Rolling Resistance and Traffic Delay Impact on a Road Pavement Life Cycle Carbon Footprint Analysis

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ABSTRACT: The application of Life Cycle Assessment (LCA) to road pavements has been continuously evolving and improving over the last years, however there are several limitations and uncertainties in the introduction of some components in the framework, such as road pavement rolling resistance – in terms of pavement surface properties – and traffic delay during maintenance activities. This paper analyses the influence of methodological assumptions and the model used to estimate the increased emissions for traffic delay and road pavement rolling resistance on the results of an LCA. The Greenhouse Gases (GHG) emissions related to these two phases of a pavement LCA will be calculated for a UK case study, using different models, and a sensitivity test is performed on some specific input variables. The results show that the models used and the input variables significantly affect the LCA results, both for the rolling resistance and the traffic delay.

1 INTRODUCTION

The rapid increase in pavement life-cycle studies in the literature shows the growing interest in improving the sustainability of this critical infrastructure system (Santero et al. 2011b). LCA is a standardized approach (International Organization for Standardization (ISO) 2006) that offers a comprehensive methodology for examining the net environmental performance of products, including all important interactions with human and natural systems.

While LCA represents a commonly accepted standard method, there are no widely accepted standards for pavement LCA (Harvey et al. 2016). The first pavement LCA studies were limited to the extraction and production of pavement materials. New studies have included other generally omitted phases, such as traffic delay, vehicle-pavement interaction, and pavement albedo showing promising reduction opportunities (Santero et al. 2011a). The lack of standardized procedures makes it difficult to perform comparable assessments, thus creating a synergistic set of literature that continuously builds upon itself rather than producing conclusions that are independent of the approach taken. In addition, the current knowledge gaps related to some phases makes the implementation of LCA principles complex and characterized by uncertainty. The impact of the traffic delay related to the work zone during the construction and the maintenance phase and the rolling resistance due to the pavement surface properties during the use phase are two components that, despite their omission from many previous LCA studies, can have a significant impact on the results.

Traffic delay results from lane or road closures at construction and maintenance work zones due to queueing or detours, around the construction site. In order to estimate the impact of this component, a two-step method, including a traffic model and an emission model, is usually used. In previous studies, two approaches have been used:

- A more sophisticated approach, using a microsimulation model to describe the work zone, by defining the average queue length and the instantaneous speed of individual vehicles

(Galatioto et al. 2015; Huang et al. 2014). Usually, these software tools include one or more emission models able to define the impact from the work zone.

- A simplified approach, based on the demand-capacity (D-C) model, defined in the Highway Capacity Manual (HCM) (Transportation Research Board 2010) that describes the work zone average queue and speed. An emission model is used, based on the output provided by the traffic models. This model was used by the Federal Highway Administration (FHWA) to develop a computational approach to analyse the user cost of work zone traffic delay, in life cycle cost analysis (LCCA) (Walls III and Smith 1998).

The advantage of using a simplified approach is the ease of implementation, requiring limited data input, such as hourly traffic volume, capacity and Traffic Management (TM) layout. However, the accuracy of the results could be compromised especially when the TM scheme is particularly complex (Wang et al. 2014b) or the area of impact is extensive and requires the modelling of a wider network.

By contrast, an approach based on microscopic modelling is more flexible and accurate, producing disaggregated traffic data and it can readily include the wider network. However, these models are usually incorporated in commercial software that increase the cost of the analysis and require detailed traffic data, which can limit the size of the network model. The model used to calculate the emissions related to this component can affect the results, especially for high traffic volume roads.

The road pavement rolling resistance is the energy loss due the pavement-vehicle interaction (PVI) and it is affected by the tire properties and by the pavement surface condition. Roughness and macrotexture, usually represented by International Roughness Index (IRI) and mean profile depth (MPD), are the pavement surface properties affecting the rolling resistance. These parameters change over the life of a pavement and their variation may be different for each lane, depending on the traffic volume and type, the surfacing type and the regional climate.

In order to estimate the impact of the pavement surface properties on vehicle fuel consumption, several models have been developed (Chatti and Zaabar 2012; Hammarström et al. 2012; Wang et al. 2014a). However, there is still uncertainty concerning the lack of validated models used to analyse the vehicle emissions and the influence of specific variables and assumptions on the results. Indeed, the literature related to the influence of road surface properties on vehicle rolling resistance and emissions shows different results, possibly because road surface components are a relatively small part of the rolling resistance and of the total driving resistance and it is difficult to isolate the road surface effects from other effects and quantify their contribution and different methods of measuring rolling resistance can lead to different results.

