Title

Environmental impact assessment of induction-healed asphalt mixtures

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Abstract

This paper demonstrates the sustainability of induction-healed asphalt mixtures (HEALROAD) by comparing the impacts this technology causes with those generated by asphalt mixtures maintained by conventional practices such as mill and overlay. The functional unit selected is a 1 km lane with an analysis period of 30 years, and the stages considered are production, construction, maintenance, congestion, leaching and end-of-life. Two case studies have been analysed to evaluate the influence of different traffic strategies on the environmental impact of each maintenance alternative. Results show the benefits of using the induction technology at hot points where traffic jams occur.

Keywords

Life cycle assessment; LCA; Environmental impact; Self-healing; Induction heating; Asphalt mixture;

1. Introduction

Road infrastructures have great importance in the daily life of millions of citizens by enabling their urban and regional mobility and also by boosting economic growth, creating jobs and facilitating commercial relationships. In Europe alone, the aggregates industry employs more than 200,000 people and the estimated annual turnover exceeds €15 billion (UEPG, 2017). However, maintaining reliable performance of roads is becoming increasingly difficult due to problems such as aging, increased traffic demand and increased truck traffic. In addition, climate change, whose consequences can already be seen worldwide and are predicted to intensify in the coming decades, is leading to more severe pavement deterioration and subsidence phenomena. Therefore, continuous construction and maintenance of roads are required to keep the pavement infrastructure at a satisfactory service level. Nonetheless, this presents economic, environmental and social impacts due to the high demand on natural resources, traffic disruption and increased potential for accidents, reducing mobility and reliability within the road network while increasing travel time.

According to the European Aggregates Association (UEPG, 2017), aggregates are the most extensively consumed resource after water and air; more than 30,000 tons are necessary for the construction of 1 km of road (around 1.35 billion tons per year). Furthermore, the use of fossil fuels is an additional example of the major natural non-renewable resource needed for pavement construction. Approximately 13 million tons of bitumen are produced every year for the construction and maintenance of paved roads (Eurobitume, 2012). Along with environmental impact, these consumptions have an economic impact that should also be considered. In this sense, the construction of 1 km of new road costs around $866,000 (€722,000) (World Bank Group, 2000). Nevertheless, this figure does not take into consideration the cost of the delay that users suffer during the roadworks, which is especially important in high trafficked roads; the UK Government estimates this cost to be £4 billion per year (€4.5 billion) (UK Department for Transport, 2017).

Although these figures are already alarming, they are expected to increase further in the near future due to the opening of freight corridors all around Europe. In fact, according to the prognosis European Road Transport Research Advisory Council made for freight traffic in Germany (ERTRAC, 2011), the volume transported on roads will increase by around 70% by 2030, thus affecting the existing roads, whose structures were not designed to support such heavy loads. Therefore, there is a need to foster the utilization of more durable, cost-effective and eco-friendly practices to reduce levels of maintenance interventions and achieve longer service lives.

In this context, and based on the existing gaps extensively explained in (Ayar et al., 2016), the HEALROAD project was carried out to further develop induction-healed asphalt mixtures to extend the service life achieved by conventional materials, reducing in this way both the use of natural resources and traffic disturbance from a life-cycle perspective. The concept of induction technology was originally developed by TU Delft (García et al., 2009) and relies on incorporating metal particles such as wool fibres (used in the HEALROAD project), by-products (M Vila-Cortavitarte et al., 2018) (Ajam et al., 2018) or even nanoparticles (Jeoffroy et al., 2016)(Jeoffroy et al., 2018) that can be induction-heated within the asphalt mixtures. When incipient cracks appear in the wearing course, an induction-heating generator (see Figure 1) passes over the road surface heating only the magnetic particles. Bitumen melts, flowing through the micro cracks and closing them, extending the lifetime of roads by more than 90% (at lab level) when only one healing treatment is applied (Ajam et al., 2017) (Gómez-Meijide et al., 2016). This is just a conservative estimate since more treatment cycles might be applied. This preventive maintenance, which postpones the replacement of the asphalt surface for several years, is almost non-intrusive and suitable for application at times when traffic demand is low, having a minimal impact on the road network capacity.

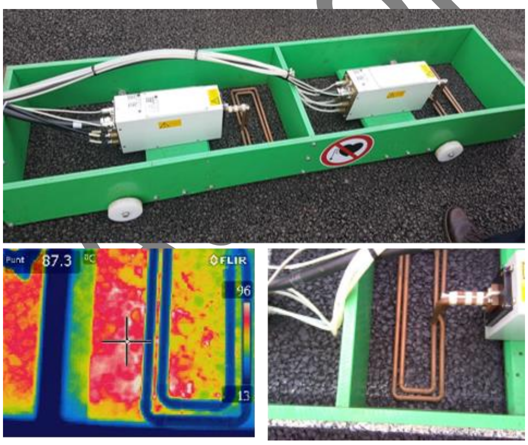

Figure 1. Induction-heating machine used in the HEALROAD project. Source: SGS Intron (The Netherlands).

In order to achieve the main goal of the project, several activities were carried out at two levels. Firstly, the mechanical performance and healing capacity of the asphalt mixes, the influence of the properties of the bitumen, the type and amount of metallic particles and the air void content were assessed and optimized in the laboratory. Then, the laboratory results were transferred to industry by up-scaling the asphalt mixture production and the construction of a pilot section in the German Federal Highway Research Institute (duraBASt).

To analyse the sustainability of induction-healing technology, a life-cycle-assessment (LCA) has been carried out following the standards ISO 14040:2006 (ISO, 2006a) and 14044:2006 (ISO, 2006b), which specify the requirements and guidelines that a proper analysis should follow. This methodology has previously been used to determine the environmental performance of pavements, principally comparing rigid and flexible layers (Häkkinen and Mäkelä, 1996), (Horvath and Hendrickson, 1998), (Zapata and Gambatese, 2005) but also studying more innovative solutions such as warm mix asphalts (Kucukvar et al., 2014), (Vidal et al., 2013) or recycled materials (Marta Vila-Cortavitarte et al., 2018). In spite of this, no records are available of its use in the evaluation of the induction-healing technology.

A LCA is commonly structured in four steps: goal and scope, inventory analysis (LCI), impact assessment (LCIA) and interpretation of the results (where after an optional sensitivity analysis, conclusions are reached).

2. Goal and Scope

The goal of this LCA is to demonstrate the sustainability of induction-healed asphalt mixtures developed during the HEALROAD project by comparing the environmental impacts this new technology produces with those generated by traditional mixtures rehabilitated by the mill and overlay technique. As the induction-healing technology has only been developed for the wearing course, the analysis has been focused on this layer, the rest of the pavement remaining unaltered.

For the analysis, a highway with 2 lanes per direction and an annual average daily traffic of 37,000 vehicles has been considered, assuming 15% of heavy traffic. The functional unit has been defined as a 1-km lane with a width of 3.75 m and a porous surface layer thickness of 0.04 m. An analysis period of 30 years has been assumed.

The selection of the system boundaries was based on the stages defined in the standard UNE-EN 15804:2012+A1:2003 (UNE-EN, 2012). However, congestion has been contemplated as an independent module of the maintenance stage in order to appreciate the advantages of the induction-healing technology as far as capacity losses and therefore, vehicles emissions are concerned (Figure 2).

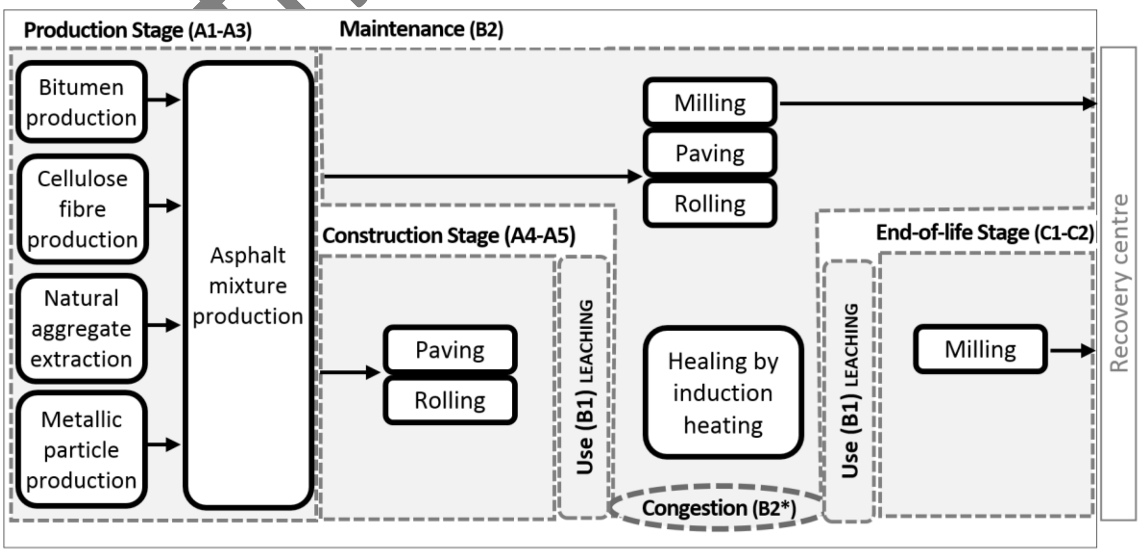

Figure 2. LCA boundaries.

