

Influence of pavement management on road traffic emissions and associated costs

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Abstract

To achieve sustainable road networks, long-term social and environmental costs and benefits related to traffic emissions should be recognised and incorporated in the decision-making process of pavement management units. 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 benefits of pavement management related to traffic emissions. A case study regarding a 1 km long section of an urban collector road located in Montréal, Canada is presented in this paper. The case study shows that pavement surface maintenance provided an estimated social and environmental benefit ranging from \$235 000 to \$5 150 000 over a 40 year analysis period, depending on the maintenance treatment applied and the discount rate used. Despite uncertainties, the results unambiguously show that benefits related to traffic emissions were significant and were the same order of magnitude as the maintenance costs. As such, they deserve to be incorporated in the life cycle assessment of pavement maintenance strategies. Preventive maintenance was also found clearly more effective than corrective maintenance to mitigate exhaust emissions.

Keys-words: *road traffic emissions, pavement condition, life cycle cost analysis, environmental impacts, social 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. 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 sociaux et environnementaux liés aux émissions routières des stratégies d'entretien des chaussées. Cet article présente les résultats d'une étude de cas réalisée sur un tronçon d'un kilomètre d'une collectrice en milieu urbain, à Montréal, au Canada. Ces résultats montrent que l'entretien de la surface de roulement induit, sur 40 ans, des bénéfices sociaux et environnementaux d'un montant estimé compris entre 235 000 à 5 150 000 \$ selon le type d'entretien et le taux d'escompte considérés. Malgré les incertitudes liés à ces estimations, les résultats montrent de façon claire que les bénéfices liés aux émissions routières sont significatifs et 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. Par ailleurs, l'entretien préventif se révèle bien plus efficace que l'entretien correctif dans la lutte aux émissions routières.

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

Introduction

Road traffic is recognised as a major contributor to the poor air quality in urban areas, but it also affects the environment in suburban and rural areas. The impacts of road traffic emissions on the environment and society include impacts on human welfare (Kunzli et al, 2000), buildings façades (Rabl and Spadaro, 1999), crops (van Essen, 2011), and ecosystems (Bignal et al., 2007). From a sustainability perspective, those impacts are now expected to be included in the decision making process of road agencies and pavement management units.

The scope and intensity of those impacts, is significantly influenced by the pavement characteristics. Pavement surface characteristics and condition affect the power required to move

vehicles and, in turn, the associated fuel consumption. Thus, pavement surface characteristics and condition affect exhaust emissions from 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. However, those impacts occurring during the use phase are often omitted by road agencies (Santero et al., 2011).

The main objective of this study was to explore and assess the influence of pavement maintenance strategies on social and environmental impacts associated with traffic emissions. This study also aimed to show that, while not including in their decision making process 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.

1. 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 costs associated with a “do nothing” base scenario versus the costs associated with the maintenance strategy in question. The next two sections present the tool used to assess the social and environmental costs and the characteristics of the case study, respectively.

1.1. Assessment of impacts

Using the Impact Pathway approach (Bickel et al., 2006), Pellecuer et al. (2016) explore the relationship between pavement surface condition, traffic nuisances (such as exhaust emissions), their impacts on society and the environment, and the associated costs. They developed a model supporting the incorporation of traffic nuisances in the decision making process of pavement management units. Based on that model, the Pavement Environmental Impact Model (PEIM) is the first attempt 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 impacts associated with noise, air pollutants, and greenhouse gases. The models underlying PEIM require 15 input variables related to the receptors affected by those emissions (population, building and ecosystems) and to the traffic, road, and climate. The study presented in this paper only considered the impacts of air pollutants (excluding greenhouse gases) on health, biodiversity, and buildings.

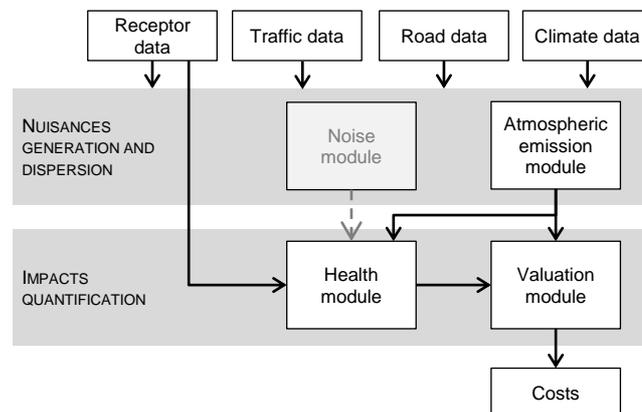


Figure 1. Schematic architecture of PEIM with solid arrows representing the links between inputs, modules and outputs and dashed arrows emphasize the link between modules and intermediate outputs (adapted from Pellecuer et al., 2014b).