In the UK, this component is not generally included in the pavement LCA framework and there are no general pavement deterioration models to predict the deterioration rate of IRI and MPD, based on UK data. Some empirical deterioration models have been developed for specific maintenance treatments and geographical areas (Lu et al. 2009; Tseng 2012). However, in these models both the IRI and MPD values tend to increase over time, so they are not applicable to a UK case study where the MPD will generally decrease with time. The model used to investigate this impact and the input deterioration model can influence the conclusions of a study, making the results unreliable.

Recent studies have included these two components (Santero and Horvath 2009; Santos et al. 2015; Trupia et al. 2016 (in press); Xu et al. 2015) and during the last Pavement LCA Symposium in 2014 (Harvey and Jullien 2014), papers related to the emissions due to the work zone traffic delay (Huang et al. 2014; Wang et al. 2014b) and the impact of the PVI rolling resistance during the use phase (Akbarian et al. 2014; Ciavola and Mukherjee 2014) were presented. Although efforts have been made to fill the research gaps related to these components, there is still a level of uncertainty concerning the methodological assumptions, the chosen methods to analyse the vehicle emissions and the parameters that can affect the results.

The aim of this paper is to explore the influence of the model used and the methodological assumptions to estimate the increased emissions due to work zone traffic delay and the PVI rolling resistance phases on pavement LCA results. The GHG emissions related to these two phases will be calculated for a UK case study, using different models from the literature, and a sensitivity test is performed on specific input variables (extent of the area of impact of the work zone traffic delay and surface condition deterioration rate for the PVI rolling resistance).

2 METHODOLOGY

The CO_2 emissions due to the traffic delay during a maintenance event and due to the influence of the pavement surface deterioration rate on the PVI rolling resistance will be estimated, using different models including a sensitivity test on specific input variables. This will allow a comparison of the models available in the literature to decide if the knowledge related to these components is sufficient to implement them in a standardized LCA framework in the UK and to give some recommendations related to how to report them.

The tailpipe GHG emissions are made up of over 99.8% of CO_2 emissions, so in this study, only this component will be taken into account. The case study analyzed in this paper is a 4 km section of the dual carriageway A1 (M) motorway located in the North East of England, UK. The Annual Average Daily Flow in 2009 was 45,862 motor vehicles and 5,640 HGVs, making this segment a medium–high trafficked road. The original construction included a chipped hot rolled asphalt surface course. In 2009, a 40 mm overlay of thin surfacing was applied to a 4 km section of both carriageways and this is the event modelled in this study.

2.1 *Work zone traffic delay*

Jean Lefebvre (UK) Technical Centre provided several potential TM solutions for the 2009 maintenance work. The one assumed in this paper involves a carriageway closure and contra-flow on the other carriageway and requires 24 hours to install the 40mm Thin Surface Course per 1 km, three days to deploy the TM and three days to remove it (Figure 1), resulting in 17 days work to resurface both carriageways.