3. Life Cycle Inventory

This stage involves the creation of a consistent database by collecting and quantifying the inputs and outputs associated with the functional unit. In this sense, data regarding resources consumed and emissions generated has been compiled from different sources. The production of electricity, the generation and combustion of fuels and the emissions produced during transportation (processes shared by all stages) have been obtained from the German database available in GaBi V8.1 and also from the National Renewable Energy Laboratory database ("NREL," 2012). The specific hypothesis and data sources used to form every stage's inventory are described next.

3.1. Production stage (A1-A3)

This stage includes the resource consumption and emissions generated during the extraction and processing of the materials (bitumen, coarse and fine aggregates, filler, metallic particles and cellulose fibres), their transportation to the asphalt plant as well as the manufacturing of the asphalt mixture. The dosage (by weight), density and air void content of the porous asphalt mixtures used in the analysis can be seen in Table 1, while the transportation distances assumed are shown in Table 2. It should be noted that a conventional 50/70 bitumen for the two asphalt mixtures has been used since the polymer modified bitumen (PMB), commonly used in porous asphalt mixtures, decreases the healing capability (Qiu, 2012). However, according to the mechanical tests carried out during the project, this change does not compromise the mechanical behaviour of the mixture because of the addition of steel wool fibres.

Table 1. Porous asphalt mixture definition.

Details	Asphalt mixture dosage (%wt.)	
	HEALROAD	Conventional
Coarse and fine aggregates (%)	89.42	90.05
Bitumen (%)	4.90	4.93
Filler (%)	4.38	4.82
Metallic particles (%)	1.10	0.00
Cellulose fibres (%)	0.20	0.20
Mixture density (kg/m^3)	2,021	2,006
Air void content (%)	20.20%	20.20%

Table 2. Transport distances assumed for the production stage.

Material	Transport distance
Coarse and fine aggregates	30 km
Bitumen	100 km
Filler	30 km
Metallic particles	100 km
Cellulose fibres	30 km
RAP	30 km

According to the National Asphalt Pavement Association (NAPA, 2016), the processing of RAP and its transportation from the recovery centre to the asphalt plant should be included in this stage. However, the German standards do not permit the use of RAP in porous asphalt wearing courses, which is the reason why the use of RAP has been studied in the sensitivity analysis. The data sources to create the inventory of the production stage can be checked in Table 3.

Table 3. Sources of the production stage inventory.

Material/process	LCI data source
Coarse and fine aggregate production	(Jullien et al., 2012), (UNPG, 2011a),(UNPG, 2011b),(Stripple, 2001), (Mroueh et al., 2000), (RE-ROAD, 2012), (Huang, 2007), (Häkkinen and Mäkelä, 1996), (Athena, 2005), (Marceau et al., 2007), NREL database
Bitumen production	(Eurobitume, 2012)
Filler production	GaBi V8.1
Metallic particle production	GaBi V8.1
Cellulose fibre production	GaBi V8.1
RAP processing	(UNPG, 2011c)
Asphalt mixture manufacturing	HEALROAD data

During the upscaling of the HEALROAD technology, the consumption of energy for the manufacturing of the asphalt mixture was measured in the plant. Results showed that 0.35 MJ of diesel, 50.40 MJ of electricity and 266 MJ of natural gas were needed to produce a tonne of asphalt mixture. The same values were used for the production of the conventional mixture as, despite the low specific heat capacity of the metallic particles and therefore, the potential reduction in the energy needed for the manufacturing of the HEALROAD mixture, the small amount of metal added is not expected to lead to significant differences.

3.2. Construction stage (A4-A5)

The construction stage involves the transportation of the mixture from the asphalt plant to the roadworks as well as the paving and compaction of the 0.04 m thick asphalt layer.

Data regarding diesel consumed by the paver, vibratory roller and static roller was collected during the upscaling stage of the HEALROAD project. Around 1.56 MJ of energy per tonne of asphalt was consumed and the distance that the asphalt mixture needs to be transported was assumed to be 30km.

3.3. Use stage (B1-B2)

Only leaching, maintenance and congestion modules have been considered in the analysis due to the lack of useful data to compare aspects like the roughness of the asphalt mixtures and also the variability of the results from the existing rolling resistance models (Trupia et al., 2017).

3.3.1. Use (B1). Leaching

To determine the potential leaching effect, both asphalt mixtures have been tested under the UNE-EN 12457-4:2002 test (UNE-EN, 2002), which is commonly used to assess the environmental behaviour of granular waste materials. However, in the HEALROAD project the tests have been applied to the loose asphalt mixtures in order to take into account the impermeability provided by the bitumen, which reduces the amount of chemical elements released into water (Rosemary, 2004). After analysing the presence of 16 different metals in the leachate, only aluminium (Al), arsenic (As) and barium (Ba) (shown in Table 4) were found to be not-null (Ajam et al., 2018).

Table 4. Leaching results per kg of asphalt mixture.

Mixture	Al (mg/kg)	As (mg/kg)	Ba (mg/kg)
HEALROAD	0.21	0.02	4.90

Conventional	0.20	0.05	5.39

Furthermore, during the analysis it was assumed that the mixture has leached the maximum possible at the moment the wearing course is removed, which implies that the more often a layer is replaced, the more leachates it produces.

3.3.2. Maintenance (B2)

Maintenance activities will depend on the mixture to be repaired as conventional asphalt mixtures will need to be replaced through the mill and overlay technique, while the HEALROAD mixture will also be healed by means of an induction-heating treatment. Therefore, the impacts of this stage are related to the two maintenance actions. The induction-heating includes the impacts related to the diesel consumed by the induction machine whereas traditional maintenance includes the impacts associated with the milling of the old asphalt layer, its transportation to the recovery centre, the production of materials, their transportation to the roadworks and the construction of the new layer.

Data provided by industrial partners within the HEALROAD project shows that 0.41 litres of diesel are needed to remove a tonne of the old asphalt layer and in the absence of more specific information, this consumption has been used for the two asphalt mixtures. On the other hand, the induction generator of 75 kVa required to heat two coils of 2 m length each consumes 21.10 litres per hour. Nonetheless, it should be noted that the vehicle used during the HEALROAD pilot section is a not-entirely optimized prototype designed to heal small sections and therefore, this consumption is expected to decrease in the future.

To define the maintenance schedule (Table 5), the usual service life of a conventional porous asphalt should be specified, which according to the many previous experiences of the HEALROAD industrial partner can be estimated as 10 years. Moreover, results of the HEALROAD project at lab level highlight that 90% life extension is possible when only one healing treatment is applied (Ajam et al., 2017) (Gómez-Meijide et al., 2016). Nevertheless, a more conservative assumption has been made in the analysis by considering only a 50% life extension.

Table 5. Maintenance schedule.

Year	HEALROAD	Conventional
0	Initial construction	Initial construction
5	Induction healing	
10		Mill and overlay
15	Mill and overlay	
20	Induction healing	Mill and overlay
25		
30	Final milling	Final milling

3.3.3. Congestion (B2*)

During maintenance work, the traffic flow of the road is affected by the closure of lanes, the reduction of their width and the reduction of the speed, consequently increasing travel time and thereby, atmospheric emissions. According to the UNE-EN 15804:2012+A1:2003 (UNE-EN, 2012) the impacts generated by this phenomenon should be included in the maintenance module. However, in this study, it has been analysed separately in order to appreciate its influence on the total impact.

For the mill and overlay activities, the closure of the lane during one day (24 hours) has been assumed (Caltrans, 2007) whereas for the induction-heating treatment, the early stage of the technology makes 8-night closure necessary (based on the coil length and healing speed achieved so far). Nevertheless, the little machinery needed to perform the healing and the ease of putting it aside enables the opening of the lane during the more heavily trafficked hours.

Two different case studies have been analysed to take into account different traffic strategies during the mill and overlay (see Figure 3). In the first strategy (S1) keeping all lanes open during maintenance is not possible. Therefore, during the lane closure 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 at the same time without affecting the other direction of the road. On the other hand, the second strategy (S2) enables the number of lanes to be maintained during the layer replacement by using the hard shoulders when the lane that is being repaired is closed. In this strategy, both directions of the roads are affected by a reduction of the width (from 3.75 m to 3.45 m) and speed (from 120 km/h to 80 km/h). Finally, the opening of the lane during the daytime when performing the induction-heating treatment of the HEALROAD mixture makes any alteration unnecessary and therefore the healing is performed by reducing the number of lanes in both cases.

