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Title

Influence of traffic delay produced during maintenance activities on the Life Cycle Assessment of a road

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Abstract

This paper analyses the relevance of the traffic delay generated during the A-8 Spanish Motorway maintenance activities in order to make recommendations for inclusion within the LCA of roads. Six congestion scenarios combining the level of service of the Motorway and the alternative N-634 route have been evaluated using two software packages: KyUCP (macro-simulation) and Aimsun (micro-simulation), whose results have been transferred into emissions using MOVES. After performing the LCA considering a functional unit of a 1-km lane with an analysis period of 30 years, results show the huge importance of this stage in all the scenarios analysed.

Keywords

Life cycle assessment (LCA); Congestion; Asphalt pavement; Road works; Traffic simulation

1. Introduction

Transport infrastructures play a very important role in the social and economic development of regions, but they also generate several environmental impacts throughout their life cycle due to the high consumption of energy and natural resources.

Life Cycle Assessment (LCA), a standardized method for measuring and comparing the potential environmental impact produced during the manufacture, use and disposal of a product has been applied several times to quantify the impact generated by roads. Häkkinen and Mäkelä (1996) and Horvath and Hendrickson (1998), among others, performed this kind of analysis to compare the impact generated by concrete and asphalt mixtures. Years later, Mroueh et al. (2000) used this methodology to determine the benefits of adding industrial by-products (such as coal ash or blast furnace slags) to the pavement structure.

More recently, Lizasoain-Arteaga et al. (2019) evaluated the benefits of using induction-healing treatment as an alternative to the conventional mill and overlay maintenance technique. However, despite this background, applying LCA to pavements is still at an immature stage (Yu and Lu, 2012) since some road life phases cannot be totally considered in the analysis due to the existence of gaps in the knowledge and lack of guidelines and methodologies which ease their inclusion.

Commonly, five stages are defined when talking about the life cycle of a road: material production, construction, use (which includes leaching, rolling resistance, albedo and lighting), maintenance (which considers traffic delay in addition to the replacement of the layers) and end of life. Nevertheless, according to Inyim et al. (2016), only 27% of studies consider all of these phases, traffic delay being analysed in only 7 of the 42 research articles reviewed by Santero et al. (2011), Trupia (2018) and Anthonissen et al. (2016).

The importance of maintenance-related traffic delay in the total environmental impact produced by roads has been analysed by some authors achieving different results depending on the road traffic volume, its hourly traffic distribution and the closure schedule (Santero et al., 2010). Results can also be influenced by the traffic model selected to calculate the queue during congestion. Micro-simulation models are based on predicting the individual behaviour of vehicles, which requires a lot information for its calibration and a long time for running the simulation. On the other hand, macro-simulation models analyse the traffic on a section by section basis (Trupia, 2018), needing less information but also being less accurate. In this regard, Yu and Lu (2012) performed an LCA to calculate the energy consumption and Global Warming Potential generated by three overlay systems. After analysing the whole life cycle, congestion (which was calculated with a macro-simulation model) was one of the most important stages; its relevance increasing as traffic volume did. Galatioto et al. (2015) studied the influence of traffic delay on atmospheric emissions when applying different management options (three overnight lane closures, two 12-hour closures and a 24-hour closure) in a UK inter-urban road. In this case, a micro-simulation model was used and, despite the fact that the extra emissions produced by congestion were found to be relatively small, they were big enough to be included in the calculation. Moreover, Kim et al. (2018) evaluated the fuel consumption and greenhouse gas emissions produced by two types of roads (a freeway and a multilane road) when two different work zones situations and three congestion levels are taken into account. Results showed an emissions increase of around 85% under heavily congested work zones when default drive schedules were applied. Therefore, it can be inferred from these studies that systematically ignoring the impact produced by congestion during the maintenance and rehabilitation interventions can bring about a lack of accuracy in the LCA results, especially in highly trafficked roads.

This paper aims to make recommendations about when and how to consider traffic delay in the LCA of a road to foster its evaluation within the total analysis. To achieve this goal, the environmental impact produced by maintenance-related congestion was analysed taking into account three different service levels of the motorway itself and an alternative route. Then, these results were compared to the total environmental impact of the road to calculate the relevance of traffic delay and to determine the possibility of simplifying the model without losing precision. Furthermore, two traffic simulation models (micro- and macro-simulation) were applied to check the sensitivity of the LCA when varying the accuracy of the traffic results.

2. Methodology

2.1. Case study definition

Making recommendations implies the analysis of a wide range of situations from which to draw conclusions. In this research, which tries to evaluate the relevance of the environmental impact produced by the congestion caused during road maintenance, aspects such as the Annual Average Daily Traffic (AADT), the existence of alternative routes, the geometry of the road or the traffic characteristics (percentage of heavy traffic and hourly distribution) can greatly affect the results. However, analysing the effect of all these variables would result in an unmanageable number of case studies. Therefore, the concept of level of service (LOS) was introduced instead, since it determines the quality of the traffic flow based on the aforementioned aspects. The Highway Capacity Manual (National Research Council (U.S.). Transportation Research Board., 2010) defines 6 LOS designated with letters, from A to F, where A describes a free-flow traffic with users unaffected by the presence of others and F represents a totally congested road.

A stretch located between the Kilometric Points 175 and 176 of the A-8 Spanish Motorway with an AADT of 41,026 vehicles, which connects the main cities on the north coast, was selected for analysis (see Figure 1). This section has an alternative route, namely the N-634 National Road (AADT of 12,151), running parallel to the Motorway. Therefore, when a queue is created in the Motorway due to the closure of a lane, a certain percentage of vehicles can be deviated onto the National Road.

Figure 1. Studied section.

As a consequence, congestion, and the consequent environmental impact produced, will not only depend on the traffic flow quality of the road that is being repaired (A-8), but also on the LOS of the alternative route (N-634). For this reason, six scenarios were studied combining the LOS of both roads (Table 1) and a 15-km stretch of each road was included in the simulations to capture the effect of the 1-km lane closure on the whole network.

Table 1. Scenarios analysed.

Scenario	A-8 LOS	N-634 LOS	A-8 AADT (vehicles/day)	N-634 AADT (vehicles/day)
1	A	A	21,166	2,562
2	B	A	54,980	2,562
3	B	B	54,980	8,196
4	C	A	78,985	2,562
5	C	B	78,985	8,196
6	C	C	78,985	14,543

The characteristics of the roads (Table 2) provided by the Spanish Ministry of Public Works (Ministerio de Fomento, 2017) were used to calculate the AADT of both roads depending on the given LOS for each scenario (Table 1). However, the peak-hour factor, type of terrain, driver factor and peak-hour direction proportion factor were assumed.

Table 2. Road characteristics.

Road characteristics	A-8	N-634
Free-Flow speed (km/h)	120	72
Average speed (km/h)	104	63
Heavy vehicles (%)	9.75	2.66
Recreational vehicles (%)	0	0
Peak-hour factor	0.95	0.88
Type of terrain	Level	Level
Driver population factor	1	1
Peak-hour AADT proportion (k)	7.02	7.02
Peak-hour direction proportion (R)	0.5	0.5

The calculations were made following the Highway Capacity Manual (National Research Council (U.S.). Transportation Research Board., 2010). This Manual defines the maximum service flow rate for different LOS and types of roads in optimal conditions (3.60 m lane width, only light vehicles, level terrain and usual drivers). However, the selected roads do not fulfil these circumstances so these values have been adapted to reflect the reality of the case studied (Figure 2 and Figure 3). As is shown in Figure 2, the AADT of a specific LOS depends on the road density and also on the free-flow speed as far as a motorway is concerned, while on the N-634 (a rural type III road which passes through small tourist villages), it depends on the percentage of Free-Flow Speed (PFFS). As a representative point, the median AADT of the LOS chosen before (Table 1) was selected.