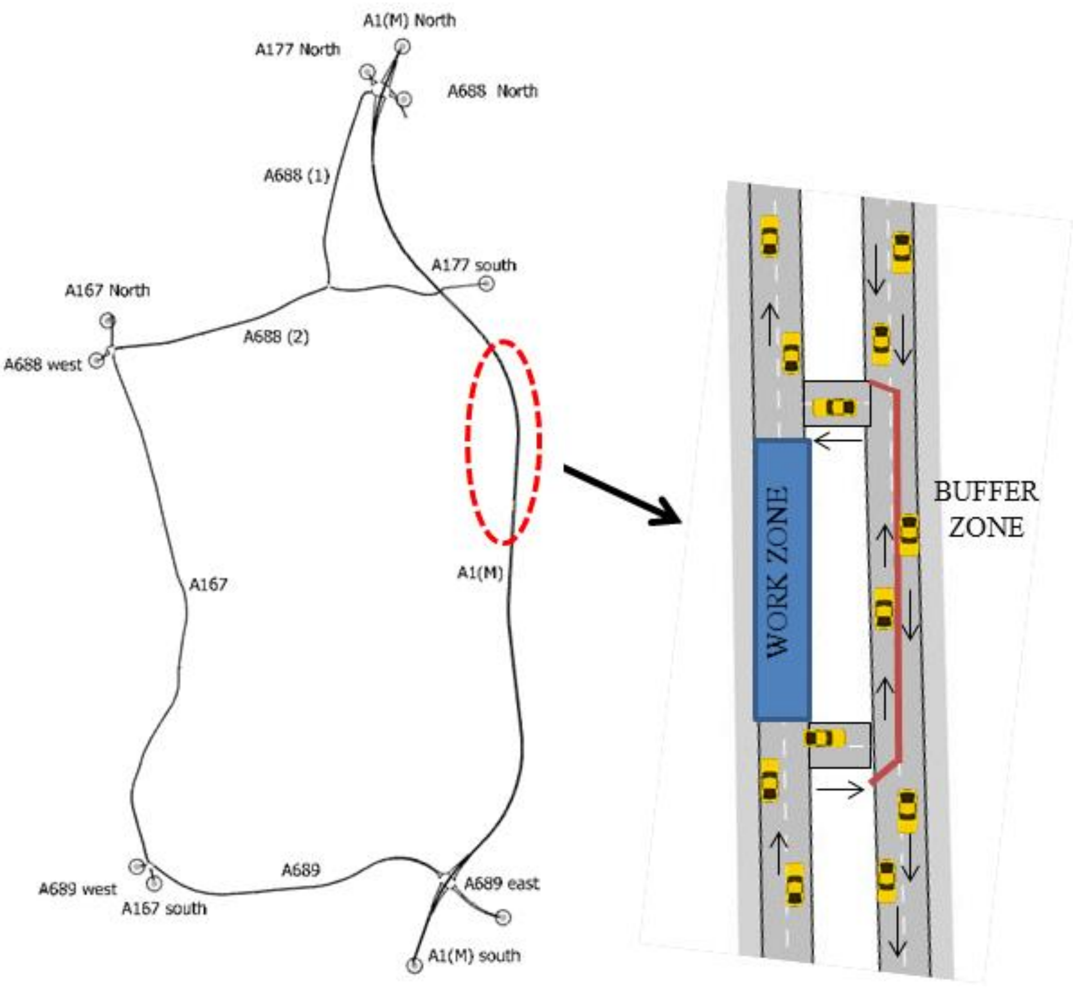

Figure 1. Work zone location and layout (northbound carriageway closure)

2.1.1 *Comparison of the traffic models*

The CO_2 emissions due to the effect of traffic delay were estimated using two different approaches: a simple approach including the traffic D-C model and a vehicle emission model, Emission Factor Toolkit (EFT) (UK Department for Environment Food & Rural Affairs 2014); and a more sophisticated approach involving the use of the microsimulation software AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) (Transport Simulation System (TSS) 2015) that includes a vehicle emission model. A detailed description of these models can be found in the references, but the key elements are described here. In both methods, the calculation of the impact of the work zone is based on the difference between the emissions during normal conditions (no work zone) and operational condition (maintenance event).

The first approach, based on the D-C model and the LCCA procedure, consists of several calculations:

1. Project future year traffic demand;
2. Work zone directional hourly demand;
3. Roadway capacity in normal condition and during maintenance;
4. Compare roadway capacity with hourly traffic demand and identify the work zone components (i.e. upstream traffic, queuing zone, slowing down zone) and the number of vehicles affected in each component.
5. Use the output from the traffic models in EFT to calculate the CO_2 emissions.

The emission factors for the CO_2 are those published by the UK Department for Transport (Boulter et al. 2009).

The microsimulation approach, with AIMSUN, uses a graphical interface and is able to model the road network geometry and the behavior of individual vehicles on the network. An interesting feature of this software is the possibility to choose a different route selection for some vehicles. In order to compare the two approaches a base case scenario was identified where the network analysed was confined to the linear segment of the A1 (M), including just the 4 km work zone (see Figure 2 'mini network'.).