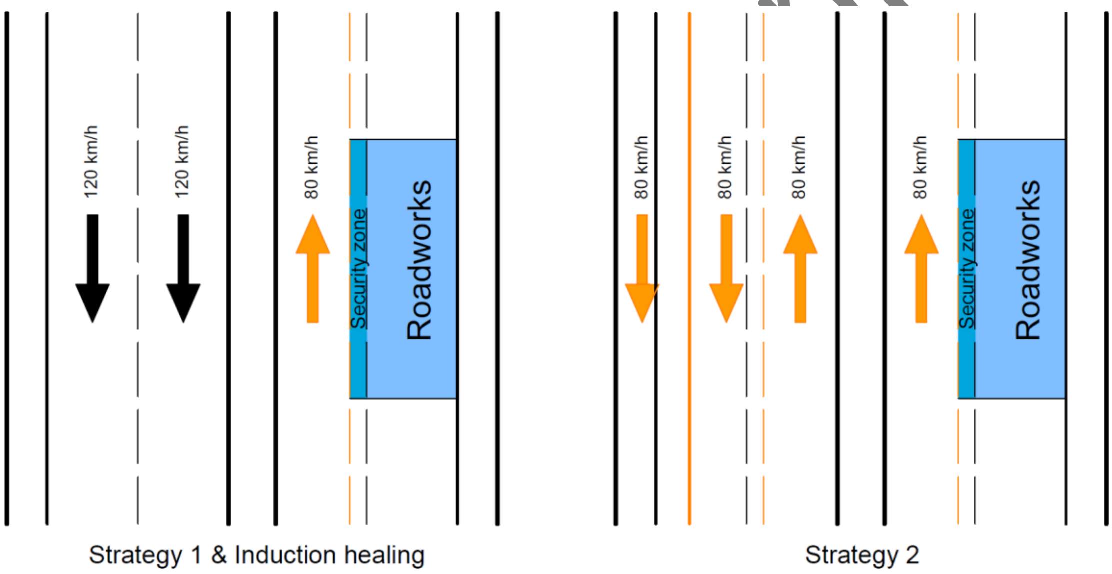

Figure 3. Maintenance strategies diagram.

For all the alternatives, the reduction in traffic capacity during the maintenance works and the potential formation of queues as well as their lengths, were estimated with the Kentucky Highway User Cost Program (KyUCP) v1.0 (Table 6). The differences in the emissions produced by all the predicted traffic scenarios compared to normal traffic conditions were calculated with EPA's Motor Vehicle Emission Simulator (MOVES) software (Table 7).

Table 6. Speed reduction and queue formation during roadworks.

	Case 1		Case 2	
	Induction healing	Mill and overlay (S1)	Induction healing	Mill and overlay (S2)
Normal conditions speed (km/h)	120	120	120	120
Roadworks speed (km/h)	80	80	80	80
Traffic jam speed (km/h)	8	8	8	8
Reduction in the lanes number	Yes	Yes	Yes	No
Maximum queue length (km)	-	3.8	-	-

Table 7. Variation in the emissions produced during a single maintenance action.

	Case 1		**Case 2**	
	Induction healing (8-night closure)	Mill and overlay (S1) (1-day closure)	Induction healing (8-night closure)	Mill and overlay (S2) (1-day closure)
CO_2 eq (kg)	-503.6	10,350.1	-503.6	-212.1
CO (kg)	-57.2	-3.1	-57.2	-24.1
CH_4 (kg)	-7.6E-02	3.2E-01	-7.6E-02	-3.2E-02
C_6H_6 (kg)	-2.2 E-02	9.8 E-02	-2.2 E-02	-9.0 E-03
NH_3 (kg)	-1.6 E-01	3.6 E-01	-1.6 E-01	-6.7 E-02
SO_2 (kg)	-1.3 E-02	1.2 E-01	-1.3 E-02	-5.0 E-03
NO (kg)	-3.5	20.2	-3.5	-1.5
NO_2 (kg)	-4.8 E-01	2.4	-4.8 E-01	-2.0 E-01
VOC (kg)	3.4 E-01	6.4	3.4 E-01	1.4 E-01
PM2.5 (kg)	-8.0 E-02	1.1	- 8.0E-02	-3.4 E-02
Energy (MJ)	-7,082.6	14,1345.1	-7,082.6	-2,981.8

In the first case study congestion is produced during the mill and overlay treatment due to the closure of the lane during the most trafficked hours. Therefore, reducing the speed from 120 km/h to 80 km/h and then to 8 km/h when traffic jams are created implies an increase in almost all of the atmospheric emissions. Conversely, no congestion occurred either during the mill and overlay maintenance in the second case study or during the healing treatment in both cases. So, in these situations, the difference between worksite and normal traffic conditions is limited to the need to reduce the vehicle speed from 120 km/h to 80 km/h. Unexpectedly, the emissions produced during maintenance works were lower than those produced under normal traffic conditions, which can be explained by the relationship between vehicle emissions and speed used by the model and shown in Figure 4.

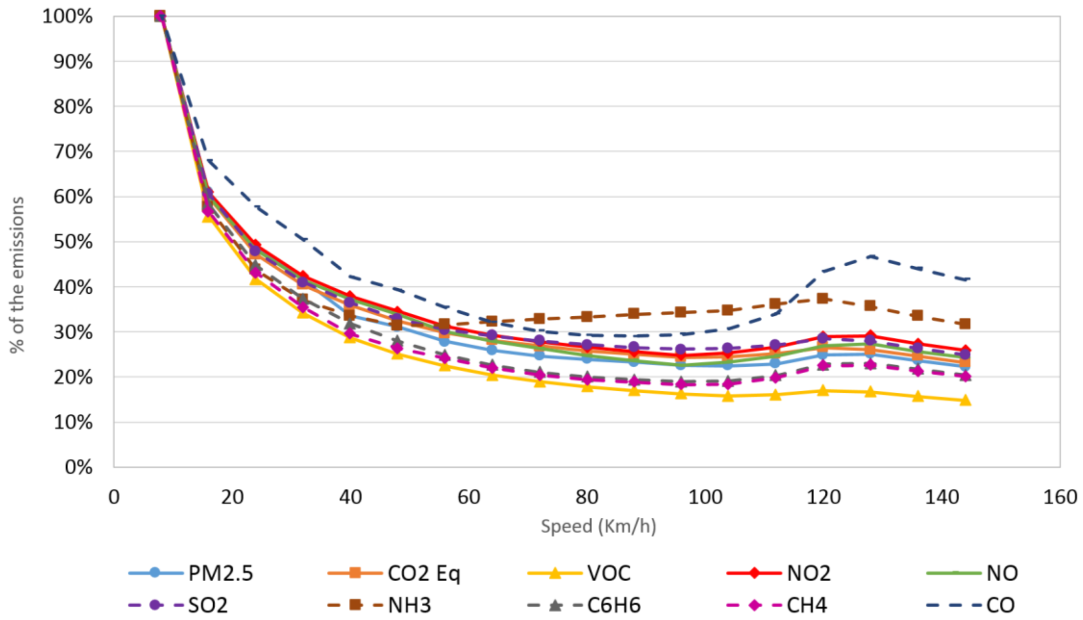

Figure 4. Relationship between vehicle emissions and speed.

3.4. End-of-life Stage (C1-C2)

This stage includes the final milling of the asphalt layer and the transportation of the RAP to the recovery centre. Nevertheless, the processing of the RAP has not been contemplated here. As explained above in the production stage (A1-A3), the National Asphalt Pavement Association (NAPA, 2016) recommends considering the impact of crushing and screening the RAP in the material supply stage. Therefore, this analysis finishes with the arrival of the RAP at the recovery centre.

4. Life Cycle Impact Assessment

Once the inventory was completed, the resources consumed and emissions detected were transformed into impact by using the ReCiPe 1.08 Hierarchical characterization method, which calculates the impact at two levels: midpoint and endpoint (see Table 8). The difference between the two levels is that while midpoint indicators are focused on single environmental problems, the endpoint ones correspond to the three areas of protection (damage to human health, damage to ecosystem diversity and damage to resource availability). However, according to the ReCiPe V1.1 Report (RIVM, 2016), the two approaches are complementary since the midpoint factors are more related to the environmental flows (implying less uncertainty) and endpoint indicators provide more information about the environmental relevance of the flows (which are less uncertain).

Table 8. Environmental categories for the LCA study.

