UNIVERSIDAD DE CANTABRIA

ESCUELA DE DOCTORADO DE LA UNIVERSIDAD DE CANTABRIA
DOCTORADO EN INGENIERÍA CIVIL

TESIS DOCTORAL

RECOMENDACIONES PARA LA APLICACIÓN DE LA METODOLOGÍA DEL ANÁLISIS DE CICLO DE VIDA EN FIRMES ASFÁLTICOS

\- - - - - -

PhD THESIS

RECOMMENDATIONS FOR THE APPLICATION OF THE LIFE CYCLE ASSESSMENT METHODOLOGY TO ASPHALT PAVEMENTS

Presentada por: **ESTHER LIZASOAIN ARTEAGA**

Dirigida por: **Prof. Dr. DANIEL CASTRO FRESNO**
Prof. Dr. GERARDO FLINTSCH

Santander, 2020

“El mundo no puede evolucionar más allá de su actual situación de crisis utilizando el mismo pensamiento que creó esta situación”

Albert Einstein

“En la naturaleza salvaje está la salvación del mundo”

Henry David Thoreau

AGRADECIMIENTOS

Quisiera agradecer en primer lugar a la Universidad de Cantabria y la Consejería de Educación del Gobierno de Cantabria por proporcionarme la financiación necesaria para la realización de esta tesis doctoral a través de la ayuda a contratos predoctorales del Programa de Personal Investigador en formación Predoctoral (CVE-2016-11670).

Quisiera agradecer también a mis directores, los catedráticos Daniel Castro y Gerardo Flintsch, no solo por haberme apoyado y ayudado durante el proceso de elaboración de este trabajo, sino por haberme recibido con brazos abiertos en sus grupos de investigación.

A mis compañeros de GITECO, especialmente a Pablo Pascual por su labor como tutor y en ocasiones incluso de psicólogo; a Pedro Lastra, por estar siempre dispuesto a echar una mano, a veces incluso las dos; pero sobre todo a Irune Indacoechea, porque sin su paciencia, dedicación y conocimientos esta tesis no hubiera sido posible. Gracias también por todos esos cafés, tan a menudo necesarios.

Gracias a todas aquellas personas que a lo largo de este proceso me han ido ayudando de una forma u otra a la realización de la tesis: los técnicos de laboratorio, personal de administración, etc.

Pero, por encima de todo, gracias a mi familia, por su cariño, por su apoyo, porque siempre puedo contar con ellos.

RESUMEN

La infraestructura vial tiene una gran importancia en la vida cotidiana de millones de ciudadanos, pero se generan grandes repercusiones económicas, ambientales y sociales al intentar mantenerla en un estado adecuado. Y aunque existen diversas prácticas que permiten a las carreteras ser más duraderas, rentables y respetuosas con el medio ambiente es necesario garantizar su sostenibilidad mediante la realización de análisis que tengan en cuenta las circunstancias particulares de su aplicación.

La metodología del análisis de ciclo de vida (ACV) se ha aplicado en numerosos casos de estudio con este fin. Sin embargo, su aplicación a carreteras todavía se encuentra en una etapa inmadura debido a la existencia de lagunas en el conocimiento y a la falta de directrices y metodologías que faciliten su inclusión. Por ello, la presente tesis doctoral trata de analizar en mayor profundidad diversos aspectos de la metodología de ACV que están generando incertidumbre en su aplicación a firmes asfálticos, de forma que se impulse la realización de ACVs más eficaces, fiables y completos.

La investigación partió con la creación de una extensa base de datos relativa a todos los procesos que intervienen a lo largo de la vida de la carretera, lo que permitió identificar aquellos aspectos que, a pesar de su posible interés y peso dentro del ACV, o no estaban estudiados en suficiente profundidad, o la existencia de datos era escasa o la información disponible era contradictoria.

A continuación, se ahondó en la sustitución de áridos naturales de alta calidad por escorias de arco eléctrico (EAFS), lo que requirió la realización de ensayos de laboratorio y la aplicación de modelos teóricos. Como principal conclusión de este estudio cabe destacar la gran importancia que tiene el método de asignación de impactos aplicado a las escorias, el porcentaje de absorción de los áridos y las medidas para reducir la humedad de los mismos a la hora de determinar la distancia a partir de la cual el uso de escoria es más conveniente que el de áridos naturales.

La investigación relacionada con la predicción de la vida de un firme asfáltico a partir de ensayos de laboratorio y su efecto en los resultados del ACV se abordó analizando tres mezclas asfálticas porosas que combinaban la sustitución de áridos naturales, la reducción de la temperatura de fabricación y el uso de betunes nanomodificados. El análisis se realizó asumiendo distintas durabilidades de las mezclas asfálticas y también realizando simulaciones del comportamiento del firme con 2 programas informáticos: Alize y 3D-Move. Los resultados hicieron evidente la gran importancia de predecir de la forma más precisa posible la vida útil del firme.

Finalmente, se evaluó la relevancia de los retrasos sufridos por los usuarios durante las operaciones de mantenimiento. Para conseguirlo, se definieron 6 escenarios que combinaban 3 niveles de servicio (NS) de una autopista y una carretera convencional, utilizada esta última como ruta alternativa a la que podían desviarse los vehículos cuando la demora era demasiado alta. El análisis se realizó aplicando 2 enfoques de simulación de tráfico (micro y macro). Los resultados permitieron concluir que la fase de congestión debe incluirse siempre en el ACV de una carretera cuando el programa de mantenimiento implique el cierre de un carril durante más de 24 horas, excepto en análisis preliminares de carreteras con muy poco flujo de tráfico.

ABSTRACT

Road infrastructure has great importance in the daily lives of millions of citizens. However, maintaining reliable performance of roads generates great economic, environmental and social impacts. Although several practices exist that make roads more durable, cost-effective and environmentally friendly, ensuring their sustainability is necessary by conducting analyses that take into account the particular circumstances of their implementation.

Life cycle assessment (LCA) methodology has been applied in numerous case studies with this aim. However, applying LCA to pavements is still at an immature stage due to the existence of gaps in the knowledge and lack of guidelines and methodologies which ease their inclusion. For this reason, this doctoral thesis attempts to analyze more deeply several aspects of the LCA methodology that are generating uncertainty in its application to asphalt pavements, so as to promote more efficient, reliable and complete LCAs.

The research started with the creation of an extensive database concerning all the processes involved in the road life cycle. This allowed the identification of those aspects that, despite their possible interest and relevance within the LCA, were either not studied deeply enough, or whose existence of data was scarce or even the information available was contradictory.

Then, the replacement of high-quality natural aggregates by electric arc furnace slags (EAFS) was studied in depth, which required the performance of laboratory tests and the application of theoretical models. The relevance of the slag impact allocation method, the aggregates absorption rate and the humidity of the aggregates were concluded when determining the distance from which the use of slag is more convenient than the use of natural aggregates.

Research related to predicting the lifespan of an asphalt pavement based on laboratory tests and its effect on LCA results was conducted by analyzing three porous asphalt mixtures combining the replacement of natural aggregates, the reduction of manufacturing temperature and the use of nanomodified bitumen. The analysis was carried out assuming different disabilities of the asphalt pavement and also simulating the pavement behavior with two different software packages: Alize and 3D-Move. Results showed the great importance of predicting as accurately as possible the service life of the pavement.

Finally, the relevance of the traffic delay produced during the maintenance of a highway on its total LCA was evaluated. With this in mind, six scenarios were defined combining three levels of service (LOS) of a motorway and a national road, the latter being used as an alternative route to which vehicles could be deviated when the queue is too long. The analysis was carried out by applying 2 traffic simulation approaches (micro and macro). The results led to the conclusion that the congestion stage should always be included in the LCA of a road when the maintenance schedule involves closing a lane for more than 24 hours, except in preliminary analyses of roads with very little traffic flow.

