Pavement vehicle interaction (PVI): the elephant in the pavement life cycle assessment (LCA) room

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Abstract

Owing to the societal pressure to embed sustainability principles in all industrial sectors, the last years have witnessed a growing interest in the environmentally conscious design and management of civil infrastructures systems. Road pavements being critical surface components of these systems that consume enormous quantities of energy and materials have been the key target of multiple policies and initiatives intended to improve the environmental performance of the built environment. Within that context, life cycle assessment (LCA) has emerged as the preferable methodology to evaluate the environmental sustainability of pavement systems. Ideally, the system boundaries of the analysis should be cradle-to-grave, comprising all phases of the pavement life cycle including the use phase. Among other aspects, this phase accounts for the environmental impacts stemming from the roughness-, macrotexture- and deflection-induced pavement-vehicle interaction (PVI). Although the pavement LCA community has progressively recognized the importance of the use phase in driving the environmental performance of pavement systems, the generality of the pavement community, and in particular practitioners and policy makers, have place their focus and resources on aspects related to materials production and pavement construction and maintenance. Considering that road pavements are expected to remain in service during decades, supporting millions of vehicles during their lifetime, the use phase has the potential to overwhelmingly dominate the environmental impacts related to their life cycle. Thus, neglecting it means jeopardizing a tremendous opportunity to make informed and far-reaching decisions able to substantially improve the sustainability of pavement systems.

Anchored in a case study, this paper aims to illustrate how the use phase components, namely the roughness-induced rolling resistance, influence the results of comparative pavement LCA studies expressed in terms of Environmental Cost Indicator (ECI). It is the ultimate goal of this paper to raise practitioners, academics and policy makers' awareness of the need for joint efforts to (1) expand and advance the knowledge on the factors affecting the PVI and (2) include the use phase in their pavement LCA exercises and downstream decisions.

Key words: Pavement vehicle interaction, life cycle assessment, environmental cost indicator

1. Introduction

Road pavements are key elements of a modern integrated transport system that strengthens the countries' global competitiveness. Thus, ensuring a well-functioning road infrastructure that can transport people and goods efficiently, safely and sustainably is of upmost importance. As such, every year enormous quantities of natural resources and energy are consumed in the construction of new and maintenance and rehabilitation of existing road pavements. For instance, in Europe, 276.9 million tonnes of hot and warm mix asphalt were produced in 2020 (EAPA, 2021). Inevitably, the magnitude of these values may instigate transport agencies and civil society alike to believe that the environmental impacts related to road pavements arise exclusively from the extraction and production of materials and the construction processes that convert those materials into a functional pavement (Xu et al., 2019).

One of the main tools used to evaluate the environmental performance of road pavements is the life cycle assessment (LCA) methodology (Santos et al., 2015a). LCA is a standardized methodology used to quantify the environmental impacts over the full life cycle of a product or system from cradle-to-grave. For pavements, a typical life cycle includes material extraction and production, construction, maintenance and rehabilitation (M&R), use, and end of life (EOL) phases (Santero et al., 2011). Among those, the use phase is one of the most important and complex to model in a pavement LCA. It accounts for the influence of the pavement on vehicle operations and the interaction between the pavement, the environment, and humans. One of the most important factors related to the use phase of pavements is rolling resistance (RR). RR is the mechanical energy loss by a tire moving a unit distance along the roadway and is effected by the properties of the tire and the pavement (Evans et al., 2009). The energy that is lost comes directly from the power that is used to propel the vehicle, and as a consequence, more fuel must be consumed to propel a vehicle over a pavement with higher RR (Bryce et al., 2014).

Road pavements can influence the fuel efficiency of vehicles, and therefore the associated environmental impacts. This interaction between pavement and vehicle is known by the expression *pavement-vehicle interaction* (PVI) and comprises three mechanisms that together are called pavement-related RR (Van Dam et al., 2015): (1) roughness, (2) macrotexture; and (3) structural stiffness. Roughness influences the consumption of vehicle energy through the working of shock absorbers and drive train components, and deformation of tire sidewalls as the wheels pass over deviations from a flat surface. Macrotexture impacts the consumption of vehicle energy through the viscoelastic working of the deformable tire tread rubber in the tire-pavement contact patch as it passes over positive surface macrotexture and converts it into heat dissipated into the rest of the tire and into. Finally, structural stiffness conditions the consumption of vehicle energy in the pavement itself through deformation of pavement materials under passing vehicles, including delayed deformation of viscoelastic materials and other damping effects that consume energy in the pavement and subgrade. It is then obvious that the relative impact of pavement-related RR on fuel economy and vehicle emissions depends to a great extent on the level of roughness, surface texture and structural responsiveness. Further, when considered from the perspective of one single vehicle, their effects may seem irrelevant. However, given that road pavements are expected to remain in service during decades, supporting millions of vehicles during their lifetime, the cumulative effects of pavement-related RR effects occurring during the pavement use phase have the potential to overwhelmingly dominate the source of environmental impacts related to the pavement life cycle. Although this fact has been increasingly acknowledged by the pavement life cycle assessment (LCA) community (Estaji et al., 2021; Santos et al., 2015b; Ziyadi and Al-Qadi, 2019), to the majority of the pavement stakeholders it remains yet unrecognized.