The assessment of the social and environmental costs associated with air pollution was performed with PEIM. PEIM computes the fuel consumption and, based on the fuel combustion reaction, estimates the amount of particulate matter (PM10 and PM2.5), sulfur dioxide, and nitrogen oxides released into the atmosphere. Then, to compute the effects on human health, PEIM 1) estimates the concentration of PM10 and PM2.5 at receptors' locations, 2) determines the nature and severity of the impacts with concentration-response functions that provided the number of different health cases, and 3) assigns an appropriate economic value (corresponding to the treatment costs) to each health case. The health outcome considered in this study included mortality, respiratory and cardiac hospital

admission and emergency visit, restricted activity day, asthma symptom day, acute respiratory symptom day, and bronchitis.

On the other hand, to compute the cost of atmospheric emissions on biodiversity and buildings, PEIM directly applies exposure-cost functions to the estimated concentration 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 building impacted by particulate matter is inferred from the observed cleaning and renovation expenditures. For more details about the assessment of social and environmental impacts, the reader can refer to Pellecuer et al. (2014a).

1.2. Case study

To explore the effect of pavement management practices on traffic emissions, 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 neighbourhood of Montréal, 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.



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

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

The traffic supported by the pavement was assumed to be light enough to maintain the deflection of the pavement at its initial value over the analysis period. Consequently, the variation of the surface condition was supposed to be well described by the variation of its roughness only. Therefore, the pavement surface condition was described by a roughness performance index (RPI) based on a 0-100 percentage scale (0 for poorest condition and 100 for new construction).

The three alternative maintenance strategies were as follow:

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

Table 1 details the key characteristics of each maintenance strategy. Figure 3 shows the variations 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 deterioration rate depending on the maintenance treatment applied, which depended on the maintenance strategy adopted.

Table 1. Characteristics of 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

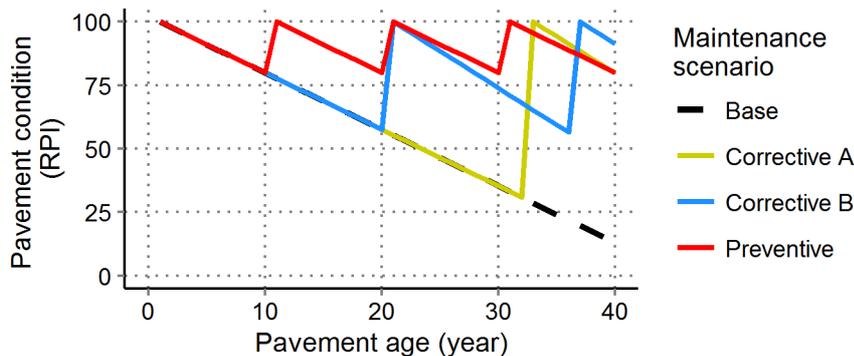


Figure 3. Pavement surface condition of base and alternative scenarios over the analysis period (adapted from Pellecuer et al., 2014b).

2. 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 value of the costs associated with each maintenance strategy (see Section 3 for a discussion of the uncertainties). The estimation of the relative costs and benefits are however suitable for the comparison of the performance of the maintenance strategies. Thus, the social and environmental benefits over the base scenario were assessed for the three alternative maintenance strategies. Figure 4 shows the variation of the expected annual benefits, in Canadian dollar, provided by each strategy through the analysis period.

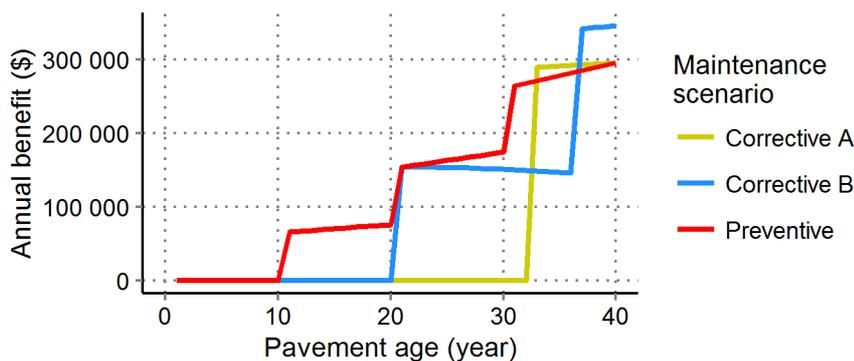


Figure 4. Central estimates of undiscounted annual social and environmental benefits of the alternative maintenance strategies.