2.1.2 *Sensitivity test on network modelling boundary*

The traffic modelling requires the identification of the extent of the network impacted by the work zone. For a comprehensive understanding, the modelling should cover the whole network affected and not only the work zone. During a maintenance event, the behavior of the vehicles is affected by the congestion occurring in the work zone and they could choose alternative routes, thus affecting other roads. Or, in the worst case scenario, the congestion could extend to an area not included in the modelling boundary. The microsimulation approach is more flexible from this point of view, allowing the area of analysis to be extended, taking into account the complex interaction of road elements, such as traffic lights, roundabouts, other junctions, etc.

In order to assess the impact of the network boundary, three different scenarios, taking into account different extensions of the analyzed network, were considered: the 'mini network' that represents the base case, a 'small network' including two roundabouts at the A1 (M) junctions and joining traffic streams and a 'big network' that includes possible diversions that vehicles could take in case of congestion (Fig. 2).

2.1 *Rolling resistance*

In order to estimate the effect of the pavement surface condition on vehicle fuel consumption, the CO_2 emissions were calculated with two different rolling resistance models; the UCPRC model developed at the University of California Pavement Research Center (UCPRC, Davis) (Wang et al. 2014a) and the model developed by the Swedish National Road and Transport Research Institute (VTI), within the European Commission project Miriam (Models for rolling resistance In Road Infrastructure Asset Management systems) (Hammarström et al. 2012). A similar analysis comparing these two models has been performed on another UK case study with a lower traffic volume (Trupia et al. 2016 (in press)). The results obtained on this second case study will allow for more confident conclusions related to the implementation of the rolling resistance model in pavement LCA and their application in the UK. The general features of the two models will be described here. Further details can be found in the references cited.

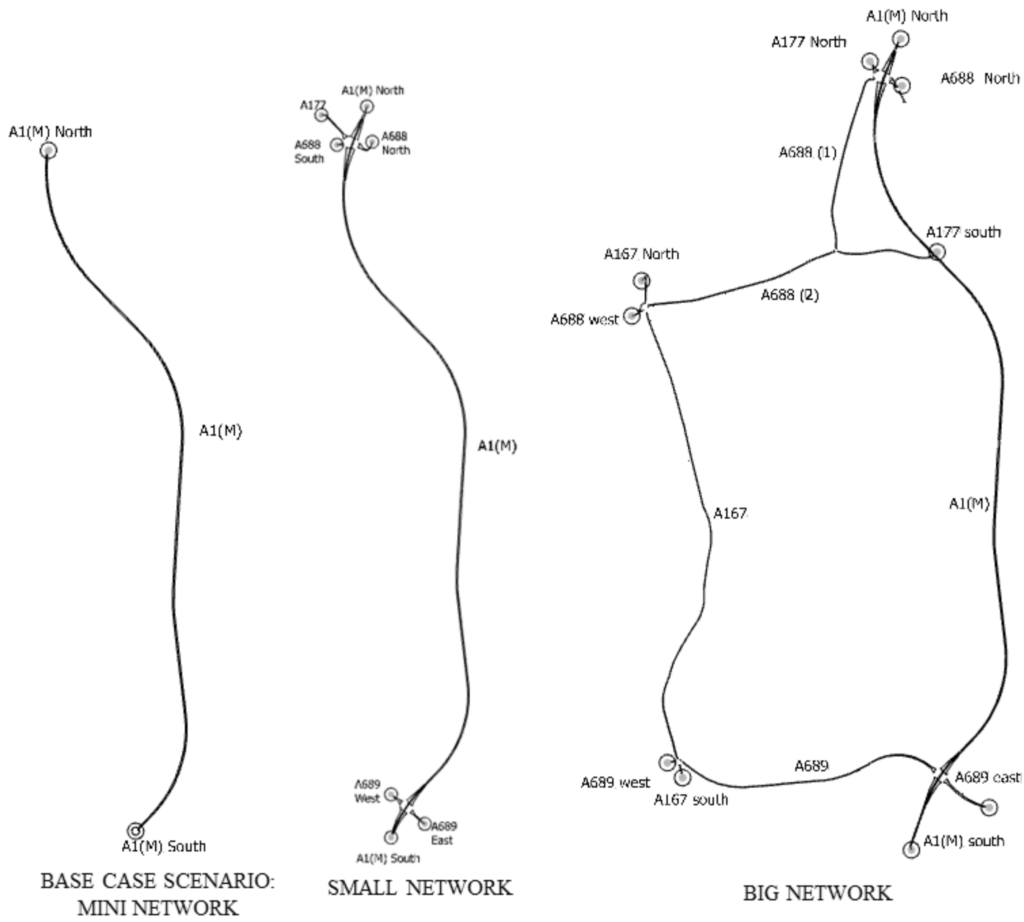

Figure 2. Network extension scenarios

In the UCPRC model, the CO_2 emissions for a specific vehicle type can be calculated directly, based on the analysed pavement segment's MPD and IRI values by using equation (1) and multiplying by the vehicle mileage travelled.