TABLA DE CONTENIDO

ÍNDICE DE FIGURAS

ÍNDICE DE TABLAS

1. INTRODUCCIÓN

1.1. Antecedentes

En septiembre de 2015, la Asamblea General de las Naciones Unidas adoptó los Objetivos de Desarrollo Sostenible (ODS) para lograr "satisfacer las necesidades del presente sin comprometer la capacidad de las futuras generaciones para satisfacer sus propias necesidades" [1]. Formado por 17 objetivos y con plazo hasta 2030, los ODS tratan de resolver tres grandes problemas compartidos a nivel mundial: la pobreza extrema, la desigualdad e injusticia y la degradación ambiental. En particular, los objetivos relacionados con el medio ambiente buscan incrementar la eficiencia en la producción y consumo de recursos, disminuir la generación de desechos, prevenir y reducir la contaminación del mar y luchar contra la desertificación y la deforestación [2].

El sector de las carreteras puede contribuir de manera significativa a la consecución de estos objetivos en materia medioambiental. La infraestructura vial tiene una gran importancia en la vida cotidiana de millones de ciudadanos al permitir su movilidad urbana y regional, impulsar el crecimiento económico, crear puestos de trabajo y facilitar las relaciones comerciales. Como ejemplo, solo en Europa la industria de los áridos emplea a más de 200.000 personas y tiene una facturación anual estimada superior a los 15.000 millones de euros [3]. Sin embargo, mantener un nivel de servicio adecuado de las carreteras es cada vez más difícil debido a problemas como el aumento de la demanda de tráfico (tanto ligero como pesado) y el envejecimiento de las infraestructuras (el cual se está viendo acentuado por el efecto del cambio climático), lo que hace necesaria la continua construcción y mantenimiento de las carreteras. Esto trae consigo repercusiones económicas, ambientales y sociales debido a la gran demanda de recursos naturales, la perturbación del tráfico y el aumento del potencial de accidentes, que reducen la movilidad y la fiabilidad de la red de carreteras y aumentan el tiempo de viaje.

Según la Asociación Europea de Áridos, los áridos son el recurso más consumido en Europa después del agua y el aire [3]. De hecho, solo en la construcción de 1 km de carretera se emplean más de 30.000 toneladas de áridos, lo que supone unos 1.350 millones de toneladas al año. Los derivados del petróleo son otro ejemplo del uso de grandes cantidades de recursos no renovables en el sector de la carretera, dado que cada año se destinan alrededor de 13 millones de toneladas de betún para su construcción y mantenimiento [4]. Este consumo de recursos no solo produce impacto ambiental, sino también económico. En este sentido, se estima que en 2014 se destinaron 21.206 millones de euros para el mantenimiento de la infraestructura vial europea [5]. Sin embargo, esta cifra no tiene en cuenta el costo del retraso que sufren los usuarios durante las obras, lo que es especialmente importante en las carreteras con mucho tráfico (4.5 billones de euros anuales según el Gobierno de Reino Unido [6]).

Aunque estas cifras ya son destacables, se espera que aumenten aún más en un futuro próximo ya que se estima que el tráfico de mercancías se triplicará entre 2015 y 2050, afectando así a las carreteras existentes, cuyas infraestructuras no fueron diseñadas para soportar tal cantidad de cargas. Por consiguiente, es necesario fomentar la utilización de prácticas más duraderas, rentables y respetuosas con el medio ambiente garantizando su sostenibilidad mediante análisis que tengan en cuenta las circunstancias particulares de su aplicación.

El análisis de ciclo de vida (ACV) es un método normalizado que se emplea para medir y comparar el posible impacto ambiental producido durante la fabricación, utilización y eliminación de un producto. Su empleo se remonta a finales de la década de los 60, principios de los 70, época en la que debido a la crisis de petróleo, la disminución del consumo energético se consideró una gran prioridad [7]. En 1972, por ejemplo, Ian Boustead calculó la energía total consumida durante la producción de varios tipos de envases de bebidas, incluyendo vidrio, plástico, acero y aluminio [8]. Sin embargo, una vez pasada la crisis del petróleo, la importancia del consumo energético disminuyó y, aunque el interés por la metodología continuó, ésta fue progresando más lentamente. No fue hasta principios de los años 90 cuando el interés en los ACV resurgió de nuevo extendiéndose su aplicación a ámbitos tan dispares como el pintado de automóviles [9], la optimización de plantas de producción de ácido nítrico [10] o la producción de vino [11].

Respecto a su aplicación en el ámbito de las carreteras, Häkkinen y Mäkelä [12] y Horvath y Hendrickson [13], entre otros, realizaron este tipo de análisis a finales de la década de los 90 para comparar el impacto generado por las mezclas de hormigón y asfalto. Años más tarde, Mroueh et al. [14] utilizaron esta metodología para determinar los beneficios de añadir subproductos industriales (como cenizas volantes o escorias de alto horno) a la estructura del firme. Jullien et al. [15] compararon el impacto ambiental de utilizar 4 porcentajes distintos de asfalto en la construcción de una carretera. Kucukvar et al. [16] desarrollaron un modelo para comparar diferentes tipos de mezclas templadas con mezclas de asfalto calientes. Lu et al. [17] se centraron en estudiar los beneficios de los firmes permeables con respecto a las mezclas densas tradicionales. Sin embargo, a pesar de estos antecedentes, la realización de ACVs de carreteras se encuentra todavía en una etapa inmadura debido a la existencia de lagunas en el conocimiento relativas a ciertas fases de su vida útil y a la falta de directrices y metodologías que faciliten su inclusión [18]. En concreto, destacan 4 grandes lagunas relacionadas con:

- el uso de materiales reciclados en mezclas asfálticas;
- la durabilidad del firme;
- la resistencia a la rodadura;
- la importancia de los atascos generados durante las labores de mantenimiento.

La sustitución de áridos naturales por residuos y subproductos es una de las técnicas más empleadas para reducir el impacto ambiental de las carreteras ya que se consigue un beneficio doble. Por un lado, la extracción de materias primas disminuye, y con ello el consumo de agua, electricidad y diésel, así como la generación de ruido y polvo. Por otro lado, el reciclado de materiales evita su depósito en vertedero, lo que prolonga la vida útil del mismo y reduce las emisiones atmosféricas. La escoria procedente de hornos de arco eléctrico (EAFS) es un buen ejemplo de materiales reciclados con estos fines.

Según la Asociación Mundial del Acero [19], en Europa se produjeron en 2017 alrededor de 168,4 millones de toneladas de acero bruto, un 40 % del cual (67,36 millones de toneladas) procedió de hornos de arco eléctrico. Si por cada tonelada de acero producido en hornos de arco eléctrico se generan 130 kg de escorias [20], en 2017 se generaron en Europa alrededor de 9 millones de toneladas de EAFS, de las cuales 4 millones se utilizaron para la construcción de carreteras [21].

El comportamiento mecánico de mezclas asfálticas en las que el árido grueso natural se ha sustituido por EAFS se ha evaluado en profundidad obteniendo muy buenos resultados en lo que respecta a la compactibilidad, rigidez, resistencia a fatiga, sensibilidad al agua y deformación permanente [22–25]. Sin embargo, los aspectos ambientales no se han estudiado con tanto detalle.