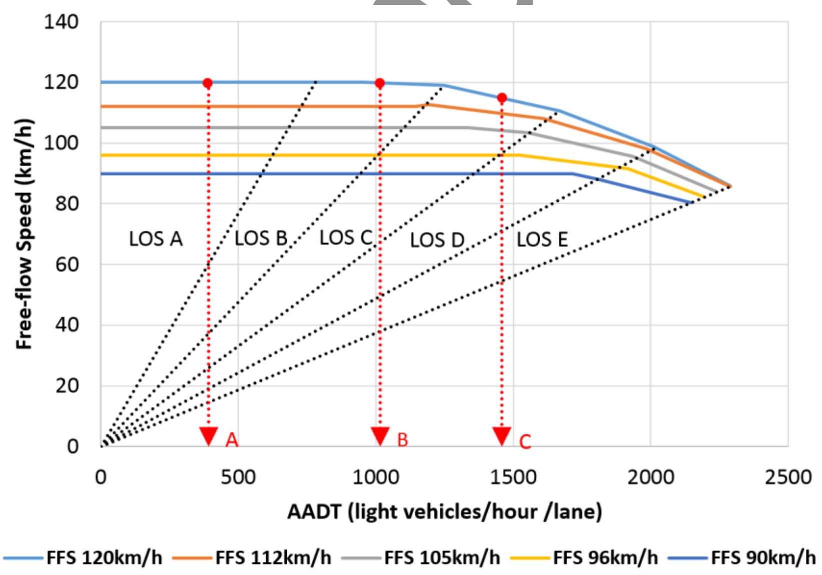


Figure 2. AADT LOS A-8. Real conditions.

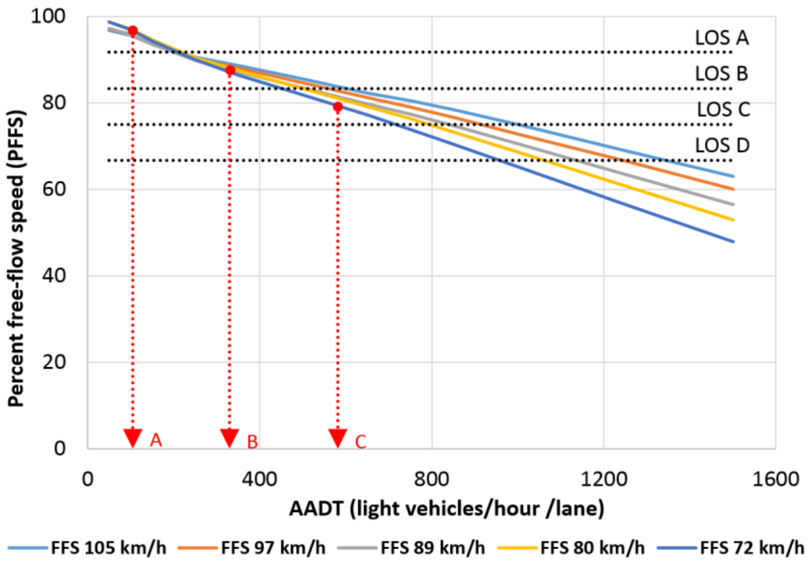


Figure 3. AADT LOS N-634. Real conditions.

2.2. Traffic software employed

As mentioned before, two traffic simulation software packages (macro and micro) were used in this paper to calculate the congestion produced by traffic delay during road maintenance.

The Kentucky Highway User Cost Program v1.0 (KyUCP) was selected for the macro-simulation. This software, programmed in Excel following the Highway Capacity Manual, enables the queue length of a roadwork to be calculated based on the AADT, normal and work zone speed limits and number of lanes closed during construction. However, it has been modified since it does not originally take into account the possibility of having an alternative route that could absorb part of the demand when queues are created. Considering the design of the road network used in the study, 30% of the demand was rerouted when a 1-km queue was detected (Erke et al., 2007), (Koo and Yim, 1998), (Knoop et al., 2010), (Kucharski and Gentile, 2019).

On the other hand, Aimsun Next v8.3.0 was used for the micro-simulation. In this case, the real network needs to be created and calibrated with real traffic data to ensure that the model replicates the vehicles' real behaviour. In this regard, data from traffic stations of the Spanish Ministry of Public Works and of the Transport Systems Research Group of the University of Cantabria were employed. Then, the origin-destination matrix was modified to fit the AADT to the one previously defined for each scenario. Nevertheless, this change in the number of vehicles could affect the travel time associated with the different available routes, thus affecting the path selected by every vehicle simulated and consequently the results. To avoid this, for each scenario, vehicles were forced to follow the original trajectories and again, during the maintenance stage, 30% of the vehicles were deviated to the National route as is expected to occur during real traffic congestion.

The traffic strategy taken into account during the maintenance work was defined following the Spanish 8.3-IC Standard for roadwork signposting (Ministerio de Fomento, 1989). As shown in Figure 4, when closing a road lane the adjacent lane width is reduced by 0.30 m to create a security zone, reducing the speed from 120 km/h to 80 km/h gradually.

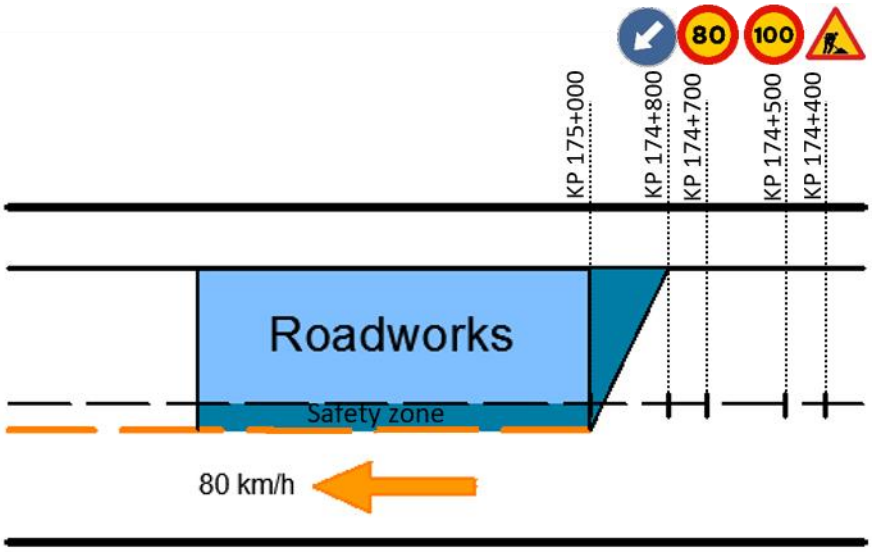


Figure 4.Maintenance strategy diagram.