In general, the three alternative maintenance strategies provided constantly increasing social and environmental benefits with pavement age. Most of this 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 volume growth tended to accentuate the benefits resulting from the maintenance treatments. The social and environmental benefits from pavement maintenance were indeed 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 corrective strategy B between the years 21 and 36 while the decrease of the benefits associated with the deteriorating pavement condition was exceeding the increase of the

benefits related to the traffic volume growth.

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 benefits calculated with two different discount rates: the discount rate usually applied by the MTQ (6.5%), and a zero discount rate used to better apprehend the intrinsic total value of the life cycle benefits. The error bars shown in Figure 5 illustrate the uncertainty pertaining to the quantification and monetization of health effects (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 benefits.

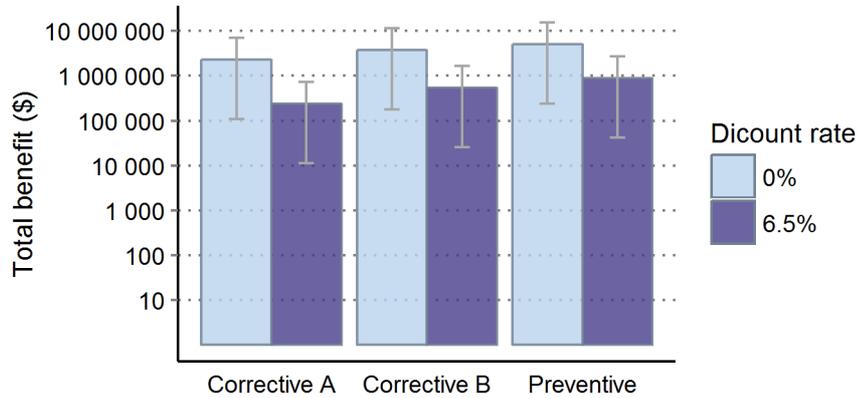


Figure 5. Total social and environmental benefits of the alternative maintenance strategies.

The results reveal that, over the 40 year analysis period, pavement surface maintenance provided central estimate of social and environmental benefits ranging from \$235 000 to \$5 150 000 (from \$11 000 to \$243 000 for low estimates and from \$723 000 to \$15 700 000 for high estimates), depending on the maintenance strategy and the discount rate used. The differences in benefits between the strategies were consistent with their associated pavement condition: the better the pavement condition, the higher the benefit. On the other hand, regardless of the 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.

Based on the MTQ treatment costs (see Table 1), the total costs associated with pavement surface maintenance of each alternative maintenance strategy were computed. Table 2 shows that those costs ranged from \$22 500 to \$360 000, depending on the maintenance strategy and the discount rate. Interestingly, regardless of the strategy, discount rate, and benefits estimate (low, central, or high), life cycle maintenance costs were found to be lower than or similar to the life cycle social and environmental benefits. In particular, central estimates of benefits were consistently higher than maintenance costs.

Table 2. Total pavement surface maintenance costs of the alternative maintenance 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

3. Discussion

While analysing 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 parameterisation, 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 distresses and all types of impacts associated with emissions. This is expected to result in minimizing 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 social and environmental benefits associated with traffic emissions. However, they provide a unique opportunity to apprehend the influence of pavement age (and condition) on the social and environmental benefits and to provide an order of magnitude of these benefits, which are essential for comparing the performances of pavement management alternatives. Social and environmental benefits related to traffic emissions were found to be significant and at least the same order of magnitude as the maintenance costs. 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 benefits 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 need to perform a sensitivity analysis of the estimate of the social and environmental benefits to discounting method in order to ensure that the impacts associated with traffic emissions are adequately addressed.

Conclusion

Despite unavoidable uncertainties due to gaps in scientific knowledge, the results unambiguously show that benefits related to traffic emissions were significant and were the same order of magnitude as the maintenance costs. The case study reveals that, over the 40 year analysis period, pavement surface maintenance provided social and environmental benefits ranging from \$235 000 to \$5 150 000 (central estimates), depending on the maintenance strategy and the discount rate. As such, they would deserve to be incorporated in the life cycle assessment of pavement maintenance strategies. Moreover, preventive maintenance was found clearly more effective than corrective maintenance to mitigate social and environmental impacts associated with exhaust emissions. The study also points out the need to take into account the influence of the discounting method for the assessment of the social and environmental benefits.

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