La mayoría de los análisis ambientales sobre la utilización de escorias en las carreteras se han centrado en el empleo de escorias de alto horno (BFS) en capas granulares. Mroueh et al. [26] evaluaron las ventajas de sustituir áridos naturales por ceniza volantes, hormigón reciclado y BFS, demostrando que estos dos últimos materiales permiten reducir el consumo de energía. Sayagh et al. [27] analizaron la influencia de los procedimientos de asignación de impactos en los resultados del ACV comparando un firme semiflexible en el que las capas base y subbase contenían BFS con un firme rígido. Los resultados concluyeron que el considerar las BFS como residuo o como subproducto puede afectar tremendamente la selección de un firme u otro. Huang et al. [28] también investigaron el procedimiento de asignación de impactos pero en este caso, las BFS se utilizaron en toda la sección del firme, obteniendo la misma afección en los resultados que los ya observados por Sayagh et al. [27].

Por el contrario, pocos autores han centrado su investigación en el análisis de EAFS empleadas en capas asfálticas. Mladenovič et al. [29] compararon la producción y construcción de 2 capas de rodadura en las que el árido silícico había sido sustituido por escorias de acería y, a pesar de necesitar más betún que las mezclas convencionales, las escorias terminaron siendo la opción más sostenible en 4 de los 7 impactos analizados. Un año más tarde, Ferreira et al. [30] realizaron un análisis similar en el que se destacó la variabilidad de los resultados ambientales según la porosidad de las escorias. Aun con todo, ninguna de estas investigaciones consideró aspectos tan importantes como la lixiviación de las mezclas asfálticas, diferencias en el calor específico de los áridos o variaciones de la energía de compactación de las mezclas.

Además de la sustitución de áridos naturales, existen otras tecnologías que permiten reducir el impacto ambiental de las carreteras. Un ejemplo de esto son las mezclas templadas (WMA), que tratan de reducir la temperatura de fabricación de las mezclas entre 20 y 40 ºC modificando la viscosidad del betún o mejorando la envuelta de los áridos con el betún a través de aditivos químicos [31]. Otro ejemplo es la reducción del contenido de betún de las mezclas mediante la incorporación de plásticos reciclados que están siendo enviados a vertedero [32]. Actualmente, muchas investigaciones se están centrando en aumentar la durabilidad de los firmes ya sea añadiendo fibras [33], empleando betunes nanomodificados [34] o diseñando mezclas susceptibles de ser sanadas por inducción [35], entre otros. Sin embargo, la sostenibilidad de estas tecnologías está muy influenciada por la durabilidad de las mezclas asfálticas. Normalmente, al realizar ACVs de asfaltos novedosos de los que no se disponen datos reales sobre su durabilidad, se les suele asumir la misma vida útil que los firmes tradicionales, siempre que cumplan con los requerimientos técnicos y mecánicos establecidos en las normativas [36–39]. Otros autores optan por suponer un incremento de vida en base a los resultados obtenidos en los ensayos de fatiga realizados en el laboratorio [40–42]. No obstante, estas hipótesis pueden tanto sobreestimar como subestimar los beneficios ambientales de las tecnologías.

Existen diversas maneras de calcular la durabilidad de un firme asfáltico, cada una de ellas llevando asociado un coste y una fiabilidad muy distinta: ensayos de laboratorio, ensayos de pavimento acelerados, tramos de pruebas y datos de carreteras en uso. La forma más básica de cálculo es la que utiliza directamente los resultados obtenidos en los ensayos de laboratorio. Sin embargo, teniendo en cuenta los distintos mecanismos de fallo de las mezclas según su tipo y disposición dentro de la estructura del firme y la correlación entre las distintas propiedades del mismo, es necesaria la utilización de programas informáticos que integren los resultados obtenidos en los test. Estos programas se han utilizado en numerosas ocasiones para diseñar y evaluar el comportamiento mecánico de diversos paquetes de firme [43–45], pero pocos los han utilizado en el ámbito de los ACV y ninguno ha estudiado la sensibilidad de los resultados al utilizar programas con metodologías de cálculo distintas.

En lo que respecta a la fase de uso, ésta representa la fase más larga del ciclo de vida de una carretera, por lo que puede contribuir de forma significativa a su impacto ambiental [46]. De todos los procesos que intervienen en esta fase (albedo, iluminación, carbonatación del hormigón, etc.) la resistencia a la rodadura puede llegar a ser un aspecto tremendamente importante, sobre todo en carreteras con un volumen de tráfico elevado ya que pequeñas variaciones del consumo de los vehículos pueden suponer cientos de miles de litros a lo largo de la vida del firme [46]. La resistencia a la rodadura depende a su vez de distintas variables, algunas de ellas relacionadas con el propio vehículo (masa, velocidad, tipo de rueda, etc.) y otras relacionadas con las características del firme, en concreto con la macrotextura y la regularidad superficial. Existen pocos modelos que combinen estos dos parámetros y los relacionen con el consumo energético de los vehículos y, al aplicarlos a una misma sección del firme, pueden incluso llegar a dar resultados totalmente contradictorios. Trupia et al. [46] investigaron en profundidad este tema al utilizar el modelo desarrollado por el Centro de Investigación de Firmes de la Universidad de California (UCPRC) y el del Instituto Nacional Sueco de Investigación Vial y de Transportes (VTI) en un caso de estudio ya utilizado anteriormente por Galatioto et al. [47]. Los resultados mostraron que, al utilizar el modelo UCPRC, las emisiones de CO_2 producidas debido al deterioro de la carretera eran mayores que las que se producirían si los valores de macrotextura y regularidad se mantuvieran constantes con el paso del tiempo. Por su parte, el modelo de VTI predecía una reducción de las emisiones con el deterioro de la carretera.

Por último, la congestión producida por los cortes de tráfico ocasionados durante las labores de mantenimiento es otro de los aspectos del ACV de carreteras que rara vez se incluye dentro de los límites del sistema. De hecho, solo 7 de los 42 análisis revisados por Santero et al. [48], Trupia [49] y Anthonissen et al. [50] lo incluyeron.

A pesar de que su importancia ha sido analizada por distintos autores, la gran variación de los resultados según el volumen de tráfico de la carretera, su distribución horaria y el horario de cierre, ha impedido alcanzar resultados concluyentes [51]. Además de estos factores ya mencionados, los resultados también pueden verse influidos por el modelo de tráfico seleccionado para calcular la congestión. Los modelos de micro simulación se basan en la predicción del comportamiento individual de los vehículos, lo que requiere mucha información para su calibración y mucho tiempo para ejecutar la simulación. Por otra parte, los modelos de macro simulación analizan el tráfico sección por sección, necesitando menos información pero también siendo menos precisos [49]. A este respecto, Yu y Lu [18] realizaron un ACV para calcular el consumo energético y el potencial de calentamiento global (GWP) generado por 3 opciones de rehabilitación. Tras analizar todo el ciclo de vida, la congestión (que fue calculada con un modelo de macro simulación) resultó ser una de las etapas más importantes, incrementándose su relevancia a medida que lo hacía el volumen de tráfico. Galatioto et al. [47] estudiaron la influencia del tiempo de demora de los usuarios en las emisiones atmosféricas al aplicar diferentes planes de corte (tres días de cortes nocturnos, dos días cortando el tráfico durante 12 horas y un único corte de 24 horas) en una carretera interurbana del Reino Unido. En este caso, se utilizó un modelo de micro simulación y, a pesar de que se comprobó que las emisiones producidas por la congestión eran relativamente pequeñas, eran lo suficientemente considerables como para tener que incluirlas en el ACV. Además, Kim et al. [52] evaluaron el consumo de combustible y las emisiones de gases de efecto invernadero producidas por dos tipos de carreteras (una autopista y una carretera multicarril) teniendo en cuenta dos tipos distintos de planes de corte y tres niveles de congestión. Los resultados mostraron un incremento de las emisiones de alrededor de un 85 % en carreteras muy congestionadas. Por lo tanto, de estos estudios se puede inferir que ignorar sistemáticamente el impacto producido por la congestión durante las intervenciones de mantenimiento y rehabilitación puede provocar una falta de precisión en los resultados del ACV, especialmente en las carreteras con mucho tráfico. Sin embargo, es necesario hacer recomendaciones sobre cuándo y cómo considerar la congestión en el ACV de una carretera para fomentar su evaluación dentro de un análisis global.