Categories		UNITS
ReCiPe 1.08 Midpoint (H)		
ALO	Agricultural land occupation	m2a
CC	Climate change	kg CO2 eq.
FD	Fossil depletion	kg oil eq.
FET	Freshwater ecotoxicity	kg 1,4 DB eq.
FE	Freshwater eutrophication	kg P eq.
HT	Human toxicity	kg 1,4-DB eq.
IR	Ionising radiation	U235 eq.
MET	Marine ecotoxicity	kg 1,4-DB eq.

ME	Marine eutrophication	kg N eq.
OD	Ozone depletion	kg CFC-11 eq.
PMF	Particulate matter formation	kg PM10 eq.
POF	Photochemical oxidant formation	kg NMVOC eq.
TA	Terrestrial acidification	kg SO2 eq.
TET	Terrestrial ecotoxicity	kg 1,4-DB eq.
ULO	Urban land occupation	m2a
WD	Water depletion	m3
MD	Metal depletion	kg Fe eq.
ReCiPe 1.08 Endpoint (H)		
HH	Damage to Human Health	DALY
ED	Damage to Ecosystem Diversity	Species.yr
RA	Damage to Resource Availability	$

Table 9 presents the results of the cradle-to-grave analysis performed on HEALROAD and conventional mixtures when used in the two case studies previously described (with and without reduction of lanes during the mill and overlay treatment).

Table 9. Environmental category results for the two cases analysed.

MIDPOINT CATEGORIES				
Environmental category	HEALROAD mix Case 1	Conventional mix Case 1	HEALROAD mix Case 2	Conventional mix Case 2
ALO [m2a]	4,549.5	5,559.5	3,365.5	3,193.2
CC [kg CO2 eq.]	56,380.6	73,627.9	43,578.9	48,040.3
FD [kg oil eq.]	17,876.1	23,665.0	14,034.7	15,987. 6
FET [kg 1,4 DB eq.]	61.5	91.4	59.6	87.5
FE [kg P eq.]	0.6	0.8	0.5	0.7
HT [kg 1,4-DB eq.]	6,478.9	9,954.5	6,226.4	9,449.7
IR [U235 eq.]	1,031.5	1,085.8	1,002.8	1,028.4
MET [kg 1,4-DB eq.]	20.2	29.5	17.4	23.8
ME [kg N eq.]	16.1	16.8	13.0	10.7
OD [kg CFC-11 eq.]	3.6E-08	2.8E-08	3.3E-08	2.3E-08
PMF [kg PM10 eq.]	103.2	98.1	99.2	90.2
POF [kg NMVOC eq.]	299.3	234.2	290.3	216.8
TA [kg SO2 eq.]	204.7	177.8	194.8	158.2
TET [kg 1,4-DB eq.]	1.2	1.6	1.1	1.5
ULO [m2a]	7.5	8.0	7.4	7.9
WD [m3]	26,825.1	28,526.0	26,011.1	26,899.1
MD [kg Fe eq.]	4,122.6	100.0	4,115.6	86.0
ENDPOINT CATEGORIES				
HH [DALY]	1.1E-01	1.4E-01	9.1E-02	9.7E-02
ED [Species.yr]	5.3E-04	6.9E-04	4.1E-04	4.4E-04
RA [$]	3, 244.4	3,911.9	2,610.1	2,644.1

The relationship (in percentage) between the midpoint impacts produced by HEALROAD and conventional mixtures in each of the case studies analysed can be seen in Figure 5 and Figure 6. The better performance of the HEALROAD mixture in 12 and 10 of the 17 impacts analysed in the case 1 and 2, respectively, can be observed. Freshwater ecotoxicity and human health are especially reduced by using HEALROAD mixtures because of the less leachate and material produced in the maintenance stage. However, the emissions caused during the processing of metal and the consumption of diesel in the healing treatment make the conventional mixture a much better option as far as ozone depletion and photochemical oxidant formation are concerned. More importantly, metal depletion is the impact causing the greatest differences between the two alternatives as, while the HEALROAD mixture incorporates metal particles in its composition, traditional techniques only require metal for the production of electricity.

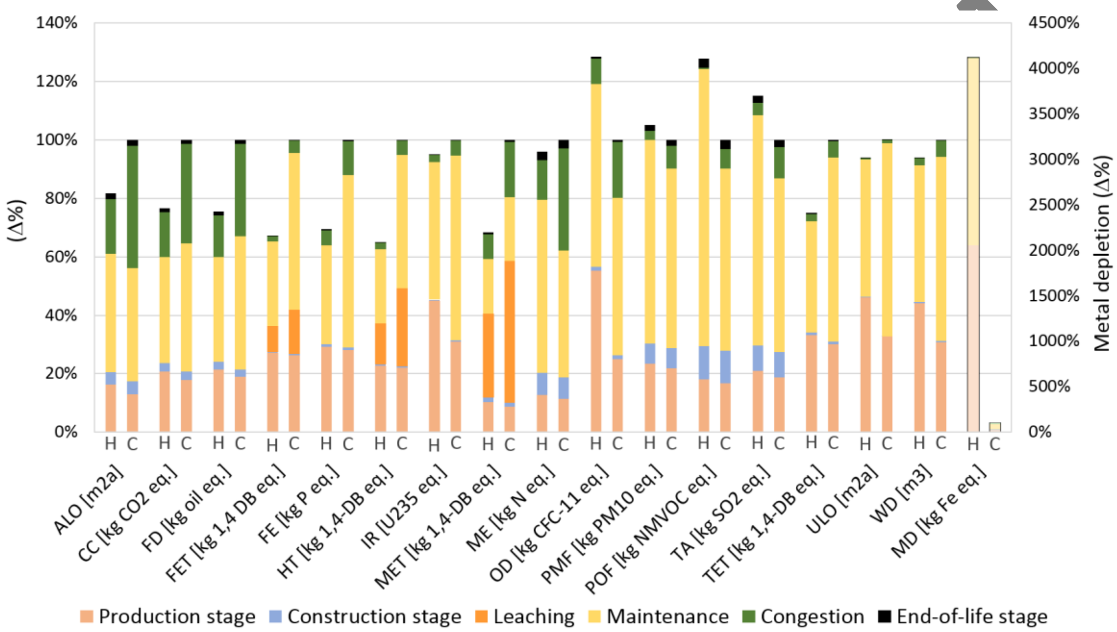

Figure 5. ReCiPe Midpoint Impact Category. Total impact – Case 1.

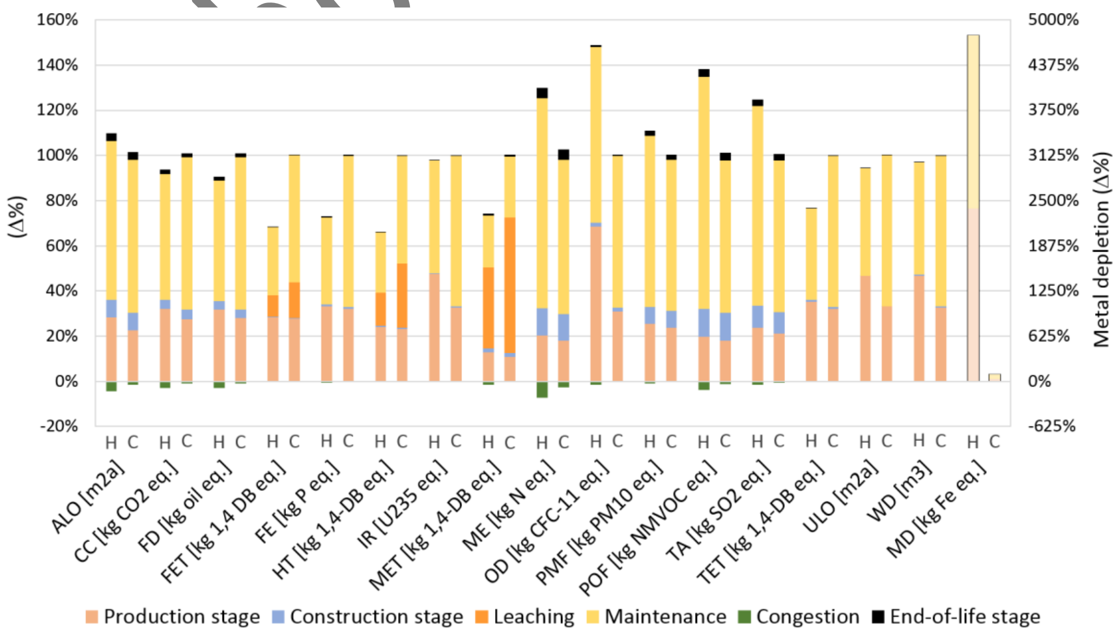

Figure 6. ReCiPe Midpoint Impact Category. Total impact – Case 2.