2.3. Emission model calibration

For the evaluation of the environmental impact, as KyUCP does not include a pollutant emission model, the EPA's Motor Vehicle Emission Simulator (MOVES) was selected due to its wide acceptance by the scientific community and the vast number of pollutants that are available. In the case of Aimsun, the Panis Emission Model (Int Panis et al., 2006) is already incorporated in the software to calculate the pollutant emissions produced by the simulated traffic. This model provides the emissions for 4 pollutants (Carbon Dioxide, CO_2; Nitrogen Oxides, NOx; Volatile Organic Compounds, VOC; Particulate Matter, PM) based on each vehicle's instantaneous speed and acceleration and distinguishing between different types of vehicles and fuels. However, due to the limited number of pollutants addressed by the Panis Model, the integration of MOVES in Aimsun was proposed in this work.

To define the most relevant pollutants for this analysis, the emissions produced by 100 vehicles driving at a constant speed (8 km/h) along a 1-km lane were calculated with MOVES considering the age and fuel consumed by the region's current vehicle census (Dirección General de Tráfico, 2017). A basic LCA was carried out with the emissions obtained to determine their importance within the different impact categories according to the ReCiPe methodology. The contaminants selected for the calculation were CO_2, CO, NOx, CH_4, C_6H_6, NH_3, VOC and $PM_{2.5}$. According to the results (Table 3), the emissions of VOC and CH_4 could be neglected while still guaranteeing the accuracy of the environmental assessment.

Table 3. Contribution of the pollutants to the LCA impact categories.

Impact / Pollutant	CO_2	CO	NOx	CH_4	C_6H_6	NH_3	VOC	$PM_{2,5}$
Climate change	100%							
Freshwater ecotoxicity					100%			
Human toxicity					100%			
Marine ecotoxicity					100%			
Marine eutrophication			38%			5%		
Particulate matter formation			76%			6%		12%
Photochemical oxidant formation		33%	61%					

Terrestrial acidification	76%		18%
Terrestrial ecotoxicity		100%	

Concerning MOVES, within the calculation options offered, it is possible to define on-road activity by using individual vehicle trajectories obtained by traffic micro-simulation. However, due to the high number of records per vehicle in the scenarios evaluated in this paper and the difficulties in handling them (more than 15 million), this option was discarded and the integration of the MOVES emission model in Aimsun was preferred. Thus, the Panis model (Int Panis et al., 2006), integrated in Aimsun, was recalibrated to fit the MOVES emission model. It should be noted that the emission rates in MOVES are linked to 23 operating modes for running, which combine speed and the vehicle specific power (VSP), as well as other operating modes for idling, braking, hotelling, among others. The VSP, which can be calculated with eq. (1) (Jiménez-Palacios, 1999), gives an indication of the amount of energy demanded by the engine during running, and combines multiple physical factors that influence the vehicle's consumption and emissions such as vehicle speed $v_n(t)$, acceleration $a_n(t)$ or load parameters (Koupal et al., 2003).

Considering this, new traffic simulations were carried out in Aimsun (100 vehicles in a 1-km lane) by introducing several traffic light timings, which resulted in different vehicle acceleration and deceleration patterns. In total, more than 30,000 trajectories were recorded in Aimsun's database. With the instantaneous speeds and accelerations from the 30,000 trajectories and with their VSP determined through eq. (1), it was possible to distribute each trajectory into the operation modes proposed in MOVES and therefore calculate the emissions related to each trajectory.

Then, trajectory speeds $v_n(t)$, accelerations $a_n(t)$ and emissions were correlated according to the Panis function eq. (2) (Int Panis et al., 2006). For this, a fit regression model was used with Minitab 17 Statistical Software to determine E_0 and f_1 to f_6. This methodology was applied for the two types of vehicles considered in this paper (passenger cars and single unit long-haul trucks) and the six pollutants mentioned above. The results are presented in Table 4.

$$\text{VSP} = v_n \times [1.1a_n + 9.81grade\ (\%) + 0.132] + 0.000302{v_n}^3 \quad (1)$$

$$Emission\ (t) = max\ [E_0, f_1 + f_2v_n(t) + f_3v_n(t)^2 + f_4a_n(t) + f_5a_n(t)^2 + f_6v_n(t)a_n(t)] \quad (2)$$

In order to obtain a better correlation, the emission function of certain pollutants was fitted twice, for acceleration trajectories ($a_n(t) \geq -0.5$ m/s^2) and deceleration trajectories ($a_n(t) < -0.5$ m/s^2), thus resulting in different values for E_0 and f_1 to f_6 (see Table 4). As the need of splitting the model into two functions was already observed in Int Panis et al. (2006), the emission model available in Aimsun already contemplates the possibility to insert different factors for an(t) ≥ − 0.5 m/s2 and an(t) < − 0.5 m/s2. In Figure 5, the correspondence between the CO_2 emissions calculated by distributing the trajectories in operation modes (MOVES) and by using the "recalibrated" Panis Function is shown.

Table 4. Calibrated factors for the Panis equation.

Pollutant	Type of vehicle	E_0	f_1	f_2	f_3	f_4	f_5	f_6
CO_2	Car	8.70E-01	8.44E-01	8.82E-02	2.72E-03	2.23E+00	-8.13E-01	2.29E-01
	Truck	2.53E+00	2.24E+00	9.61E-01	6.93E-03	1.04E+00	-2.58E+00	2.99E+00
CO	Car a ≥ $-0.5\ m/s^2$	0.00E+00	1.39E-02	3.56E-04	1.50E-05	-5.66E-02	-2.44E-03	1.74E-02
	Cars a < $-0.5\ m/s^2$	0.00E+00	1.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Truck	-2.58E-02	1.51E-02	6.46E-03	-9.01E-05	-1.58E-02	-6.03E-03	1.45E-02

NOx	Car a ≥ $-0.5\ m/s^2$	9.00E-04	-6.87E-04	2.15E-04	5.00E-06	4.78E-03	-1.72E-03	6.56E-04
	Car a < $-0.5\ m/s^2$	9.00E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Truck a ≥ $-0.5\ m/s^2$	0.00E+00	4.21E-02	1.85E-03	3.05E-04	1.79E-02	-4.03E-02	2.29E-02
	Truck a < $-0.5\ m/s^2$	0.00E+00	2.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C_6H_6	Car	1.78E-05	1.58E-05	1.88E-07	2.50E-08	2.29E-06	-6.93E-06	5.60E-06
	Truck a ≥ $-0.5\ m/s^2$	0.00E+00	1.88E-05	1.79E-05	-5.50E-07	1.08E-04	5.57E-05	4.90E-06
	Truck a < $-0.5\ m/s^2$	0.00E+00	3.80E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NH_3	Car a ≥ $-0.5\ m/s^2$	0.00E+00	6.16E-05	-3.70E-06	4.75E-07	4.39E-05	-3.49E-05	1.07E-05
	Car a < $-0.5\ m/s^2$	0.00E+00	7.20E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Truck a ≥ $-0.5\ m/s^2$	0.00E+00	1.14E-04	-1.68E-06	4.80E-07	1.06E-05	4.66E-06	-3.90E-07
	Truck a < $-0.5\ m/s^2$	0.00E+00	1.67E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
$PM_{2.5}$	Car a ≥ $-0.5\ m/s^2$	3.65E-05	3.23E-05	2.79E-06	7.51E-08	-1.48E-03	3.71E-04	1.74E-04
	Car a < $-0.5\ m/s^2$	3.65E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Truck a ≥ $-0.5\ m/s^2$	0.00E+00	1.28E-03	3.25E-04	-1.53E-06	-6.95E-04	2.04E-04	1.05E-03
	Truck a < $-0.5\ m/s^2$	0.00E+00	9.15E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