2. Objectives

The objective of his paper is to illustrate how the use phase components, namely the roughness-induced RR, influence the results of comparative pavement LCA studies expressed in terms of Environmental Cost Indicator (ECI). It is the ultimate goal of this paper to rise practitioners, academics and policy makers' awareness of the need for joint efforts to (1) expand and advance the knowledge on the factors affecting the PVI and (2) include the use phase in their pavement LCA exercises and downstream decisions.

3. Case study and methodology

3.1. General description

In order to accomplish the objectives outlined above we performed a comparative LCA study of two alternative M&R strategies applied in a 1km-long road pavement section with 6 lines, each 3.75km-wide, and a structural number (SN) equal to 4.75. The initial average annual daily truck traffic (AADTT) at the beginning of a 30-year analysis period is 8000 and corresponds to 12% of the total annual daily truck traffic (ADTT). The traffic is expected to grow according to a normal distribution with a mean value equal to 0.02 and a standard deviation equal to 0.015. All this information about the pavement structure, dimensions and traffic is taken from the case study described in (Renard et al., 2021).

Regarding the M&R strategies, in the first one, hereafter named *Scenario A*, no M&R treatments are applied during the 30-year analysis period. In the second one, hereafter named *Scenario B,* a 5-cm mill and fill treatment is applied at every 5 years. In both scenarios the pavement deterioration, namely pavement roughness measured in units of meters per kilometer, is assumed to evolve according to the stochastic model developed by (Omar et al., 2018) and represented by Equation (1).

$$IRI_t = IRI_{t-1} + 0.08 \times \ln(age) \times \ln(AADTT) \times SN^{-2.5} + \varepsilon \qquad (1)$$

Where IRI_t is the international roughness index (IRI) value in year *t*; IRI_{t-1} is the IRI value in year *t-1*; *age* is the pavement age; *AADTT* is the average annual daily truck traffic; *SN* is the structural number; and ε is the random error of the deterioration process, which is assumed to follow a normal distribution with a null mean and standard deviation equal to 0.05.

The pavement's initial IRI in both scenarios is equal to 1 m/km. This is also the IRI value considered in *Scenario B* after the application of the mill and fill treatment. Regarding the effect of this treatment on the pavement age, it is considered that its thickness is not enough to restore it to 0. Further, the SN is conservatively assumed to remain constant over the analysis period in both scenarios. Finally, the macrotexture value expressed as mean profile depth (MPD) is also assumed to remain constant and equal to 1 mm in both scenarios due to the absence of credible models to predict the evolution of macrotexture over time.

The LCA was performed according to an attributional approach with the system boundaries illustrated in Figure 1. It adopts the phases and coding considered in the Dutch reference documents (Keijzer et al., 2020; Schwarz et al., 2020). The asphalt mixture employed in the mill and fill treatment considered in *Scenario B* is the AC surf 0% PR defined in (Schwarz et al., 2020). Data referring to mixture composition, consumption of utilities (i.e., natural gas, electricity and diesel) for mixture production, transportation distances between the facilities where the asphalt mixture components were produced and the asphalt plant, transportation distance between the asphalt plant and the road pavement section, operation rates and fuel consumption of construction equipment were all taken from (Keijzer et al., 2020; Schwarz et al., 2020). The inventory datasets used to model the background and foreground process were sourced from the ecoinvent 3.3.

