 for low estimate and from $11 270 000 to $27 890 000 for high estimate). The differences in benefit between the three alternative strategies were consistent with their associated pavement condition: the better the pavement condition, the higher the benefit. On the other hand, whatever the maintenance strategy, non-discounted and discounted benefits were found to be significantly different. This was due to the fact that most of the annual benefits occurred at the end of the analysis period.

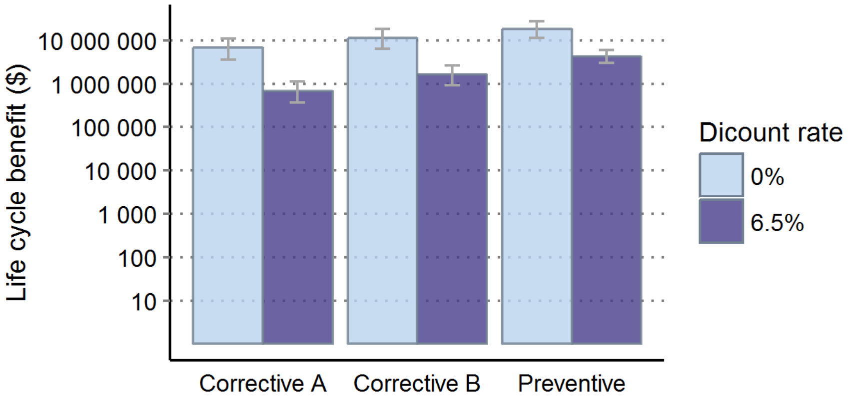

Figure 5. Total social and environmental benefit of the alternative maintenance strategies (adapted from Pellecuer et al., 2014b).

Based on the MTQ treatment costs (see Table 1), the total cost associated with the pavement surface maintenance of each alternative strategy was computed. Table 2 shows that this cost ranged from $22 500 to $360 000, depending on the strategy and the discount rate. Interestingly, whatever the maintenance strategy, discount rate, and benefit estimate (low, central, or high), the life cycle maintenance cost was found to be consistently lower than the life cycle social and environmental benefit.

Table 1. Total pavement surface maintenance costs of the alternative strategies.

Alternative strategy	Total undiscounted costs ($)	Total costs discounted at 6.5% ($)
Corrective A	180 000	22 500
Corrective B	360 000	68 500
Preventive	180 000	58 000

4. Discussion

While analyzing the results presented above, it should be kept in mind that assigning an economic value to traffic emission impacts implies unavoidable uncertainties (Bickel et al. 2006, van Essen et al. 2011). As detailed in Pellecuer et al. (2014a), these uncertainties pertain to variable estimation, model parameterization, and gaps in scientific knowledge. The lack of scientific knowledge affects in particular the health impact quantification (e.g. number of early deaths) and the impact valuation (e.g. cost of biodiversity loss). However, it is important to stress that these uncertainties are not inherent to the methodology and can be reduced by careful data collection and further research. Moreover, the lack of scientific knowledge prevents from addressing all types of pavement distress and all types of impact associated with road traffic emissions. This is expected to result in minimized social and environmental impacts, costs, and benefits (Pellecuer et al. 2014a).

Due to the focus on pavement condition, this study assumed steady free flow traffic conditions. It did not cover the influence of traffic conditions and traffic management devices (e.g. traffic signals) on the impacts and costs associated with traffic emissions. Variable traffic conditions and traffic management devices induce variation in speed and acceleration that causes more traffic emissions. Therefore, it is expected that not assuming steady free flow traffic conditions would have resulted in more intense impacts and higher costs.

Overall, the results presented in this paper are rough estimates of the social and environmental benefit provided by alternative pavement maintenance strategies. However, they provide a unique opportunity to apprehend the influence of pavement age (and condition) on this benefit and to provide an order of magnitude, which is essential to compare the performance of pavement management alternatives. The social and environmental benefit related to traffic emissions was found to be significant and at least the same order of magnitude as the maintenance cost. This suggests that the impacts of traffic emissions were significant and would deserve to be incorporated in the life cycle assessment of pavement maintenance strategies. In particular, it was found that the preventive maintenance strategy was the best to help reduce the impacts associated with traffic emissions, supporting conclusions from Chan et al. (2011).

On the other hand, comparing the discounted and non-discounted benefits reveals that discounting dramatically minimized the total social and environmental benefit of pavement management on the pavement life cycle. This is in accordance with the conclusions of Hellweg et al. (2003) that discounting long-term impacts may influence the total social and environmental benefit of any strategy more than all other factors. This highlights the necessity to perform a sensitivity analysis of the estimate of this benefit to discounting method in order to ensure that the impacts associated with traffic emissions are adequately addressed.

This study compares the social and environmental benefit and the pavement surface maintenance cost occurring during the use phase of the pavement life cycle. Even if the use phase is the most influential in the pavement life cycle (Santero et al. 2011), the results of this study need to be confirmed by including the agency and environmental costs related to the construction and maintenance operations (e.g., crack sealing and patching) that were not accounted for in this study.