When analysing the endpoint impacts (Figure 7), HEALROAD mixture is always the best option in the first case study due to the more advantageous results of induction technology in two of the most representative stages (maintenance and congestion). However, the difference between the two alternatives is not so important in the second case study. In this scenario, maintenance is still the stage that contributes most to the total impact, but congestion is negative because of the benefits of reducing the speed during the maintenance work when no traffic jams are created (see Figure 4). On the other hand, construction and end-of-life stages are barely meaningful in the two cases analysed, contributing around 4.0% and 1.8% to the total impact; and leaching, which only affects the damage to human health impact, supposes less than 1.9%.

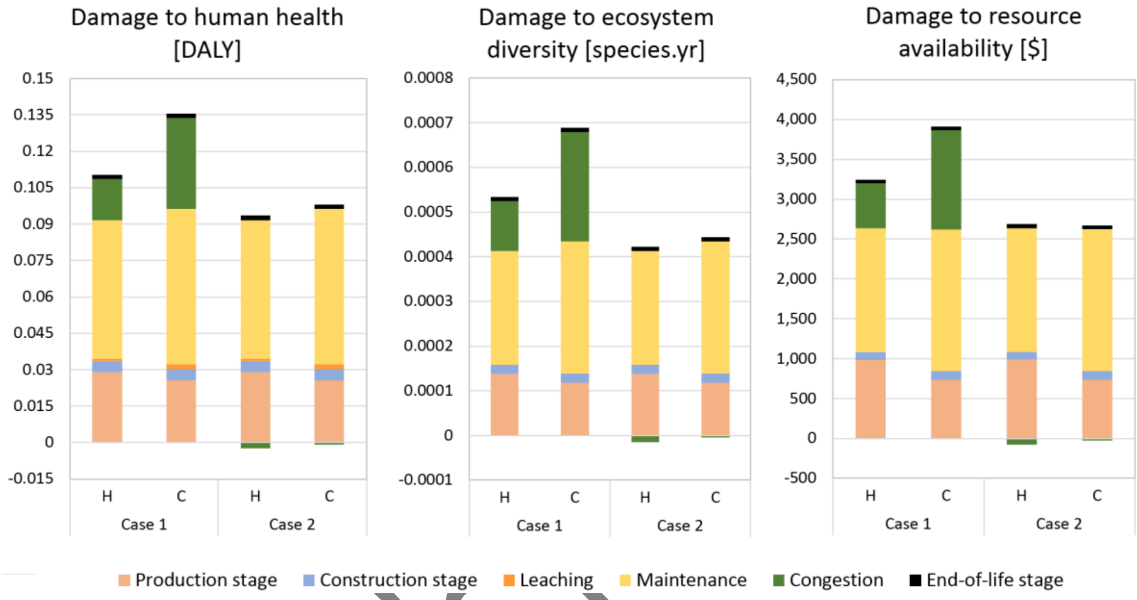

Figure 7. ReCiPe Endpoint Impact Category. Total impact.

Considering that using induction technology is more beneficial in the first case study (when the number of lanes is reduced during the mill and overlay actions), this scenario has been more deeply studied trying to achieve a better understanding of the results. With this aim, the contribution of every process to the endpoint impacts of each stage has been analysed (Figure 8, Figure 9, Figure 10).

Asphalt mixture manufacture is the main cause of the impact generated during the production stage due to the great amount of energy required to heat the aggregates and bitumen, its influence on the three endpoint impact being greater in the conventional asphalt mixture (49.0%, 62.0% and 64.9%) than in the HEALROAD mixture (43.5%, 53.3% and 49.0%). Asphalt production is followed by the production of metallic particles in two of the three impacts, this meaning 11.5%, 14.2% and 24.5% in the damage to human health, to ecosystem diversity and to resource availability, respectively, despite accounting for 1.1% in the asphalt mixture dosage.

Furthermore, the diesel consumed during paving and compacting surpasses the diesel required for transporting the asphalt mixture by around 52.2%, a more balanced situation being observed in the end-of-life stage.

Larger differences can be observed between the two asphalt mixtures in the maintenance stage. The additional mill and overlay treatment needed by conventional technology requires the consumption of more material and energy. This explains why the production of asphalt mixture (39.2%, 49.2% and 54.0%) and bitumen (20.6%, 13.0 and 17.3%) contribute more to the impact. On the other hand, induction technology still requires the replacement of the asphalt layer in year 15, which is around 67% of the total maintenance.

Finally, the congestion produced during two induction-healing treatments (each requiring 8-night closures) means -11.4% of the total HEALROAD congestion. This negative figure implies a reduction in the impact generated during the conventional maintenance and it is caused by both the MOVES' emission model and the speed reduction used in this analysis.

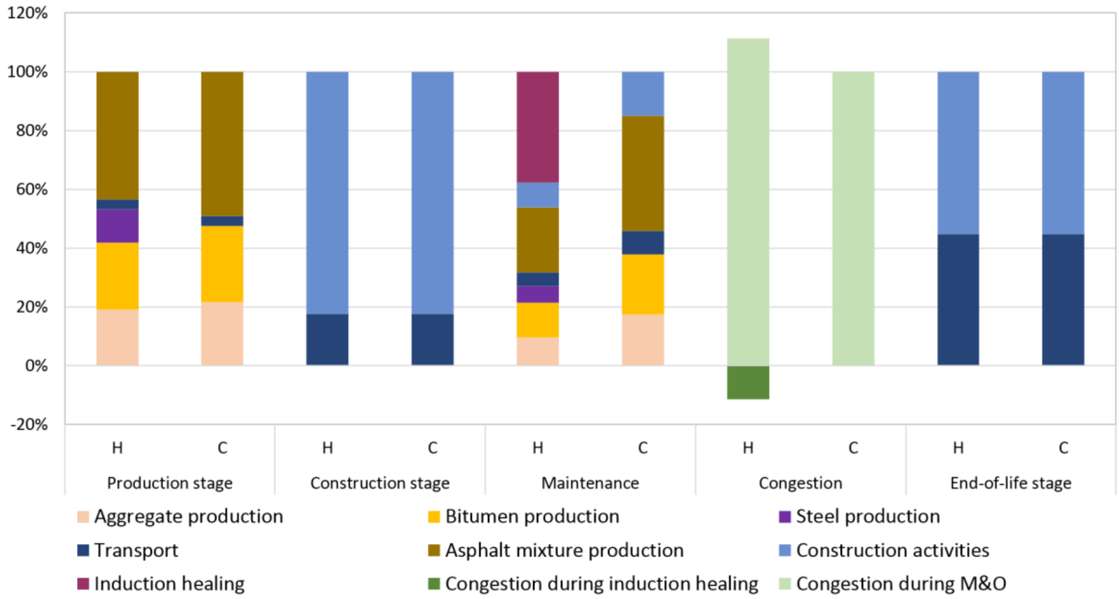

Figure 8. Process contribution to the Damage to human health impact. Case 1.

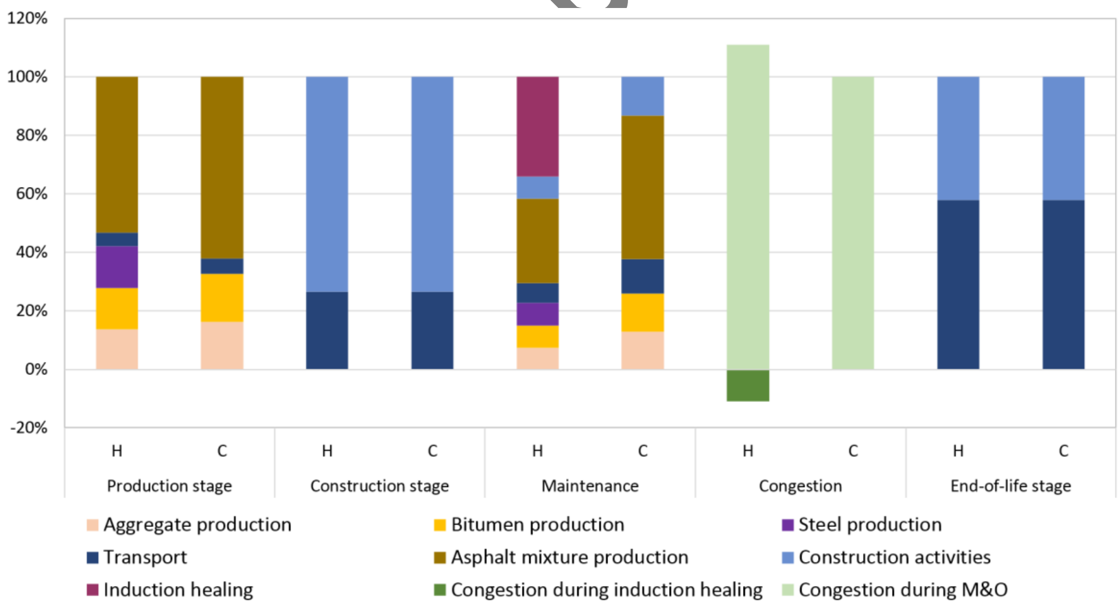

Figure 9. Process contribution to the Damage to ecosystems diversity impact. Case 1.