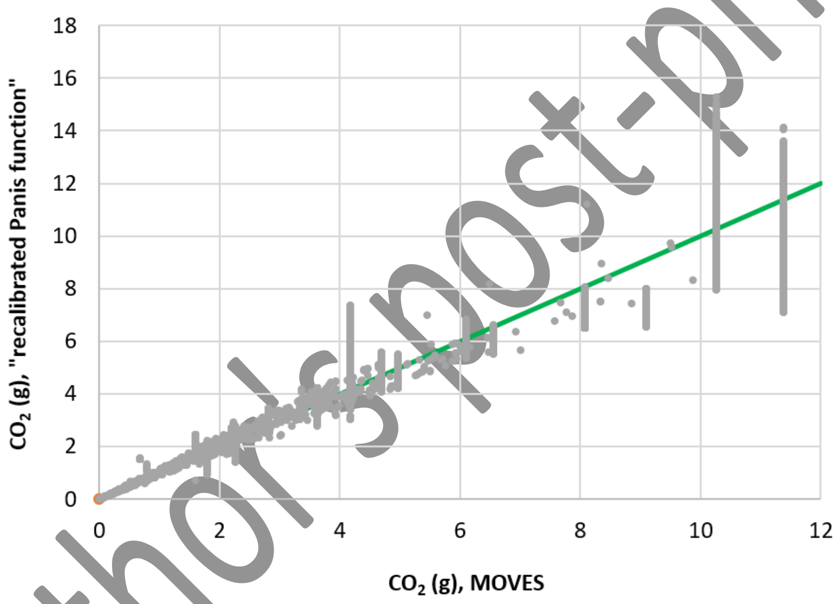


Figure 5. Correspondence between the CO_2 emissions calculated with MOVES' emission rates (horizontal axis) and the "Recalibrated" Panis Function (vertical axis).

2.4. LCA

The relevance for the environment of the traffic delay produced during road maintenance for different LOS was evaluated by means of the LCA methodology following the standards ISO 14040:2006 (ISO, 2006a) and 14044:2006 (ISO, 2006b).

For the assessment, a 1-km lane of the Spanish A-8 Motorway and an analysis period of 30 years was considered as a functional unit. Regarding the pavement thickness, it depends on the heavy traffic category (defined by the Annual Average Daily Truck Traffic, AADTT) of the road according to the Spanish Standard 6.1-IC (Ministerio de Fomento., 2003) concerning pavement sections. Based on this document, two pavement sections were analysed in this paper, a T1 traffic category (800 ≤ AADTT <2,000) that corresponds to the "A" LOS and a T0 (2,000 ≤ AADTT <4,000) traffic category that corresponds to the "B" and "C" LOS (Figure 6).

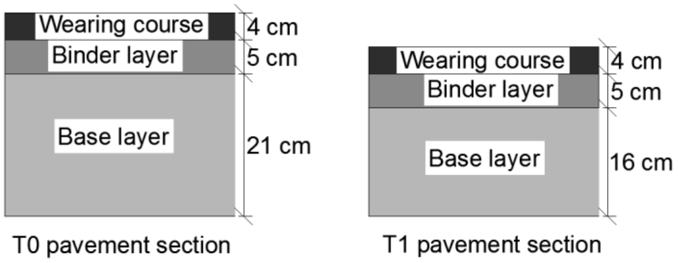


Figure 6. Pavement sections.

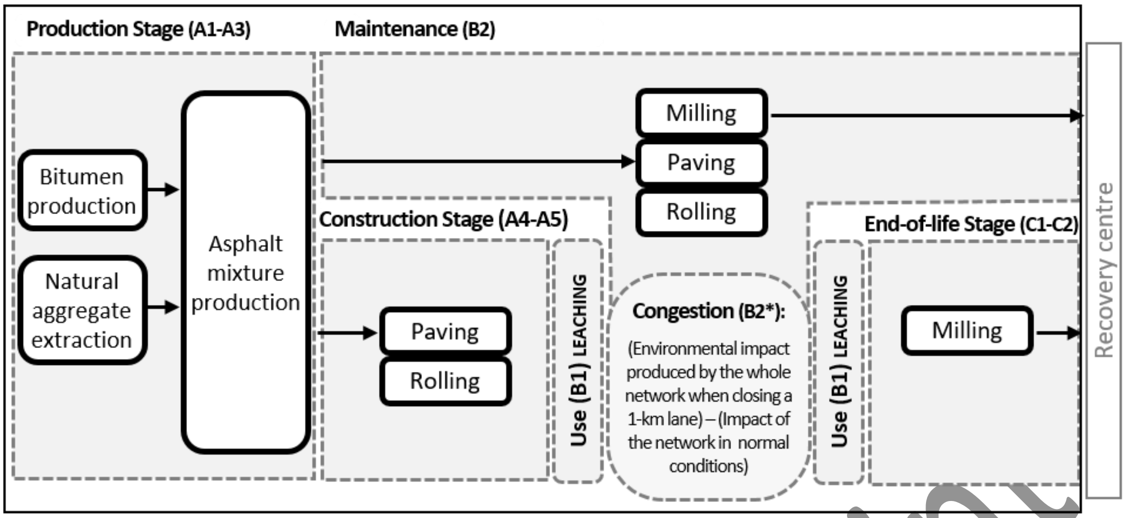
Normally, when comparing two roads in which the only difference is the wearing course, the model is simplified analysing only the distinctive aspects (Chiu et al., 2008) (Jullien et al., 2006). However, in those scenarios where the differences are present in all the structure or a detailed analysis is needed, the whole pavement should be studied. Therefore, this research considers both approaches in the analysis of the relevance of the traffic delay in environmental assessment.

The characteristics of the asphalt mixtures considered for each asphalt layer can be seen in Table 5 (Moral Quiza, 2016).

Table 5. Asphalt mixture definition.

Details	Wearing course	Binder layer	Base layer
Type of mixture	AC 16	AC 16	AC 22
Coarse and fine aggregates (% wt.)	90.4	89.4	92.2
Bitumen (% wt.)	4.6	4.6	3.8
Filler (% wt.)	5	6	4
Mixture density (kg/m^3)	2,459	2,357	2,371

The LCA was performed taking into account 6 stages of the road life (Figure 7): material production, construction, maintenance, congestion, leaching and end-of-life, which are more extensively explained in a previous research where the inventory data is also detailed (Lizasoain-Arteaga et al., 2019). However, unlike in that work, instead of a porous asphalt (PA), here an asphalt concrete (AC) layer is being considered for the wearing course, which, according to EAPA (2007) and Nicholls et al. (2010), has a life expectancy of about 15 years. Therefore, the maintenance schedule shown in Table 6 was proposed. Furthermore, regarding the leaching stage, the values shown in Lizasoain-Arteaga et al.(2019) for the conventional asphalt mixture were used. As the AC layer is a dense asphalt mixture and, therefore, impermeable, only the wearing course is considered to be in contact with rainwater, being the only layer with possible leachates.



* Module added to the original UNE-EN 15804:2012 classification

Figure 7. LCA boundaries.