1.2. Motivación y objetivos

A pesar de que la metodología de ACV se ha aplicado en numerosos casos de estudio desde los años 90 y que desde entonces ha aumentado la disponibilidad tanto de herramientas como de (pre) estándares [53], la mayoría de los análisis realizados en carreteras no considera todas las fases de la vida de la misma debido a la existencia de lagunas en el conocimiento, falta de datos fiables y falta de consenso en las directrices y metodologías.

Por ello, el objetivo principal de la presente tesis doctoral es analizar en mayor profundidad diversos aspectos de la metodología de ACV que están generando incertidumbre en su aplicación a firmes asfálticos, de forma que se impulse la realización de ACVs más eficaces, fiables y completos.

Para alcanzar este objetivo principal se plantearon y abordaron los siguientes objetivos específicos:

- Identificación de las fases, procesos y procedimientos que suscitan dudas a la hora de aplicar la metodología del ACV en firmes asfálticos.
- Establecimiento de una metodología que permita realizar ACVs de firmes que reemplacen áridos naturales por EAFS.
- Estudio de la influencia de la durabilidad en los resultados del ACV al analizar los impactos tanto del firme completo como solo de la capa de rodadura.

- Comparación de la durabilidad de firmes asfálticos estimada con programas informáticos que utilizan distintas metodologías de cálculo.
- Evaluación de la importancia de la congestión producida por las labores de mantenimiento en el ACV de una carretera al considerar distintas hipótesis de partida y programas de cálculo.

A pesar del gran interés de estudiar la resistencia a la rodadura de mezclas asfálticas, esta fase quedó fuera del alcance de la presente tesis doctoral debido a la gran dificultad de obtener datos útiles y fiables, así como por la gran variabilidad de los resultados calculados según el modelo que se emplee.

1.3. Artículos constitutivos de la tesis

Esta tesis doctoral está constituida por una compilación de 4 artículos enmarcados dentro de una misma línea de investigación: la evaluación del impacto ambiental producido por firmes asfálticos. Las publicaciones se exponen siguiendo el orden que les corresponde dentro de la metodología planteada, y no en el orden cronológico de publicación.

La primera publicación es la titulada “Environmental impact assessment of induction-healed asphalt mixtures” [54]. El objetivo inicial de esta publicación era tratar de demostrar la sostenibilidad del sanado por inducción respecto a técnicas tradicionales de mantenimiento, como el fresado y reposición. Para ello se aplicó la metodología del ACV a 2 mezclas asfálticas: una convencional y una susceptible de ser sanada mediante el uso de un inductor magnético. La realización del ACV requirió la selección de los límites del sistema a incluir en el análisis, así como la creación de una extensa base de datos relativa a todos los procesos que intervienen a lo largo de la vida de la carretera. Esto condujo a la identificación de aquellos aspectos que, a pesar de su posible interés y peso dentro del ACV, o no estaban estudiados en suficiente profundidad, o la existencia de datos era escasa o la información disponible era contradictoria. Por lo tanto, esta investigación sirvió de base y dio lugar al resto de publicaciones de la tesis doctoral.

La segunda publicación, titulada “Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures” [55] ahondó en la sustitución de áridos naturales de alta calidad por EAFS. El objetivo de este trabajo era doble: por un lado, proporcionar recomendaciones en la selección y el uso de EAFS en mezclas asfálticas de forma que se garanticen las mejoras ambientales y por otro, establecer una metodología para realizar ACVs de mezclas asfálticas que incorporen este material. Para ello se realizó un exhaustivo ACV de tres mezclas asfálticas en las que el árido grueso ofítico fue sustituido por 2 EAFS de distintas procedencias y propiedades. Las lagunas del inventario se subsanaron mediante la realización de ensayos de laboratorio y la aplicación de modelos teóricos. Además, se analizó la sensibilidad de los resultados al aplicar varios procedimientos de asignación de impactos, contenidos de humedad de los áridos, distancias de transporte y modelos de caracterización. Como principal conclusión de este estudio cabe destacar la gran importancia que tiene el método de asignación de impactos aplicado a las escorias, el porcentaje de absorción de los áridos y las medidas para reducir la humedad de los mismos a la hora de determinar la distancia a partir de la cual el uso de escoria es más conveniente que el de áridos naturales.

La investigación relacionada con la predicción de la vida de un firme asfáltico a partir de ensayos de laboratorio y su efecto en los resultados del ACV se recoge en la tercera publicación, titulada "Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures" [56]. El objetivo de esta publicación era tratar de reducir el impacto ambiental de las mezclas asfálticas sin comprometer el aspecto económico ni mecánico. Con esta idea en mente, la publicación analizó tres mezclas asfálticas porosas que combinaban la sustitución de áridos naturales, la reducción de la temperatura de fabricación y el uso de betunes nanomodificados. El análisis se realizó bajo un doble enfoque: comparando exclusivamente las capas de rodadura y comparando las secciones completas del firme. Teniendo en cuenta la importancia de la durabilidad en todas estas tecnologías y, ante la falta de datos de carreteras reales que las hayan utilizado previamente, la investigación se realizó asumiendo distintas durabilidades de las mezclas asfálticas. De esta manera se pudo determinar tanto la influencia de la durabilidad en los resultados de ACV y ACCV (análisis de costo de ciclo de vida) como la durabilidad mínima que debería tener cada una de las tecnologías para reducir los impactos producidos con respecto a las mezclas tradicionales. Posteriormente, se llevó a cabo una simulación del comportamiento del firme con 2 programas informáticos distintos: Alize y 3D-Move. Los parámetros necesarios para alimentar estos modelos se obtuvieron de los ensayos mecánicos previamente llevados a cabo para la demostración de la viabilidad técnica de las mezclas. Los resultados hicieron evidente la gran importancia de predecir de la forma más precisa posible la vida útil del firme ya que la potencial ventaja económica y ambiental de una nueva tecnología depende en muchos casos del aumento o disminución en la vida útil del firme con respecto a las tecnologías convencionales. Además, hay que tener en cuenta que, aunque con ambos programas de simulación se obtuvieron incrementos porcentuales muy similares de la vida de las tecnologías, no calcularon la misma vida útil en valor absoluto.

Finalmente, la quinta publicación titulada "Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road" [57], trata de dar recomendaciones sobre cuándo y cómo considerar en el ACV los retrasos sufridos por los usuarios durante las operaciones de mantenimiento, para evitar la pérdida de precisión en los resultados. Para conseguirlo, se definieron 6 escenarios que combinaban 3 niveles de servicio (NS) de una autopista y una carretera convencional, utilizada esta última como ruta alternativa a la que podían desviarse los vehículos cuando la demora era demasiado alta. La longitud de cola y las emisiones e impactos ambientales producidos por el tráfico se calcularon aplicando 2 enfoques de simulación (micro y macro) y los resultados se compararon con los impactos generados por la carretera a lo largo de un periodo de 30 años. Los resultados permitieron concluir que la fase de congestión debe incluirse siempre en el ACV de una carretera cuando el programa de mantenimiento implique el cierre de un carril durante más de 24 horas, excepto en análisis preliminares de carreteras con muy poco flujo de tráfico. Además, los resultados mostraron que la macro simulación solo debería utilizarse para cálculos aproximados debido a su menor precisión a la hora de reproducir el comportamiento real de los vehículos.