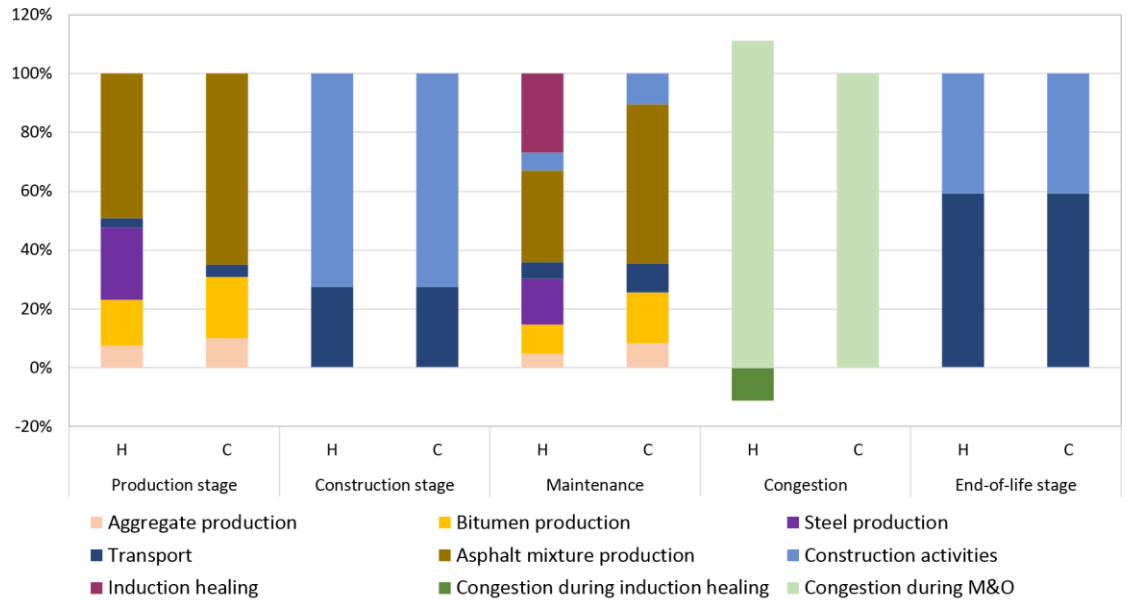

Figure 10. Process contribution to the Damage to resource availability impact. Case 1.

5. Sensitivity analysis

The variability of the LCA results when certain parameters are modified can be analysed by means of a sensitivity analysis. To this end, three different scenarios have been taken into account: 1) the further development of the technology has been contemplated by improving the efficiency of the induction-healing treatment (varying the diesel consumption of the induction vehicle as well as its speed); 2) a change in the standards has been simulated by studying the addition of various percentages of RAP to the mix; 3) the reliability of the results has been proved by using another characterization method when calculating the environmental impacts.

5.1. Efficiency of the induction-healing treatment

LCA analysis was carried out considering the speed and diesel consumption of the induction-heating machine used in the HEALROAD project, which is a prototype and therefore, is expected to be more efficient in the future. In order to take into account the expected function, both variables (consumption and speed) have been modified.

Figure 11 shows the total impact of the first case study when the diesel consumption of the induction vehicle is reduced between 0% and 40%. Metal depletion is the least sensitive midpoint impact to consumption changes, its reduction being less than 1% in all scenarios. On the other hand, photochemical oxidant formation can be reduced between 5% and 19%. However, the small variability of the midpoint impacts that most affect the three areas of protection (climate change in the damage to human health and in the ecosystem diversity impacts and fossil depletion in the resource availability impact) leads to a reduction between 1% and 8% in the endpoint impacts.

Regarding the speed increase, the target is to be able to heal one km of a road in a night (supposing an 8-hour shift). The impacts generated under this hypothesis have also been studied (Figure 12) showing an increase in their values. As explained above, reducing the vehicles' speed from 120 km/h to 80 km/h without creating traffic jams is beneficial for the environment since it reduces the atmospheric emissions (Figure 4).

Therefore, under this specific conditions, the more the induction treatment last, the better for the environment.

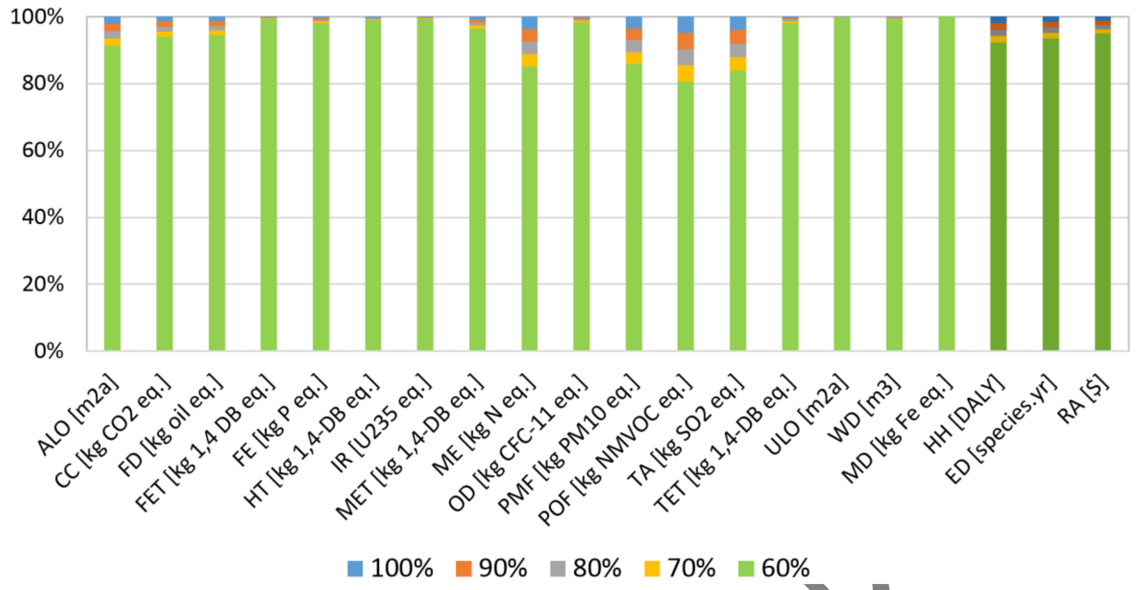

Figure 11. ReCiPe. Total impact. Induction-heating machine's diesel consumption variability.

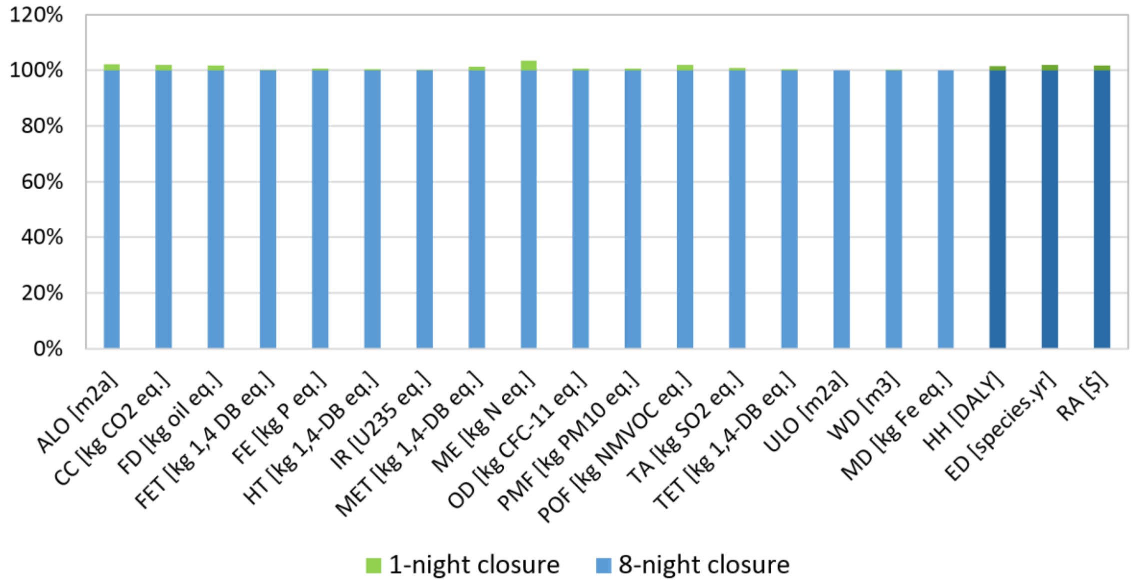

Figure 12. ReCiPe. Total impact. Induction-heating machine speed variability.