Table 6. Maintenance schedule

Year	0	15	30
Activity	Section construction	Wearing course mill and overlay	Final milling of the section

Regarding the transformation into impacts of the resources and emissions detected during the inventory phase, the ReCiPe 1.08 Hierarchical characterization method was used. This method enables the transformation of the midpoint impacts, which are focused on a single environmental problem, into endpoint impacts which have the benefit of combining the effect of the midpoint impacts to calculate the damage to the three areas of protection (damage to human health, damage to ecosystem diversity and damage to resource availability) (RIVM, 2016).

3. Results

Once the micro- and macro-simulation were performed for the 6 scenarios considering a length of 15-km for both the motorway and the national road, the following queues have been detected on the motorway when closing 1 km of a road lane during 24 hours due to maintenance activities (Table 7).

Table 7.Traffic queue length (km).

Hour	S1		S2 & S3		S4 & S5 & S6	
	Macro	Micro	Macro	Micro	Macro	Micro
1	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.1	0.1	1.2	0.3
9	0.0	0.0	0.6	0.1	2.8	0.9
10	0.0	0.0	1.4	0.1	3.6	0.9

11	0.0	0.0	1.1	0.1	4.2	0.9
12	0.0	0.0	0.3	0.1	4.6	0.9
13	0.0	0.0	0.1	0.1	4.8	0.8
14	0.0	0.0	0.3	0.1	5.1	0.9
15	0.0	0.0	0.8	0.1	5.6	1.0
16	0.0	0.0	1.4	0.1	6.2	0.9
17	0.0	0.0	1.0	0.1	6.7	0.9
18	0.0	0.0	0.2	0.1	7.4	0.9
19	0.0	0.0	0.5	0.1	8.4	1.0
20	0.0	0.0	1.3	0.1	9.1	0.9
21	0.0	0.0	0.7	0.0	8.7	0.6
22	0.0	0.0	0.0	0.0	7.2	0.0
23	0.0	0.0	0.0	0.0	4.8	0.0
24	0.0	0.0	0.0	0.0	1.7	0.0

When the lane closure is performed in a road in which the peak-hour corresponds to an “A” LOS, no congestion is created in any of the models employed to carry out the simulations (KyUCP and Aimsun) (Table 7). In this scenario (S1), around 740 vehicles arrive at the studied section in the most trafficked hour and the capacity of a single lane (1587 light vehicles per hour ((National Research Council (U.S.). Transportation Research Board., 2010))) is enough to absorb the traffic demand. Furthermore, no speed variation is produced thorough the day in the different sections of the road (Figure 8), vehicles only adapting to the speed limits fixed for the roadworks.

In scenarios 2 and 3, in which the A-8 Motorway presents a “B” LOS, a slight reduction in the vehicle speed is observed during the most trafficked hours (8 a.m. – 8 p.m.) in the micro-simulation model (Figure 8). This decrease is more relevant in the section before the roadwork (P.K. 174-175) since vehicles travelling in the right lane have to find a gap in the traffic flow to change lanes. This traffic manoeuvre creates a small bottle neck that is not big enough to make drivers change their trajectory and therefore, the National Road (N-634) is not affected by congestion. On the contrary, KyUCP software does not consider intermediate velocities between 104 km/h (average A-8 speed) and 8 km/h (congested speed) and as a consequence, bigger queues are calculated. In fact, under this approach 2,498 vehicles change their route to avoid the motorway congestion.

Queues created when the Highway presents a “B” LOS are transformed into bigger ones when the AADT increases. In this sense, in scenarios 4, 5 and 6 (C LOS) the macro-simulation model calculates queues of around 9-km length despite the 30% demand deviation. However, traffic disruption remains close to 1 km in the micro-simulation, vehicle speed being highly reduced in the section before the roadwork.

Figure 8 also shows that the rerouted vehicles are easily absorbed on the National Road with only 7% speed reduction when it originally has an “A” LOS. The disruption worsen when the traffic flow quality decreases, producing almost 60% speed reduction in the most trafficked hours when scenario 6 (C LOS) is considered.

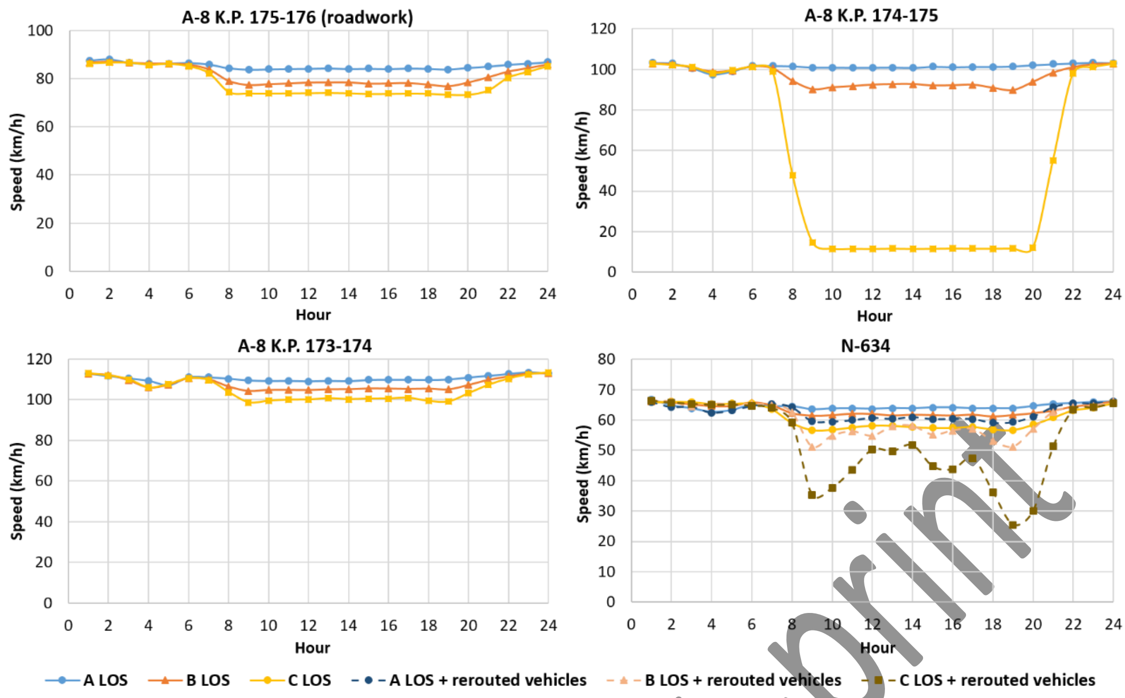


Figure 8. Aimsun average speed variation.

In view of this speed reduction on the alternative route, it could be thought that deviating cars from the A-8 Motorway to the N-634 road when the latter presents a high AADT could imply a transfer of the traffic problem from one road to the other, the overall network being equally congested. That is why the traffic network performance was evaluated by using the Network Macroscopic Fundamental Diagram (NMFD) (Geroliminis and Daganzo, 2008). The NMFD has been widely reported in several studies as a useful tool to measure and evaluate the overall state of a traffic network (Alonso et al., 2019; Sirmatel and Geroliminis, 2018; Wu et al., 2011; Yildirimoglu et al., 2018). Thus, Figure 9 shows the estimated network fundamental diagram for scenario 6 comparing the network performance when both 30% traffic divergence and no traffic strategy (called "do nothing") are implemented. As expected, traffic conditions worsen as demand increases. However, while the network still remains stable when the traffic management strategy is followed, it reaches the unstable region in the "do nothing" case.