2. COMPENDIO DE ARTÍCULOS

2.1. Artículo Nº1: Environmental impact assessment of induction-healed asphalt mixtures

Autores: Esther Lizasoain-Arteaga
Irune Indacoechea-Vega
Pablo Pascual-Muñoz
Daniel Castro-Fresno

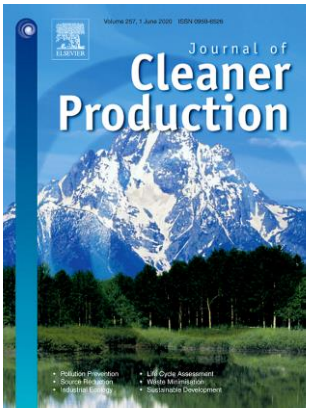
Año: 2019

Revista: Journal of Cleaner Production

Volumen: 208

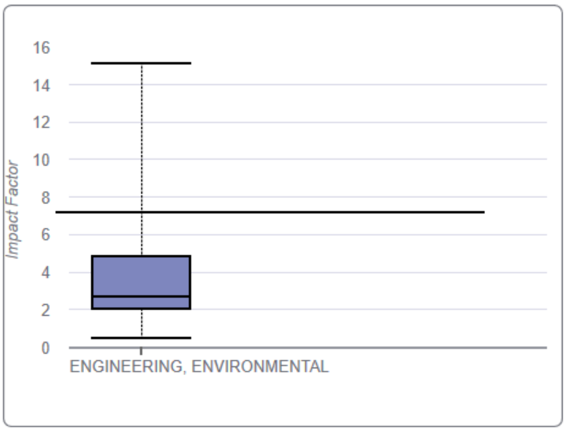
Páginas: 1546-1556

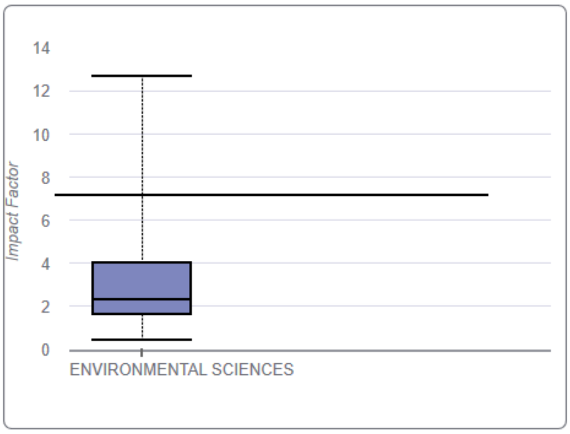
DOI: 10.1016/j.jclepro.2018.10.223



Categoría	Año	Ranking	Cuartil	Percentil
Engineering, Environmental	2019	8/53	Q1	85.849
Environmental sciences	2019	19/265	Q1	93.019

Factor de Impacto JCR (2019): 7.246





Author's post-print: E. Lizasoain-Arteaga, I. Indacoechea-Vega, P. Pascual-Muñoz, D. Castro-Fresno. "Environmental impact assessment of induction-healed asphalt mixtures". J. Clean. Prod. 208 (2019), 1546-1556. ISSN: 09596526. DOI: https://doi.org/10.1016/j.jclepro.2018.10.223

Environmental impact assessment of induction-healed asphalt mixtures

E. Lizasoain-Arteaga[1]*, I. Indacoechea-Vega[1], P. Pascual-Muñoz[1], D. Castro-Fresno[1]

[1]GITECO Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain

Email addresses: lizasoaine@unican.es (E. Lizasoain-Arteaga); indacoecheai@unican.es (I. Indacoechea-Vega); pascualmp@unican.es (P. Pascual-Muñoz); castrod@unican.es (D. Castro-Fresno)

*Corresponding author. Tel +34942203943; Fax: +34942201703

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.

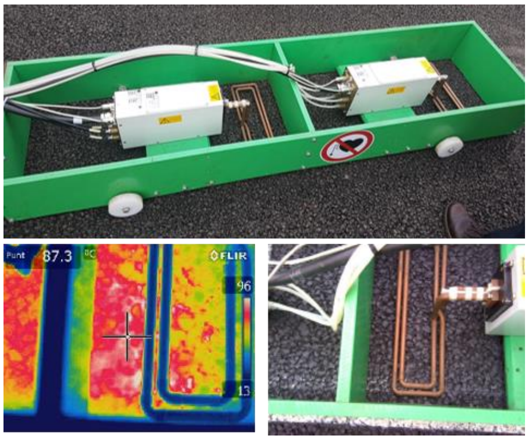


Figure 1. Induction-heating machine used in the HEALROAD project. Source: SGS Intron (The Netherlands).

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).

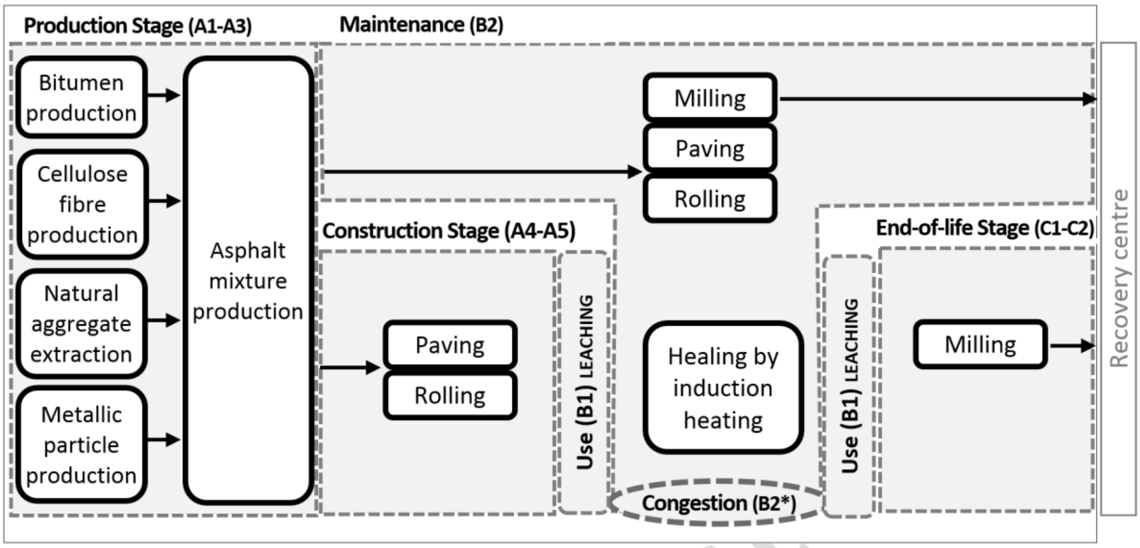


Figure 2. LCA boundaries.

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 litres of diesel 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.