5.2. Use of reclaimed asphalt pavement (RAP)

Currently, the use of RAP across Europe is basically limited to the binder and base courses, allowing the use of a certain percentage of this material in the wearing course, but principally in asphalt concrete mixtures. However, the dissemination of the circular economy philosophy together with the good results achieved at laboratory level in different European projects (like DURABROADS) make it possible to foresee a future change of this outlook for porous mixtures. In fact, the recyclability of HEALROAD mixtures was studied within the project, with very promising results from the mechanical and healing viewpoints. With this in mind, the changeability of the environmental impact when varying the amount of RAP between 0% and 40% in the HEALROAD mixture was analysed.

Figure 13 shows that higher reductions in the midpoint impacts can be achieved by the addition of RAP rather than modifying the induction-heating machine efficiency. For instance, the reduction in the metal depletion impact is proportional to the amount of material saved, therefore, a 40% decrease can be observed. Similar results are obtained in the terrestrial ecotoxicity and urban land occupation impacts, which can decrease 32% and 37% respectively. Nonetheless, as occurred above when varying the diesel consumption of the induction vehicle, climate change and fossil fuel depletion (the impacts that contribute most to the three areas of protection) are barely affected. Consequently, less noticeable improvements can be observed in the endpoint impacts, which are reduced 10%, 8% and 11%, respectively.

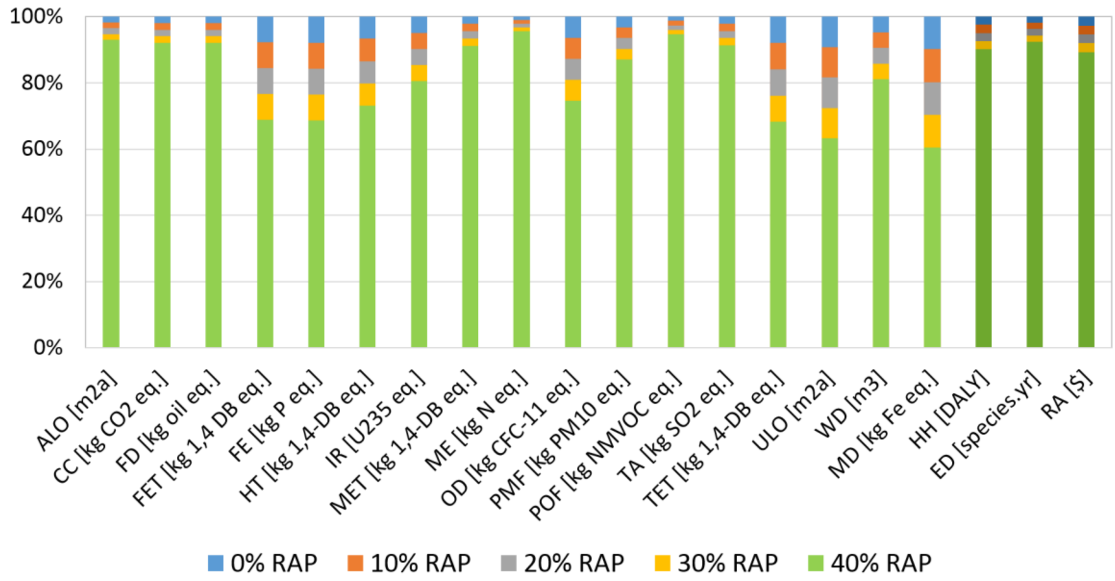

Figure 13. ReCiPe. Total impact. RAP variability.

5.3. CML 2001 (January 2016 update) characterization method

When performing an LCA, results may change depending on the method used to calculate the impacts. For that reason, the LCA has been recalculated using the CML 2001 (January 2016 update) characterization method in order to check the consistency of the results obtained above. The impacts analysed by this method are shown in Table 10. Although both methods (ReCiPe and CML) were developed by the University of Leiden, certain hypotheses considered when calculating the characterization factors may affect the final scores. One example of this is the different units used to measure the impacts, which affect the conversion of the emissions into impacts. Another example is that, while ReCiPe assumes the average European weather conditions, CML considers that the sun always shines (PE International, 2014).

Table 10. CML 2001 (January 2016 update) environmental categories.

Categories		UNITS
ADP elements	Abiotic Depletion (elements)	[kg Sb eq.]
ADP fossil	Abiotic Depletion (fossil)	[MJ]
AP	Acidification Potential	[kg SO2 eq.]
EP	Eutrophication Potential	[kg Phosphate eq.]
FAETP	Freshwater Aquatic Ecotoxicity Pot.	[kg DCB eq.]
GWP	Global Warming Potential (GWP 100 years)	[kg CO2 eq.]
HTP	Human Toxicity Potential	[kg DCB eq.]
MAETP	Marine Aquatic Ecotoxicity Pot.	[kg DCB eq.]
ODP	Ozone Layer Depletion Potential	[kg R11 eq.]
POCP	Photochem. Ozone Creation Potential	[kg Ethene eq.]

TETP	Terrestric Ecotoxicity Potential	[kg DCB eq.]

The relationship between the impacts produced by the two asphalt mixtures studied here (HEALROAD and conventional) for the first case study can be seen in Figure 14. Similar global results are obtained to those of the ReCiPe method, since induction-healing technology is beneficial for the environment in 8 of the 11 impacts analysed. Under this CML method, differences are not appreciated as important as those found when using ReCiPe as the metal consumption is included in the “ADP elements” with the rest of the resources consumed. Besides, the correlation between the two mixtures regarding freshwater ecotoxicity, global warming potential, marine ecotoxicity and ozone depletion remains similar to those obtained with ReCiPe. Nonetheless, the benefits of using HEALROAD technology are reduced under this method as far as human health is concerned due to the intrinsic characteristics of the calculations.

On the other hand, to appreciate the relative importance of each impact, results need to be normalized by dividing the scores by a reference situation’s scores. In this analysis, the impact produced by the 28 member states of the European Union in 2000 was used. In Figure 15, the large contribution of the Marine Aquatic Ecotoxicity Potential can be observed, which is advantageous for the HEALROAD mixture, the importance of the rest of the impacts being almost one order of magnitude smaller. Moreover, it should be noted that the negative figure of the photochemical ozone creation potential in the conventional mixture indicates that pollution is being reduced, what was not observed with ReCiPe. This is caused by nitrogen monoxide emission, which, according to CML is beneficial for air quality, whereas ReCiPe considers that it does not affect it (PE International, 2014).

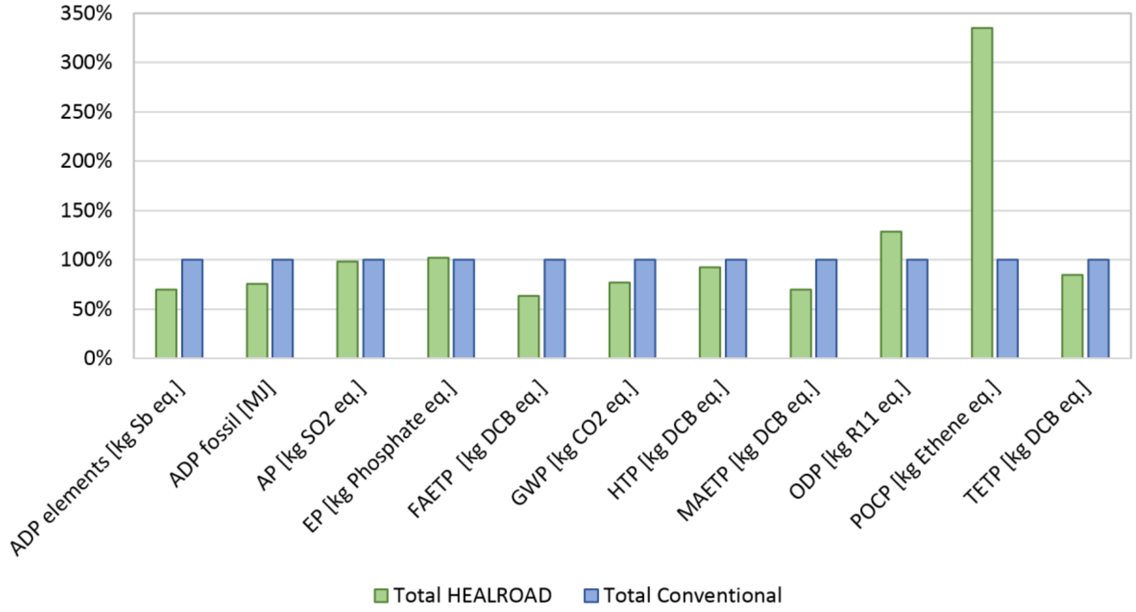

Figure 14. CML 2001 Jan 16. Total impact – Case 1.