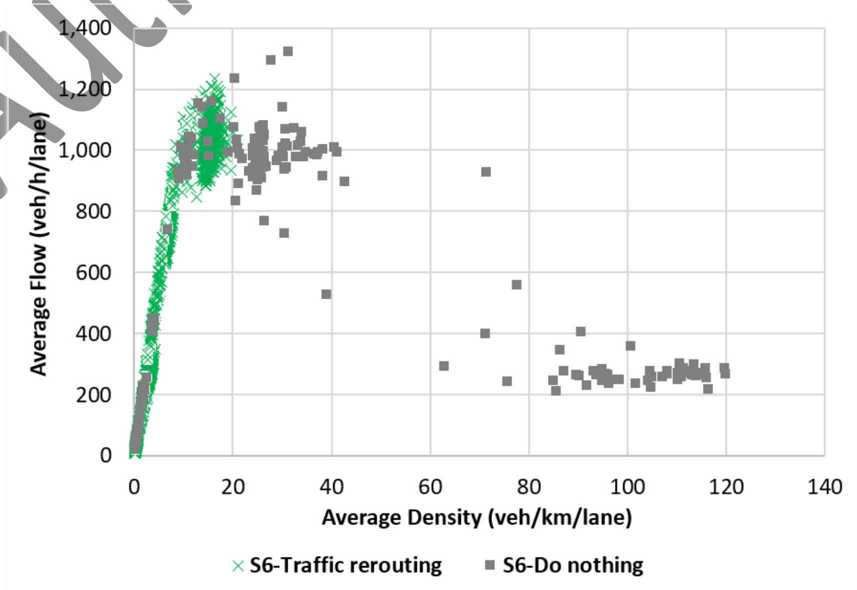


Figure 9. Network Fundamental Diagram comparing scenario 6 with traffic management strategy (30% rerouting) and "do nothing" case

Speed variation and queue creation affect the emissions generated by vehicles. The emissions produced by traffic during the maintenance activities can be seen in Table 8 and Table 9 for the macro- and micro-simulation, respectively. These quantities have been calculated by subtracting the pollution generated in normal conditions from the emissions produced during the roadworks. Therefore, the macro-simulation results are the same for scenario 2 and 3 and also for 4, 5 and 6. As the only difference among them is the number of vehicles that originally travel via the N-634 and no variation in the speed due to the increment in the number of vehicles is being considered, the differences disappear when performing the subtraction.

Figure 10 (Lizasoain-Arteaga et al., 2019) shows the relationship between vehicle emissions and speed. For the same distance travelled, the maximum emissions are obtained when vehicles drive at 8 km/h (congestion speed). This amount is reduced as speed increases until around 100 km/h is reached, when the minimum emission factor is produced. However, this tendency is not followed for NH_3 since the minimum emission is generated at 50 km/h. This explains the results in Table 8. For instance, reducing the speed from 104 km/h to 80 km/h in scenario 1 implies an increase in almost all the emissions analysed except for the NH_3. Moreover, when similar queues are predicted, the differences between the roadwork and normal traffic conditions is greater in the micro-simulation since the program enables a certain level of adaptability of the vehicles' speed to the traffic conditions, which in scenario 1, 2 and 3 is more detrimental for the environment. This situation changes in the other scenarios due to the much longer queues calculated with the macro-simulation model (the longer the queue length, the more emission is generated).

Table 8. Macro-simulation environmental emissions results (calculated by subtracting the pollution generated in normal conditions from the emissions produced during the roadworks).

Scenario	CO_2 (Kg)	CO (Kg)	NOx (Kg)	C_6H_6 (Kg)	NH_3 (Kg)	$PM_{2.5}$ (Kg)	Energy (MJ)
1	1.63E+02	8.95E-01	5.00E-01	3.02E-03	-6.16E-03	1.93E-02	2.21E+03
2	1.04E+04	8.87E+01	3.08E+01	1.60E-01	3.33E-01	1.23E+00	1.41E+05
3	1.04E+04	8.87E+01	3.08E+01	1.60E-01	3.33E-01	1.23E+00	1.41E+05
4	1.22E+05	1.03E+03	3.65E+02	1.88E+00	4.25E+00	1.47E+01	1.66E+06
5	1.22E+05	1.03E+03	3.65E+02	1.88E+00	4.25E+00	1.47E+01	1.66E+06
6	1.22E+05	1.03E+03	3.65E+02	1.88E+00	4.25E+00	1.47E+01	1.66E+06

Table 9. Micro-simulation environmental emissions results (calculated by subtracting the pollution generated in normal conditions from the emissions produced during the roadworks).

Scenario	CO_2 (Kg)	CO (Kg)	NOx (Kg)	C_6H_6 (Kg)	NH_3 (Kg)	$PM_{2.5}$ (Kg)	Energy (MJ)
1	3.79E+03	4.03E+01	1.05E+01	6.27E-02	-5.02E-02	1.89E+00	5.18E+04
2	1.04E+04	1.14E+02	2.53E+01	1.83E-01	-1.30E-01	5.14E+00	1.42E+05
3	1.17E+04	1.20E+02	3.72E+01	1.87E-01	-1.16E-01	5.53E+00	1.60E+05
4	3.88E+04	3.65E+02	1.84E+02	8.35E-01	3.92E-01	1.88E+01	5.30E+05
5	4.00E+04	3.74E+02	1.92E+02	8.54E-01	4.11E-01	1.93E+01	5.46E+05
6	4.15E+04	3.91E+02	2.05E+02	9.28E-01	5.21E-01	2.13E+01	5.66E+05

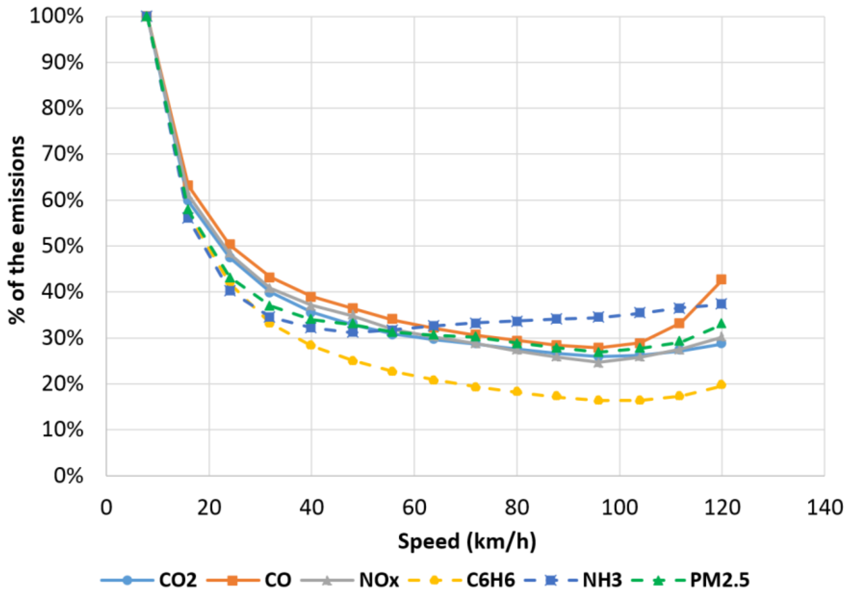


Figure 10. Relationship between vehicle emissions and speed ((Lizasoain-Arteaga et al., 2019)).