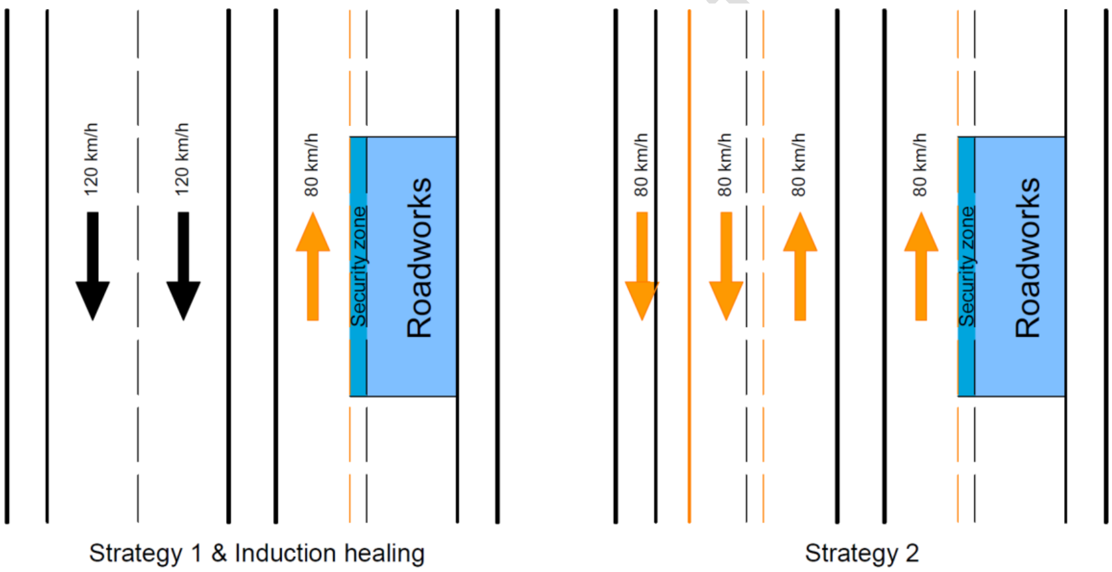


Figure 3. Maintenance strategies diagram.

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.

Characteristic	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.

Emission	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
$PM_{2.5}$ (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.

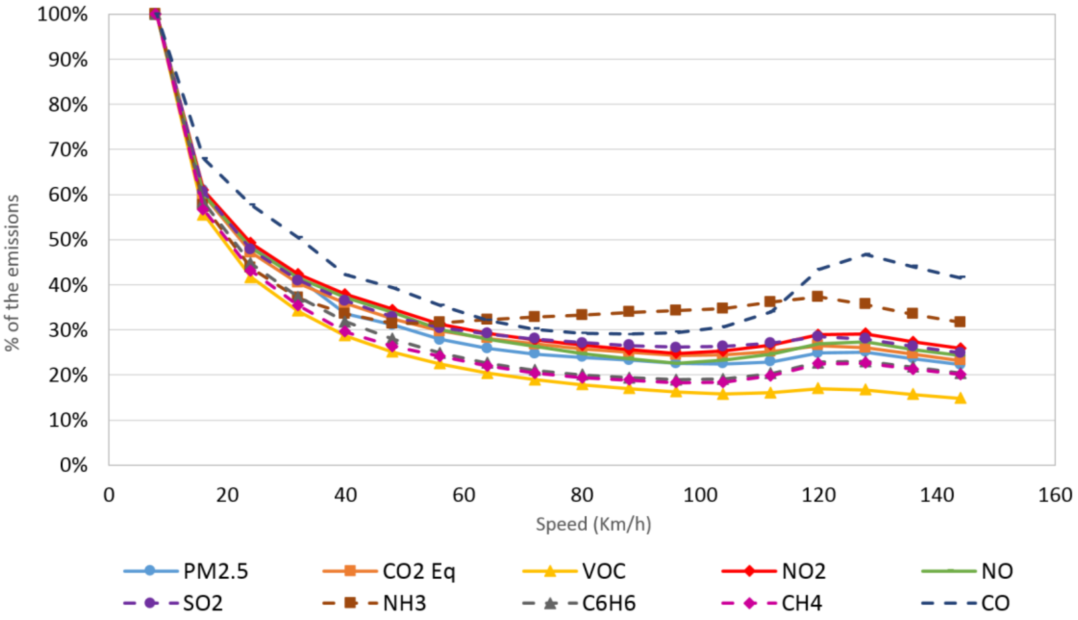


Figure 4. Relationship between vehicle emissions and speed.

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.

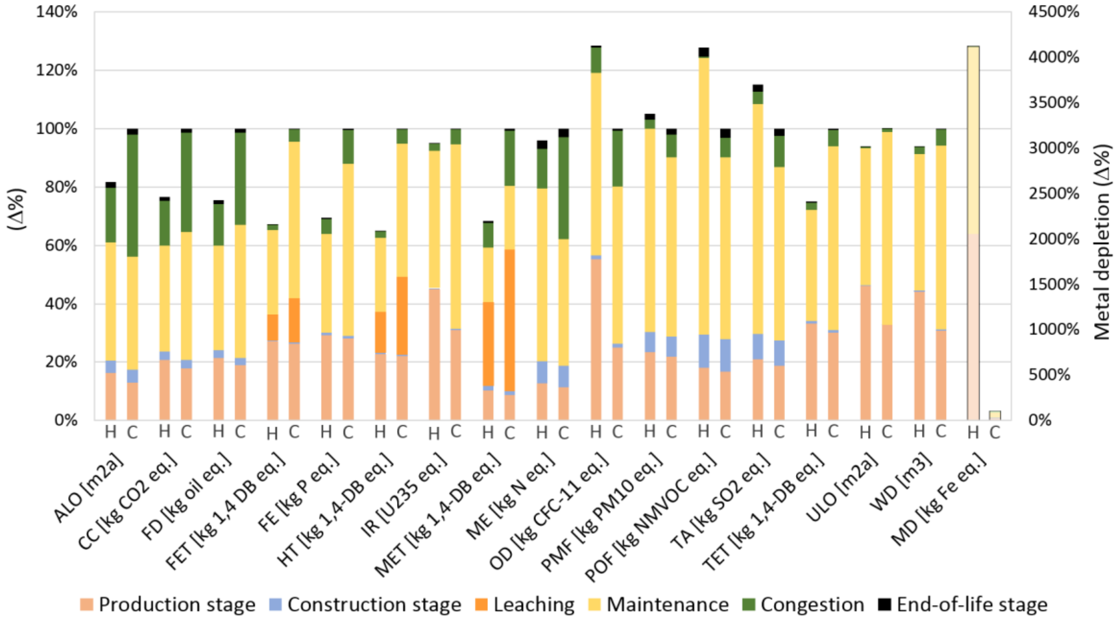


Figure 5. ReCiPe Midpoint Impact Category. Total impact – Case 1.