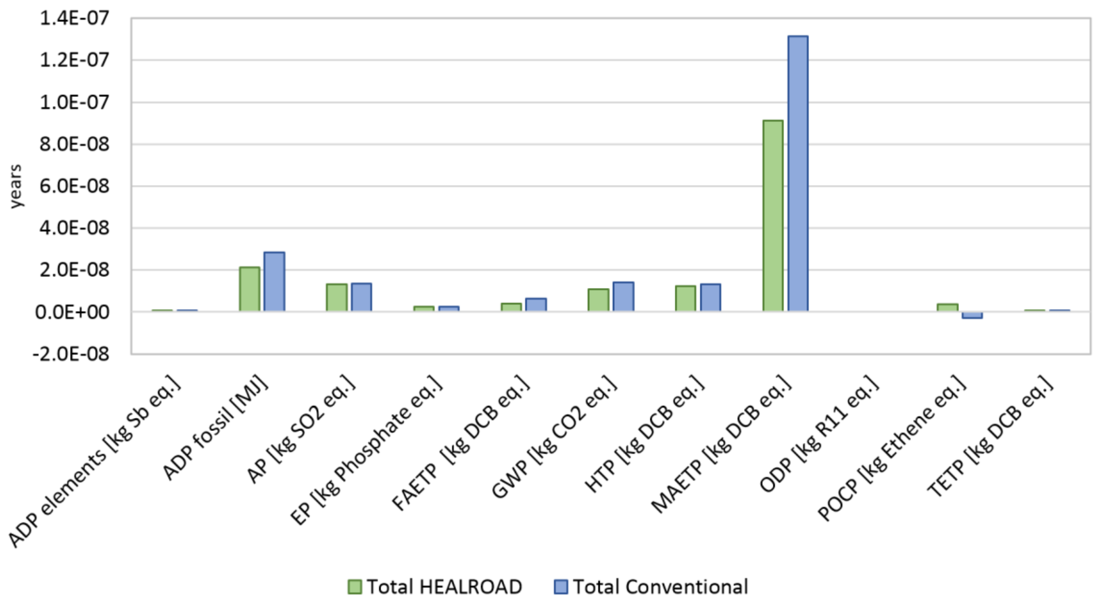

Figure 15. CML 2001 Jan 16. Total impact (Normalised) – Case 1.

After the normalization of the impacts, they have been weighted to add them all together. As the CML 2001 does not propose any weighting factor, a mean of those recommended by the EPA, BEES, NOGEPA and BREE (Huppes and Van Oers, 2011) (Abbe and Hamilton, 2017) has been used by adapting them to the categories contemplated by the CML method (see Table 11).

Table 11. Weighting factors.

Impacts	Weighting factors
Abiotic Depletion (elements)	8.0
Abiotic Depletion (fossil)	7.7
Acidification Potential	6.3
Eutrophication Potential	8.7
Freshwater Aquatic Ecotoxicity Pot.	4.2
Global Warming Potential (GWP 100 years)	27.8
Human Toxicity Potential	14.5
Marine Aquatic Ecotoxicity Pot.	4.8
Ozone Layer Depletion Potential	7.4
Photochem. Ozone Creation Potential	6.6
Terrestric Ecotoxicity Potential	4.0

Once weighted (Figure 16) and in agreement with the results obtained with the ReCiPe method, induction-healing technology is still the best option causing 20.7% less impact than the conventional mixture. Nevertheless, the importance of each stage has changed. Under the ReCiPe method, congestion was one of the most important stages together with maintenance, leaching being negligible in two of the three endpoint categories. However, according to the CML method, leaching is the most important aspect to be considered as far as the conventional mixture is concerned, being in the second position in the HEALROAD mixture. The reason for this change is the aforementioned importance of the Marine Aquatic Ecotoxicity Potential, in which leaching contributes 69.2% and 60.7% in conventional and HEALROAD mixtures, respectively.

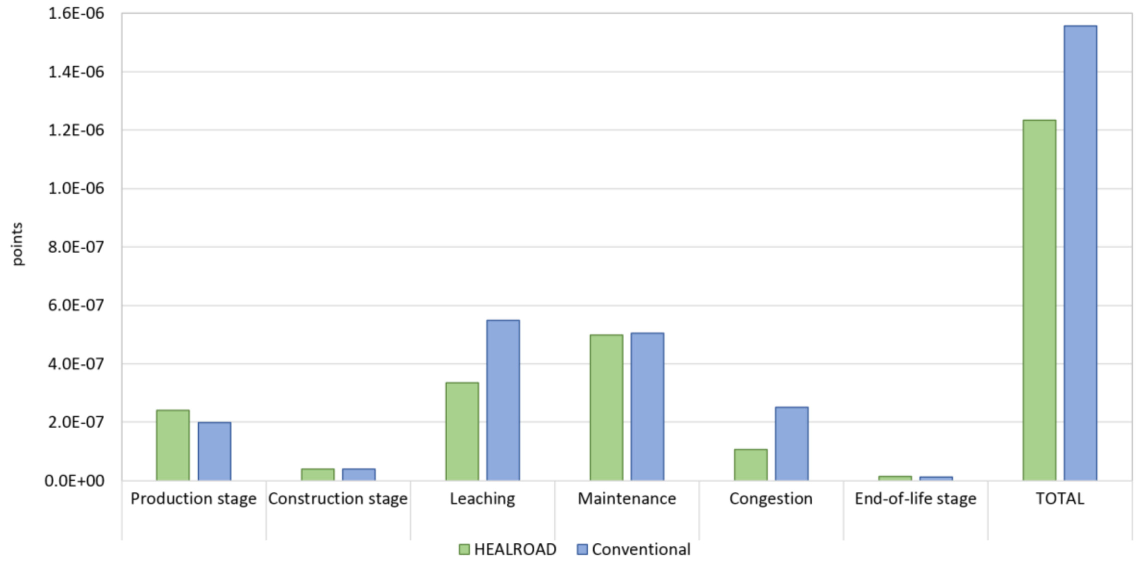

Figure 16. CML 2001 Jan 16. Total impact (Weighted) – Case 1.

6. Conclusions

In this study, the environmental sustainability of induction healing technology was assessed. A 30-year life-cycle assessment was performed on two different case studies (with and without reduction of lanes during the mill and overlay treatment) where induction-healing technology was compared with a conventional mixture traditionally maintained.

After the analysis of 6 stages of the road life under the ReCiPe characterization method and the development of a sensitivity analysis to take into account changes in the technology, standards and calculation methods, the following conclusions can be drawn:

- Induction technology provides better results when maintaining the traffic capacity of the road is difficult and consequently queues are generated. In this analysis, only the environmental effect of traffic jams was considered, since economic and social costs were beyond the scope of the study.
- In the first case study analysed, results indicate that the use of HEALROAD asphalt mixes is beneficial in 12 of the 17 midpoint impact categories. The benefits associated with service life extension and reduced maintenance outweigh the negative impacts generated by the production of metallic particles and the diesel consumption during the heating, thus very positive results were obtained in the three endpoint impacts.
- The greatest benefit of the technology is related to the reduction of the number of maintenance actions and the minimization of negative effects on traffic during roadworks.
- The induction-healing treatments needed during the 30-year analysis period makes up around 30% of the total maintenance. Nonetheless, the induction equipment used was designed for research purposes and therefore, improvements in the energy and time efficiency of the treatment are expected during its upscaling.
- Under the ReCiPe method, the leaching effect is nearly negligible when compared with the rest of the stages, contributing less than 1.9% in the two cases and mixtures analysed. Nevertheless, when calculated with CML, the release of contaminants during the service life of the asphalt layer ends up being one of the most important aspects, contributing 27.1% and 35.3% in the HEALROAD and conventional mixtures respectively.

- The influence on the results of the possible future improvement of induction technology has been analysed both in terms of reducing the diesel consumption of current equipment (between 0% and 40%) and reducing the time needed for the treatment. In the former, reductions between 1% and 8% in the endpoint impact categories were found, while in the latter, an average 1% increase was achieved.
- Congestion module results, and therefore, total results can be altered in case of modifying the emission model or the vehicles' average speed considered in the analysis.
- Adding RAP to the mixture leads to reductions in certain midpoint impacts which are proportional to the amount of material saved. However, these benefits are attenuated in the endpoint impact categories, with reductions not exceeding 11%.

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