The environmental impact produced by the 1-km lane defined above for the six scenarios and two simulation methods (micro and macro) when considering the life cycle of the wearing course (WC) and the whole pavement section (PS) is shown in Table 10. Here, the impacts produced by congestion and by the rest of the life cycle stages have been considered separately to fully appreciate the relevance of the former within the LCA analysis. Furthermore, the contribution of congestion to the three endpoint impacts can be seen in Figure 11, Figure 12 and Figure 13.

Results show that the traffic disruption during maintenance activities is significant in nearly all the situations analysed, its relevance increasing exponentially with the number of vehicles. When only the wearing course is analysed, congestion means between 0.4% and 11% in scenario 1, which corresponds to an "A" LOS, around 22% regarding "B" LOS (S2 and S3) and more than 52% as far as "C" LOS is concerned (S4, S5 and S6). In fact, this stage is relevant even when the whole pavement section is taken into account, accounting for more than 0.1%, 6% and 21% respectively in the three LOS analysed. It is only negligible (<1%) in scenario 1 when the KyUCP software is used. Moreover, results are very similar when comparing the three impacts, congestion affecting ecosystem diversity slightly more than human health or resource availability.

Furthermore, the Motorway LOS is more relevant for the LCA results than the LOS of the National Road. When the AADT of the N-634 is increased from an "A" LOS to a "C" LOS, the contribution of congestion grows less than 2%. However, applying this same concept to the A-8 Motorway it results in an increase of more than 43% and 76% in the traffic delay contribution when the micro- and macro- simulations are used, respectively, in the LCA for the wearing course, and 18% and 44% when the results are referred to the whole pavement.

The dissimilarity between the simulations models (micro and macro) changes with the AADT of the Motorway, the most similar results being produced when the A-8 has a "B" LOS. Actually, 9% grater impacts are obtained with the micro-simulation approach in scenario 1, decreasing to 2% in scenario 2 and 3. Nevertheless, contrasting results are found thereafter with 22% greater impacts for the macro-simulation in scenarios 4, 5 and 6.

To check the consistency of these results, the LCA was recalculated using the CML 2001 (January 2016 update) characterization method which considers different hypothesis and impacts categories to ReCiPe to evaluate the damage that emissions produce in the environment (PE International, 2014). To achieve a single score for each scenario analysed, impacts were normalized using the European Union 2000 impacts and the weights defined in (Lizasoain-Arteaga et al., 2019) were applied, producing the results shown in Figure 14. With this new method, similar results were obtained. In fact, the only variation between CML and ReCiPe characterization methods is that, using the former, the influence of congestion is slightly smaller (around 10%) when the wearing course is being analysed.

The results achieved in this paper are in line with the main conclusions reached by previous authors such as Yu and Lu (2012), Galatioto et al.(2015) and Kim et al.(2018) regarding the importance of traffic delay and the exponential relationship between emissions and number of vehicles. However, the differences in the referent unit, scope, system boundaries or even goal of the papers makes not possible a direct comparison of the results.

Table 10. Environmental impact results for the six scenarios, two approaches and two simulation models used.

			Damage to Human Health [DALY]		Damage to Ecosystem Diversity [Species.yr]		Damage to Resource Availability [$]	
			LCA without congestion	Congestion	LCA without congestion	Congestion	LCA without congestion	Congestion
S1	WC	Micro	7.18E-02	7.56E-03	3.21E-04	4.01E-05	2.07E+03	2.24E+02
		Macro	7.18E-02	3.11E-04	3.21E-04	1.72E-06	2.07E+03	9.56E+00
	PS	Micro	2.46E-01	7.56E-03	1.12E-03	4.01E-05	7.19E+03	2.24E+02
		Macro	2.46E-01	3.11E-04	1.12E-03	1.72E-06	7.19E+03	9.56E+00
S2	WC	Micro	7.18E-02	2.05E-02	3.21E-04	1.10E-04	2.07E+03	6.13E+02
		Macro	7.18E-02	1.98E-02	3.21E-04	1.10E-04	2.07E+03	6.10E+02
	PS	Micro	2.87E-01	2.05E-02	1.30E-03	1.10E-04	8.40E+03	6.13E+02
		Macro	2.87E-01	1.98E-02	1.30E-03	1.10E-04	8.40E+03	6.10E+02
S3	WC	Micro	7.18E-02	2.35E-02	3.21E-04	1.24E-04	2.07E+03	6.91E+02
		Macro	7.18E-02	1.98E-02	3.21E-04	1.10E-04	2.07E+03	6.10E+02
	PS	Micro	2.87E-01	2.35E-02	1.30E-03	1.24E-04	8.40E+03	6.91E+02
		Macro	2.87E-01	1.98E-02	1.30E-03	1.10E-04	8.40E+03	6.10E+02
S4	WC	Micro	7.18E-02	8.17E-02	3.21E-04	4.11E-04	2.07E+03	2.29E+03
		Macro	7.18E-02	2.33E-01	3.21E-04	1.29E-03	2.07E+03	7.18E+03
	PS	Micro	2.87E-01	8.17E-02	1.30E-03	4.11E-04	8.40E+03	2.29E+03
		Macro	2.87E-01	2.33E-01	1.30E-03	1.29E-03	8.40E+03	7.18E+03
S5	WC	Micro	7.18E-02	8.44E-02	3.21E-04	4.23E-04	2.07E+03	2.36E+03
		Macro	7.18E-02	2.33E-01	3.21E-04	1.29E-03	2.07E+03	7.18E+03
	PS	Micro	2.87E-01	8.44E-02	1.30E-03	4.23E-04	8.40E+03	2.36E+03
		Macro	2.87E-01	2.33E-01	1.30E-03	1.29E-03	8.40E+03	7.18E+03
S6	WC	Micro	7.18E-02	8.81E-02	3.21E-04	4.39E-04	2.07E+03	2.45E+03
		Macro	7.18E-02	2.33E-01	3.21E-04	1.29E-03	2.07E+03	7.18E+03
	PS	Micro	2.87E-01	8.81E-02	1.30E-03	4.39E-04	8.40E+03	2.45E+03
		Macro	2.87E-01	2.33E-01	1.30E-03	1.29E-03	8.40E+03	7.18E+03

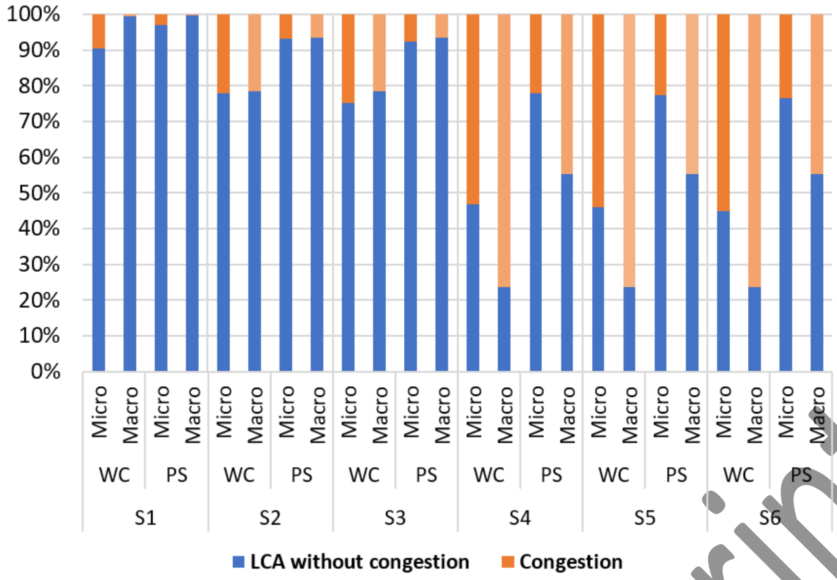


Figure 11. Congestion contribution to the "Damage to Human Health" impact.