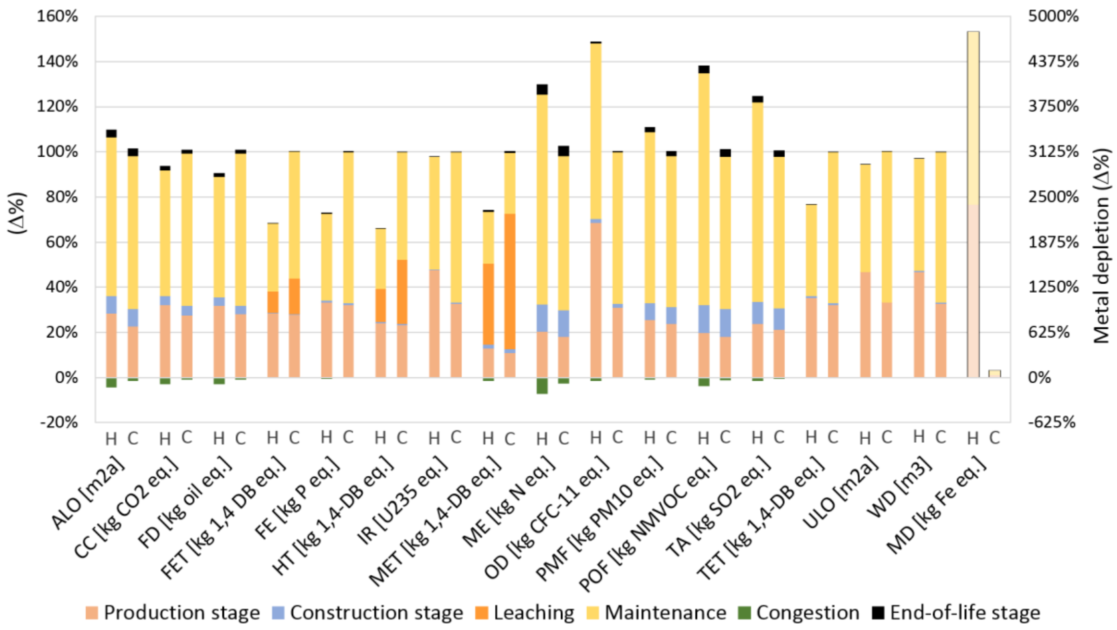


Figure 6. ReCiPe Midpoint Impact Category. Total impact – Case 2.

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%.

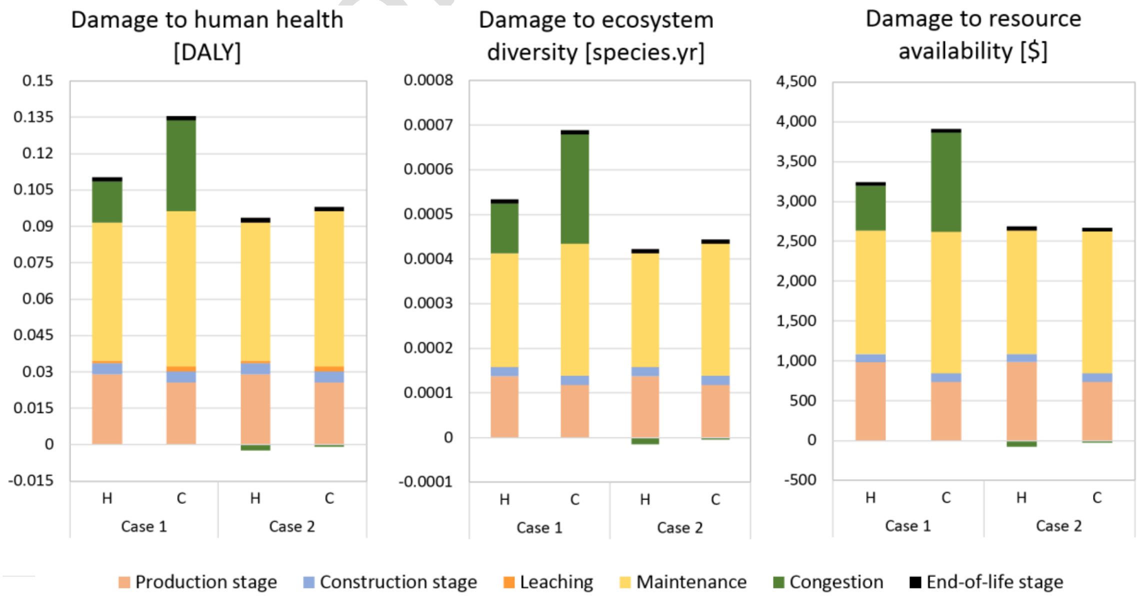


Figure 7. ReCiPe Endpoint Impact Category. Total impact.

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.

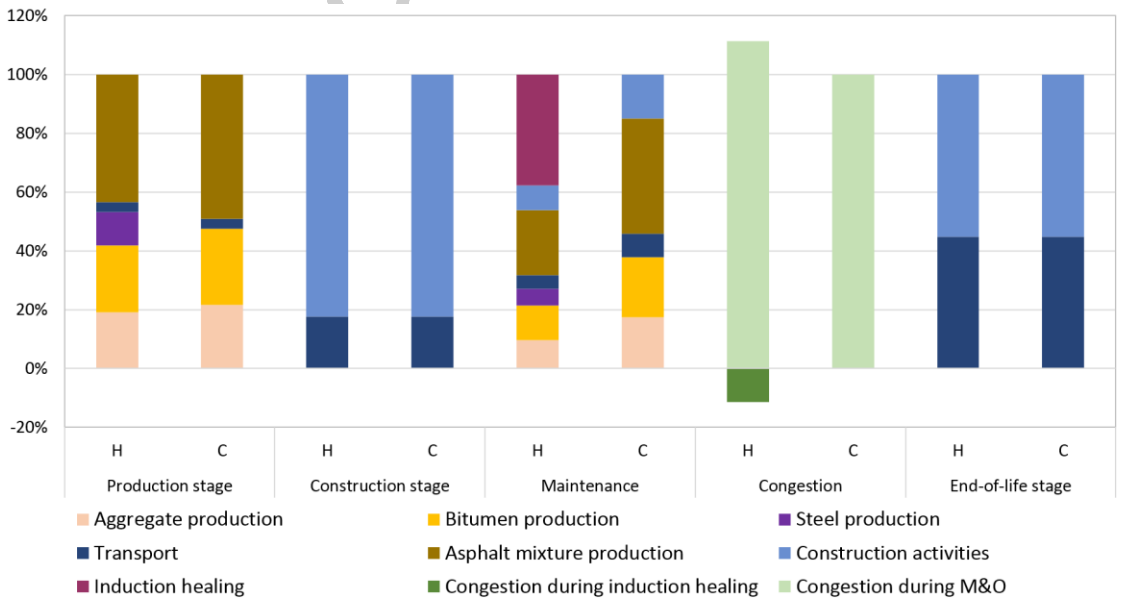


Figure 8. Process contribution to the Damage to human health impact. Case 1.

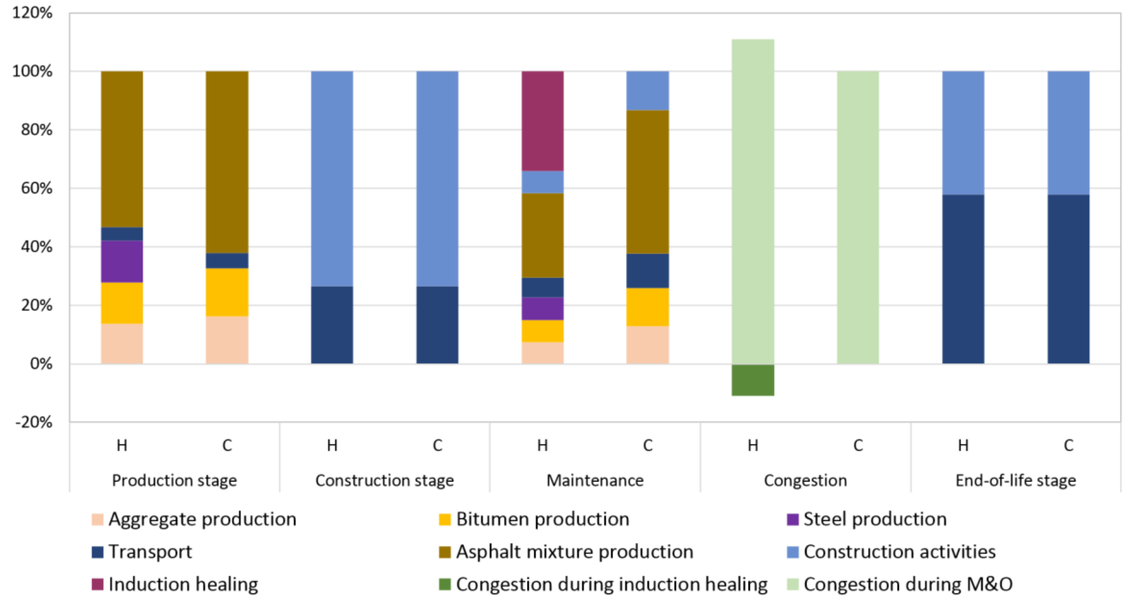


Figure 9. Process contribution to the Damage to ecosystems diversity impact. Case 1.