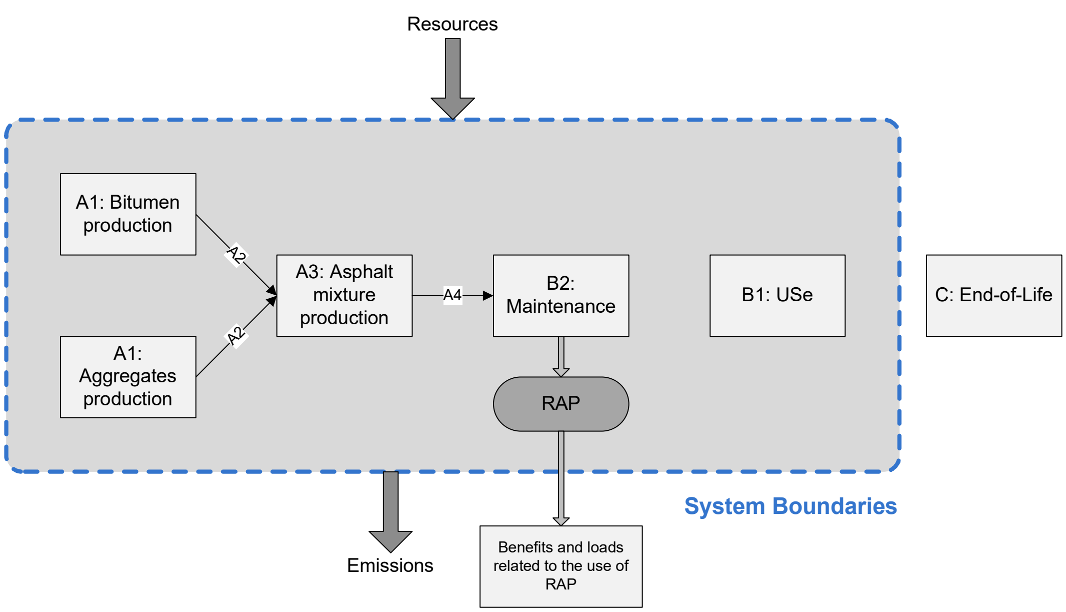

Figure 1. System boundaries of the LCA study.

Regarding the use phase, from the three pavement-related RR mechanisms described in the introduction, the structural RR was not considered in the case study due to the inexistence of sound and widely accepted models. As far as the remaining two mechanisms are concerned, the MIRIAM model described in Hammarstom et al. (2011) is adopted to quantify the marginal fuel consumption due to roughness- and macrotexture-related RR relative to a newly paved surface (i.e., IRI = 1 m/km and MPD = 1 mm). The MIRIAM model is a semi-analytical fuel consumption model developed for three types of vehicles (i.e., passenger car, heavy duty vehicles (HDV) and HDV with trailer) based on empirical results from coast down measurements in Sweden. Among other parameters, it takes into account vehicle speed, RR force and geometrical and surface characteristics of the road pavement. The values of the parameters adopted in this case study are presented in Table 1. All passenger cars are assumed to have a gasoline engine of the emissions class EURO 5, while all heavy traffic is considered to have a diesel engine of the emissions class EURO 5 and no trailer.

Table 1. Values of the MIRIAM model parameters considered in the case study.

Name	**Value**
Vehicle speed (km/h)	0
Road curvature (rad/km)	0
Slope (m/km)	0

The environmental impacts associated with the additional fuel consumed due to the RR in year *t* are determined for each type of vehicle (i.e., passenger car and HDV) according to Equation 2.

$$EnvImpRR(t)_i^j = \frac{\Delta FC_{RR}^j(t)}{FE^j} \times EnvImp_i^j \times length \tag{2}$$

Where $EnvImpRR(t)_i^j$ are the environmental impacts of category *i* produced in year *t* by vehicle type *j* due to RR*;* $\Delta FC_{RR}^j(t)$ is the additional fuel consumption due to RR in year *t* for vehicle type *j*; FE^j is the fuel efficiency (l/km) of vehicle type *j;* $EnvImp_i^j$ are the environmental impacts of category *i* corresponding to the service of transport in a vehicle type *j* for a journey length of 1 km; and $length$ is the length in km of the road pavement section under analysis. In Equation (2), $\Delta FC_{RR}^j(t)$ is obtained from the MIRIAM model, while FE^j and $EnvImp_i^j$ are sourced from the ecoinvent datasets "*transport, passenger car, medium size, petrol, EURO 5 | transport, passenger car, medium size, petrol, EURO 5 | cut-off, U*" and "*transport, freight, lorry 7.5-16 metric ton, EURO5 | transport, freight, lorry 7.5-16 metric ton, EURO5 | cut-off, U*", respectively for passenger cars and HDV.

All inputs and outputs flows related to all processes belonging to the pavement life cycle phases depicted in Figure 1 are characterized into the impact categories specified by Bouwkwaliteit (2019) and converted into a single score, internationally referred to as environmental cost indicator (ECI) and called *MKI* in the Netherlands, using the weighting factors, also known as shadow prices, defined by Bouwkwaliteit (2019).

3.2. Comparative assessment

The comparative LCA study is performed to assert the environmental superiority of one scenario over another. Given the uncertainties in the traffic growth rate and IRI evolution over time, Monte Carlo (MC) simulation is used to propagate those uncertainties into the ECI. Further, to characterize the uncertainty in the relative ECI of the two scenarios the comparison indicator presented by Huijbregts et al. (2003) is adopted. It defines the ratio between impacts of two products according to Equation 3.

$$CI_{ECI} = \frac{ECI_B}{ECI_A} \tag{3}$$

Where CI_{ECI} is the comparison indicator; and ECI_B and ECI_A are the environmental costs indicator for *Scenarios B* and *A*.