5. Conclusion

To ensure a sustainable development of road networks, pavement management units tend to expand the boundary of their life cycle cost analyses to include social and environmental concerns. In this context, this study assessed the life cycle social and environmental benefits of three pavement maintenance strategies applied to a one kilometer long road section located in a densely populated urban area.

Despite unavoidable uncertainties due to gaps in scientific knowledge, the results unambiguously show that the impacts of the maintenance strategy on society and the environment were significant. The associated social and environmental benefits were the same order of magnitude as the maintenance costs. Over the 40 year analysis period, the pavement surface maintenance provided a benefit ranging from $700 000 to $18 100 000 (central estimates), depending on the maintenance strategy and the discount rate. Therefore, the social and environmental benefit would deserve to be incorporated in the life cycle assessment of pavement maintenance strategies. Failing to do so would lead to decisions that might be unsustainable and non-optimal from society’s perspective. Moreover, the preventive maintenance was found clearly more effective than the corrective maintenance to mitigate social and environmental impacts.

More particularly, this study assessed the social and environmental impacts related to air pollution, greenhouse gases and noise. Surprisingly, the major part of the social and environmental benefit was associated with noise, whereas it is often not considered in the decision-making process of pavement management units. On the contrary, although greenhouse gases are often taken into account, the reduction of the greenhouse gases emission associated with the maintenance strategy was relatively small.

Discounting was found to dramatically minimize the estimate of the life cycle social and environmental benefit provided by pavement management. Therefore, to ensure the impacts caused by traffic emissions are adequately addressed, there is a need to take into account the influence of the discounting method that is used during the assessment of the social and environmental benefit.

References

Ackerman, F. and E. A. Stanton (2012). "Climate risks and carbon prices: Revising the social cost of carbon." Economics: The Open-Access, Open-Assessment E-Journal 6(2012-10): 1-25.

Akbarian, M., S. Moeini-Ardakani, F.-J. Ulm and M. Nazzal (2012). "Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact on Life-Cycle Assessment." Transportation Research Record: Journal of the Transportation Research Board 2306(-1): 171-179.

Bickel, P., R. Friedrich, H. Link, L. Stewart and C. Nash (2006). "Introducing environmental externalities into transport pricing: Measurement and implications." Transport Reviews 26(4): 389-415.

Bignal, K. L., M. R. Ashmore, A. D. Headley, K. Stewart and K. Weigert (2007). "Ecological impacts of air pollution from road transport on local vegetation." Applied Geochemistry 22(6): 1265-1271.

Chan, S., B. Lane, T. Kazmierowski and W. Lee (2011). "Pavement preservation: A solution for sustainability." Transportation Research Record: Journal of the Transportation Research Board 2235: 36-42.

Gillespie, J. and K. McGhee (2007). "Get In, Get Out, Come Back!: What the Relationship Between Pavement Roughness and Fuel Consumption Means for the Length of the Resurfacing Cycle." Transportation Research Record: Journal of the Transportation Research Board 1990: 32-39.

Haas, R. (1997). Pavement design and management guide. Ottawa, Ontario, Transportation Association of Canada.

Hellweg, S., T. Hofstetter and K. Hungerbuhler (2003). "Discounting and the environment should current impacts be weighted differently than impacts harming future generations?" The International Journal of Life Cycle Assessment 8(1): 8-18.

Kunzli, N., R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, M. Herry, J. F. Horak, V. Puybonnieux-Texier, P. Quenel, J. Schneider, R. Seethaler, J. C. Vergnaud and H. Sommer (2000). "Public-health impact of outdoor and traffic-related air pollution: a European assessment." The Lancet 356(9232): 795-801.

Lidicker, J., N. Sathaye, S. Madanat and A. Horvath (2013). "Pavement resurfacing policy for minimization of Life-Cycle costs and greenhouse gas emissions." Journal of Infrastructure Systems 19(2): 129-137.

Pellecuer, L., G. Assaf and M. St-Jacques (2014a). "Influence of Pavement Condition on Environmental Costs." Journal of Transportation Engineering 140(10): 04014050-04014051-04014050-04014015.

Pellecuer, L., G. Assaf and M. St-Jacques (2014b). "Life cycle environmental benefits of pavement surface maintenance." Canadian Journal of Civil Engineering 41(8): 695-702.

Pellecuer, L., G. Assaf and M. St-Jacques (2016). "Towards the Incorporation of

Environmental Impacts into Pavement Management Systems." Transport Reviews 36(3): 361-382.

Rabl, A. and J. V. Spadaro (1999). "Damages and costs of air pollution: An analysis of uncertainties." Environment International 25(1): 29-46.

Santero, N. J., E. Masanet and A. Horvath (2011). "Life-cycle assessment of pavements. Part I: Critical review." Resources, Conservation and Recycling 55(9–10): 801-809.

van Essen, H., A. Schroten, M. Otten, D. Sutter, C. Schreyer, R. Zandonella, M. Maibach and C. Doll (2011). External Costs of Transport in Europe Delft, The Netherlands, CE Delft.

Zhang, H., G. Keoleian and M. Lepech (2013). "Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization." Journal of Infrastructure Systems 19(1): 99-107.