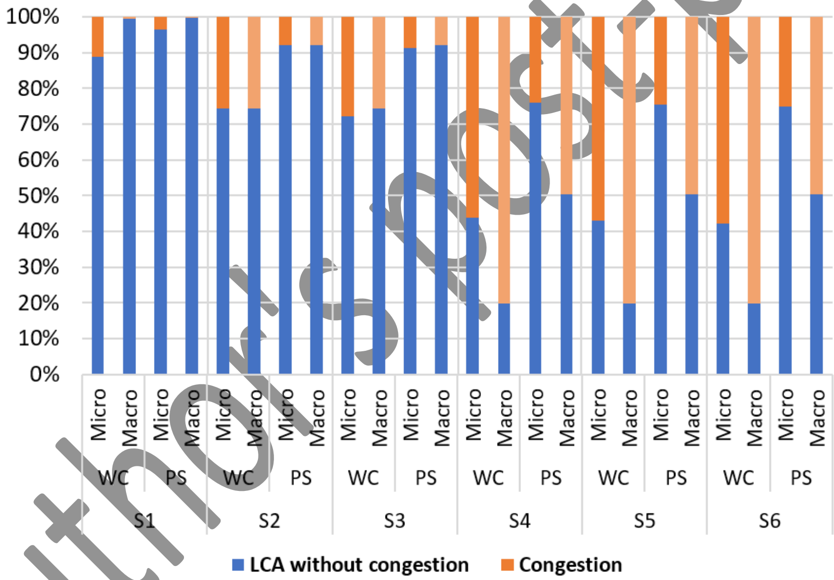


Figure 12. Congestion contribution to the "Damage to Ecosystem Diversity" impact.

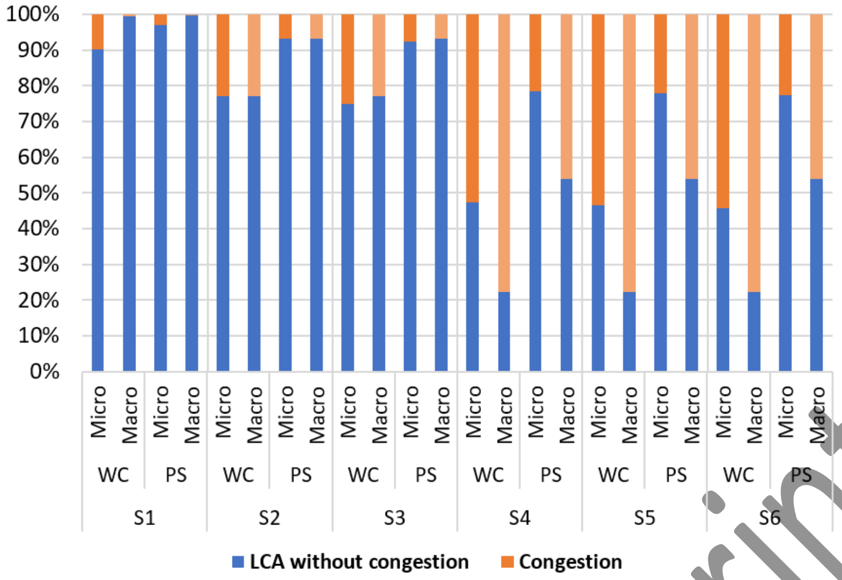


Figure 13. Congestion contribution to the "Damage to Resource Availability" impact.

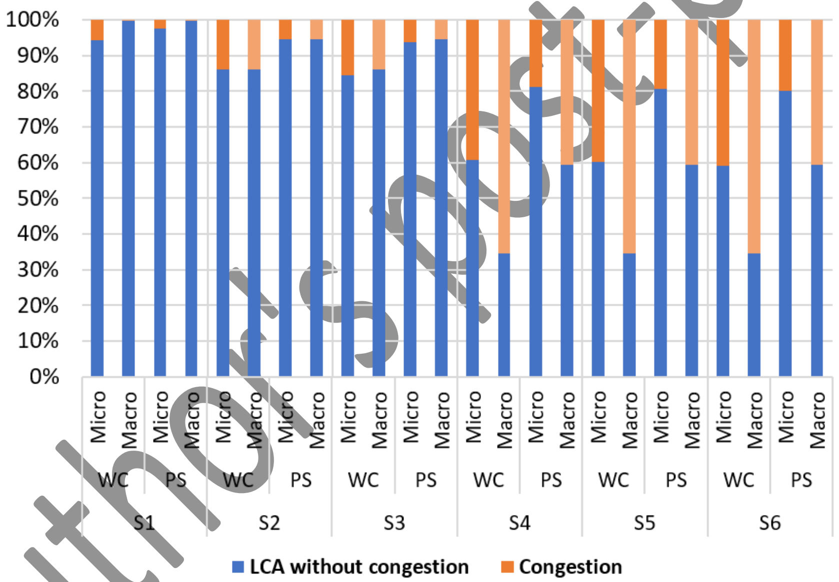


Figure 14. Contribution of congestion to the LCA results calculated with the CML 2001 Jan 16 Characterization Method.

4. Conclusions

In this study the influence of the traffic delay produced during the maintenance of a highway on its total LCA has been evaluated by comparing the queue length, emissions and environmental impacts calculated using two traffic simulation approaches (micro and macro).

After analysing 6 scenarios which combine 3 LOS for the A-8 Motorway and the N-634 (the alternative route), the following recommendations can be made:

- Macro-simulation should be used only for rough calculations or for preliminary analysis since it underestimates the emissions when the highway presents an "A" LOS and overestimates the queue length when a “C” LOS is analysed even when 30% demand deviation is taken into account. Results calculated by both approaches are only similar when a “B” LOS is studied. It should be noted that the micro-simulation model was calibrated using speed-occupacy and speed-flow relations of different detectors placed in the studied section to reflect the real user behaviour in terms of car-following, lane usage and lane changing decisions. On the contrary, the macroscopic approach is based on aggregated and average values and does not reflect the traffic dynamics and collaborative behaviour between drivers.

- The congestion stage should always be included in the LCA of a road when the maintenance schedule involves closing the lane for more than 24 hours, except for preliminary analysis of roads in which an “A” LOS is observed during its peak-hour. Traffic delay produced during a lane closure has been demonstrated to be relevant even when the whole asphalt pavement section is taken into account. However, as is obvious, its contribution is smaller than when only the wearing course is considered.
- Alternative routes should be included in the traffic analysis. Although their AADT does not significantly affect the LCA results (maximum 2% variation) their exclusion would result in an overestimation of the congestion and the real behaviour of drivers would not be represented in the model.
- At least the following 6 pollutants are recommended for consideration within the calculations in order to achieve good accuracy in the LCA results: CO_2, CO, NOx, CH_4, C_6H_6, NH_3, VOC and $PM_{2.5}$.

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