$$T_{CO_2} = a_1 \times MPD + a_2 \times IRI + Intercept \qquad (1)$$

Where T_{CO2} is the tailpipe CO_2 emission factor, the terms a_1, a_2 and *Intercept* are the coefficients derived from a regression analysis and are different for each combination of the categorical variables (pavement, road and road-access type, vehicle type), *IRI* is the road roughness (m/km) and *MPD* is the macrotexture (mm).

The model was developed using two different software calibrated for US conditions or based on empirical US data; the Highway Development and Management Model - version 4 (HDM-4) (PIARC 2002) (an empirical - mechanistic model to perform cost analysis for the maintenance and rehabilitation of roads) used to calculate the rolling resistance; and MOVES (Motor Vehicle Emission Simulator) (EPA's Office of Transportation and Air Quality (OTAQ) 2014), the US EPA highway vehicle emission model based on national data, used to model the vehicle emissions as a function of the rolling resistance. This model is included in the Pavement LCA Framework proposed for the USA by the FHWA (Harvey et al. 2016) as an appropriate modeling approach to calculate the impact of roughness and texture depth during the use phase.

The second approach is based on the VTI model to estimate the vehicle fuel consumption and emission factors proposed by International Carbon Bank & Exchange (ICBE 2010) to convert the vehicle fuel consumption into CO_2 emissions. The model includes a general rolling resistance model (equation (2)) to estimate the contribution of the rolling resistance to the total driving resistance and a fuel consumption model (equation (3)) to calculate the vehicle tailpipe fuel consumption (Hammarström et al. 2012).

$$F_r = m_1 \times g \times \left(0.00912 + 0.0000210 \times IRI \times V + 0.00172 \times MPD\right) \quad (2)$$

Where m1 is the vehicle mass (kg) and v is the vehicle speed (m/s).

$$F_{CS} = 0.286 \times \left(\begin{pmatrix} 1.209 + 0.000481 \times IRI \times V + 0.394 \times MPD + 0.000667 \times V^2 + 0.0000807 \times ADC \times V^2 \\ -0.00611 \times RF + 0.000297 \times RF^2 \end{pmatrix}^{1.163} \times V^{0.056} \right) \quad (3)$$

Where *ADC* is the average degree of curvature (rad/km) and *RF* is the road gradient (m/km). The models allows the total CO_2 emissions related to the IRI and MPD to be calculated (

Figure **3**), here defined as the “total component” (total area).

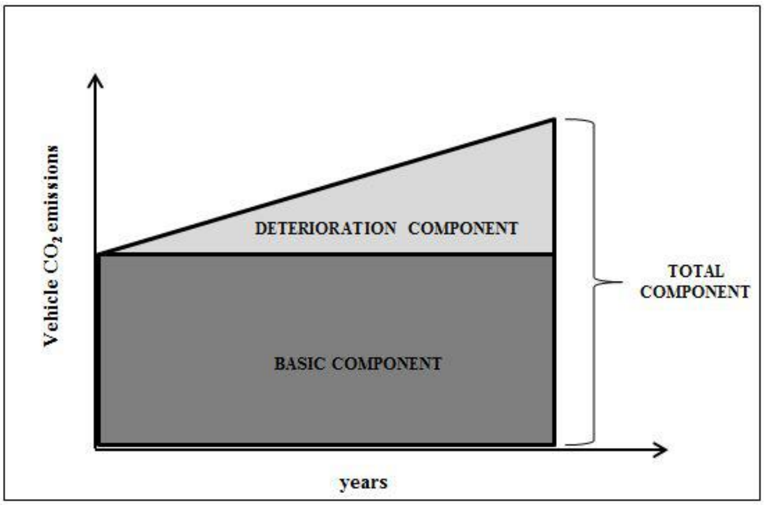

Figure 3. Total CO_2 emissions, divided into basic component (dark grey area) and deterioration component (light grey area) (from (Trupia et al. 2016 (in press)).