4. Results

Numerical realizations of the modelled ECI for both M&R scenarios are obtained by performing MC simulation with 10000 runs. The probability density function (PDF) and cumulative distribution function (CDF) of CI_{ECI} are estimated and displayed in Figure 2. Looking at the CDF plot of Figure 2 one can see that the function asymptotically approaches 1 (100%) for a CI_{ECI} lower than 1 (approximately 0.6). In other words, that means that CI_{ECI} is lower than 1 in 100% of the total MC runs, and thus the total ECI corresponding to *Scenario B* is significantly lower than that corresponding to *scenario A*, even though *Scenario B* comprises the application of 5 mill and fill treatments over the analysis period, while no M&R treatments are applied in *Scenario A*.

The explanation for this result lies on the fact that the life cycle ECI is overwhelmingly driven by the use phase, as shown in Figure 3 that present the boxplot with the 25^{th} (99.09%), median (99.29%) and 75^{th} (99.41%) percentiles of the use phase contribution to the total ECI of *Scenario B.* Thus, it becomes clear that the regular application of the mill and fill treatment in *Scenario B* allows the pavement to remain in relatively good condition over the analysis period, which, in turn, leads to the mitigation of the roughness-induced RR environmental impacts. This benefit clearly outweighs the environmental impacts related to materials and mixtures production, mixtures transportation and machinery operation incurred during the application of the mill and fill treatment.

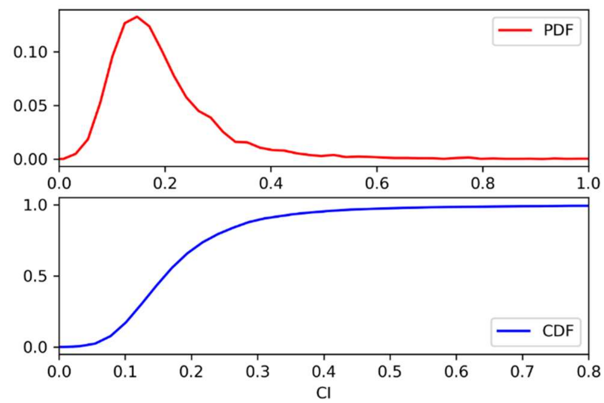

Figure 2. Probability density function (PDF) and cumulative distribution function (CDF) of the comparison indicator (CI).

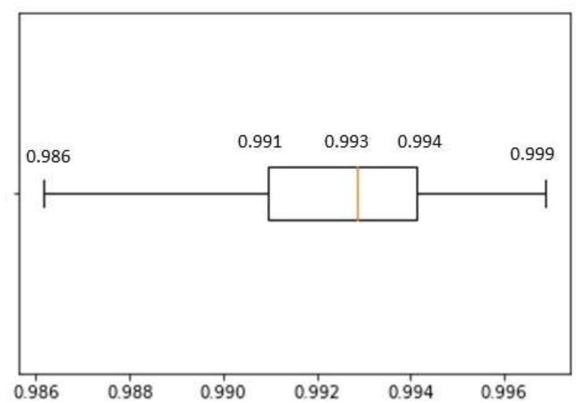

Figure 3. Boxplot of the relative contribution of the use phase to the total ECI in *Scenario B*.

5. Conclusions and future research work

This paper presents the results of a simple comparative LCA study of two alternative M&R strategies for a heavily trafficked road pavement section considering uncertainties in the roughness prediction model and traffic growth rate. The main takeaway message from this study is that the total environmental impacts of a heavily trafficked road are mainly driven by the pavement-related RR mechanisms. Thus, road authorities should incentivize the adoption of (1) construction practices and quality control protocols that result in lower initial roughness and macrotexture values and (2) maintenance and rehabilitation strategies that allow the values of those properties to remain low throughout the analysis period, even if the later comes at the expense of the consumption of additional raw materials. Other expected indirect benefits would include reduced vehicle maintenance and tire wear.

Several research opportunities exist that once accomplished would enhance the credibility of future comparative pavement LCA studies. Although it is not meant to be exhaustive, the list below unveils some topics worth pursuing:

- Development of project-specific pavement roughness and macrotexture prediction models;
- Development of probabilistic, spatially and temporally sensitive PVI models for each one of the three mechanisms (i.e., roughness, macrotexture and structural stiffness) considering the uncertainties in the predictors and real time driving conditions of the current and future vehicle fleets (i.e., hybrid and electric vehicles);
- Development of optimization-based PVI sensitive pavement design frameworks that allow practitioners to optimize various design parameters during the early design stage or decision-making process considering multi-objective functions.

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