It represents the sum of the “basic component” (dark grey area) representing the emissions if the IRI and MPD do not change over time – no deterioration, and the “deterioration component” (light grey area) equal to the difference between the first two and representing the emissions due to the deterioration of the pavement condition during the analysis period, in terms of IRI and MPD. To better understand the behaviour of the two models, all the components will be assessed in this study.

The pavement condition deterioration rate with time represents an input parameter for the use of these models. Since in the UK there are no published models to predict this process, the time progression of IRI and MPD on the assessed road segments over the analysis period (20 years) is generated based on literature data for other maintenance strategies (Aavik et al. 2013; Jacobs 1982; Wang et al. 2014a).

A sensitivity test is performed on different scenarios of deterioration of IRI and MPD for the two case studies (see Table 1), to take into account the uncertainty related to these parameters and the range of potential impact. The average deterioration values and the IRI values in the worst deterioration scenario include an initial and final condition value and a linear change with time is assumed. In the average deterioration scenario, the MPD decreases over time; this is typical in the UK were high MPD values are specified for new surfacings to assist in provision of high-speed wet skidding resistance. The MPD in the worst deterioration scenario and the MPD and IRI for the no deterioration scenario are considered constant.

Table 1. Pavement deterioration rate, in terms of IRI and MPD, during the analysis period

Scenario	MPD	IRI
	mm	m/km
Average deterioration	1.8-0.8	1.0-2.3
Worst deterioration	1.5	1.0-5.0
No deterioration	1.8	1.0

3 RESULTS

3.1 *Work zone traffic delay*

Table 2 shows the extra CO_2 emissions due to the work zone, obtained by running the two models for the 'mini-network'.

Table 2. CO_2 emissions due to traffic delay during the work zone

	Emission of CO_2 (ton)	
	Microsimulation	D-C model
TM (17 days)	73.60	113.57
Per day	4.33	6.68

The results obtained with the two models are different, but of the same order of magnitude. The D-C model generates CO2 emissions about 50% higher than the microsimulation model. Clearly, this difference will have a big impact on the results when the TM involves many days of work. Table 3 shows the results obtained performing a sensitivity test on the network boundary, using the microsimulation, in order to investigate if and how the area of impact of the work zone can affect the results and how microsimulation software can be helpful in this process.

Table 3. Sensitivity test on network boundary

	Emission of CO_2 (ton)		
	Mini	Small	Big
TM (17days)	73.60	88.42	60.59
TM (1 day)	4.33	5.20	3.56

The results obtained are sensitive to the identification of the area of impact of the work zone. The Mini network is composed of a linear segment in the A1 (M) that includes the work-zone area but does not consider any potential diversions for the vehicles. The Small network takes into account the traffic generated by the two roundabout junctions to the North and the South of A1(M) and the associated traffic streams, but it does not allow any change in route choices. This network, compared to the Mini network, estimates larger emissions, because it considers also the emissions produced at the roundabouts due the extension of the congestion from the work zone. By contrast, in the Big network, the extra emissions estimated are smaller than in the Mini network, because the vehicles have the possibility to change their route during congestion to reach the same destination point.

3.2 *Rolling resistance*

Table 4 and Figure 4 show the results for PVI rolling resistance obtained for the different pavement surface condition deterioration rates, in terms of CO_2 emissions, using the VTI and the UCPRC models.

Table 4. CO_2 emissions due to pavement surface condition (average deterioration)

A1

Model	Emission of CO_2 (ton)		
	Basic	Deterioration	Total
VTI	109344	-4205	105139
UCPRC	18058	4586	22645

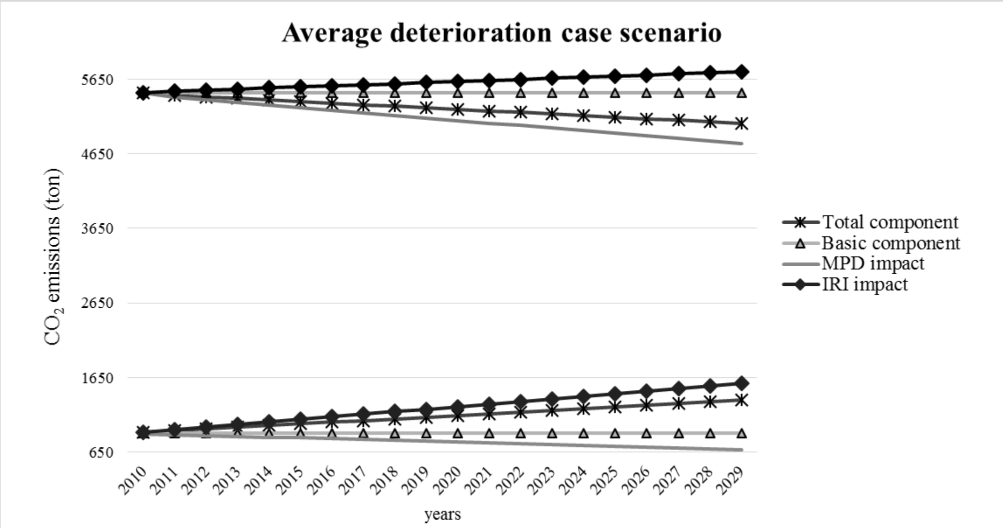

Figure 4. Impact of IRI and MPD in the VTI (above) and UCPRC (below) models

The values obtained for the basic components show that, even when not considering the deterioration rate over time, the two models produce different results. This difference in the basic component for the two models also affects the calculated values of the total component, which are also significantly different. The deterioration component for the VTI model is negative and this means that the evolution of the pavement surface condition generates an overall reduction in the total CO2 emissions. This result is due to two factors; in this case study the MPD tends to decrease over time and the VTI model assigns to the MPD term a greater impact on the rolling resistance and on the emission estimate than for IRI (even at high speed, which increases the impact of the IRI). In the UCPRC model, instead, the decrease of the MPD term over the years is offset by the increment of the IRI term that has a larger impact in this model. So the different weight that the two models give to the IRI and MPD terms can affect the results, especially for a case study where the MPD evolution is negative.

The potential impact of the pavement surface condition on the results is confirmed by the sensitivity test (see Table 5).

Table 5. Sensitivity Test Results

Scenario	Emission of CO_2 (ton)					
	VTI			UCPRC		
	B*	D**	T***	B*	D**	T***
Average	109344	-4205	105139	18058	4586	22645
Worst	109344	4716	114059	18058	19634	37693
No	109344	0	109344	18058	0	18058

* Basic component, ** Deterioration component, *** Total component

The results are very sensitive to the pavement deterioration rate, in particular:

- The two models generate the lowest emissions under different deterioration scenarios, average for the VTI model and no deterioration in the UCPRC. In the VTI model the deterioration component decreases over time, producing in the average scenario an overall reduction of the emissions.

- The highest emissions for the two models occur for the worst case scenario for both cases. Under this scenario, the VTI model does not generate a negative term for the deterioration component, since the IRI effect is larger than the MPD effect.

These results confirm the findings for the previous case study with a lower level of traffic (Trupia et al. 2016 (in press)). The results are significantly sensitive both to the pavement deterioration rate assumed and the rolling resistance/fuel consumption model used. The different validation of the two models, together with the different approaches used, can be considered the main reasons for this significant difference in the results, indeed, the models were calibrated for different countries with different input data, in terms of weather, vehicles, and roads.

4 CONCLUSIONS

The methodological assumptions and the models chosen for a pavement LCA, in terms of traffic delay due to a maintenance work zone and PVI rolling resistance model and pavement condition deterioration, significantly affect the results.

For the traffic delay, the type of traffic model used can affect the results. In addition, the extent of the road network modelled is an important factor in the analysis of the traffic delay component. Further research is necessary in this area to understand if it is possible to standardize this element and the type of traffic model required for a specific LCA study.

The results related to the comparison of the rolling resistance models confirm the findings of a previous case study with a lower level of traffic. The results are sensitive both to the model used to estimate the PVI rolling resistance CO2 emissions, and to the surface deterioration rate chosen. Site specific elements and methodological choice affect the development of the rolling resistance and fuel consumption models, meaning they are not suitable for all geographical locations. In the UK, pavement deterioration models and rolling resistance models need to be developed in order to introduce this component into the pavement LCA framework.

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