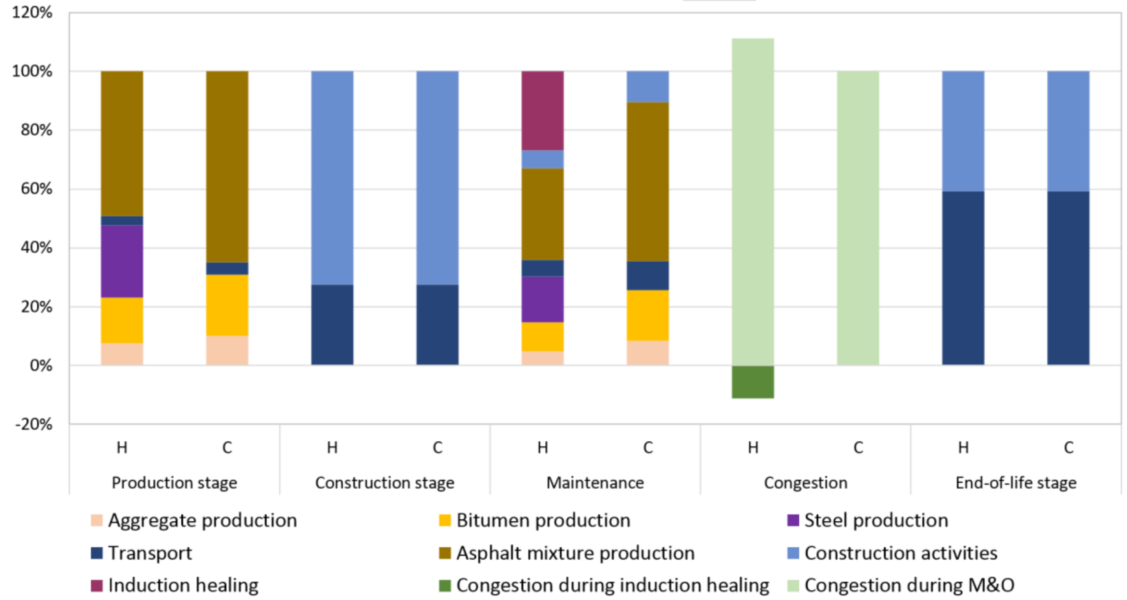


Figure 10. Process contribution to the Damage to resource availability impact. Case 1.

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 these specific conditions, the more the induction treatment last, the better for the environment.

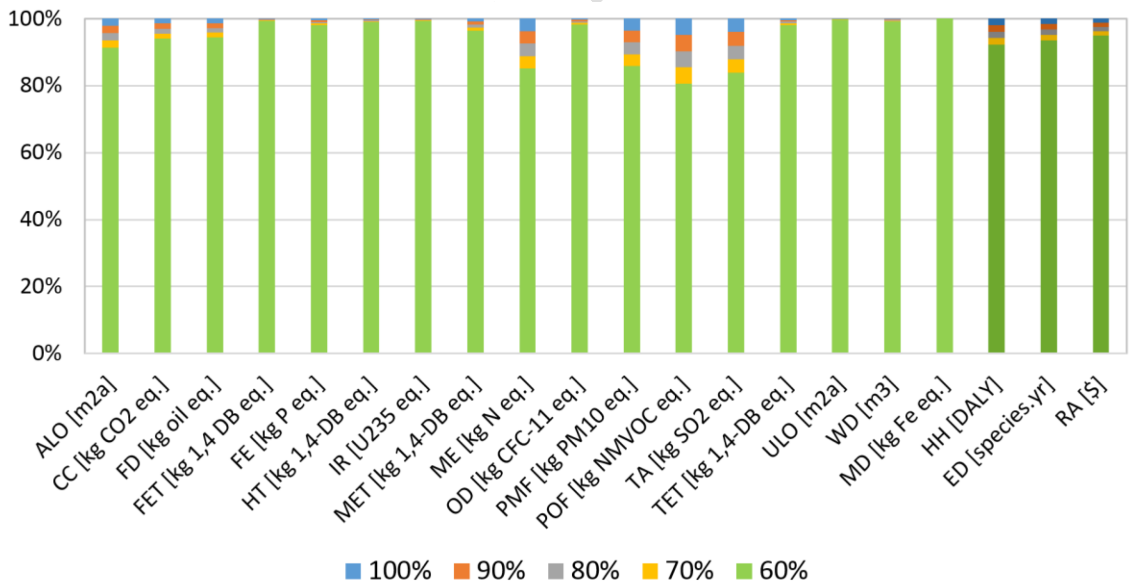


Figure 11. ReCiPe. Total impact. Induction-heating machine's diesel consumption variability.

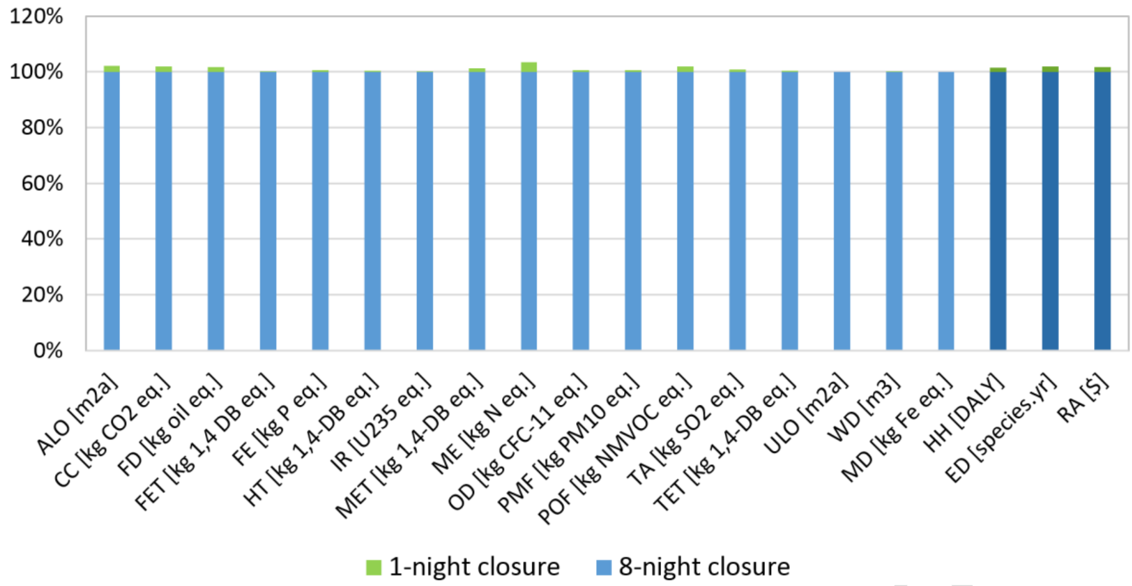


Figure 12. ReCiPe. Total impact. Induction-heating machine speed variability.

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.

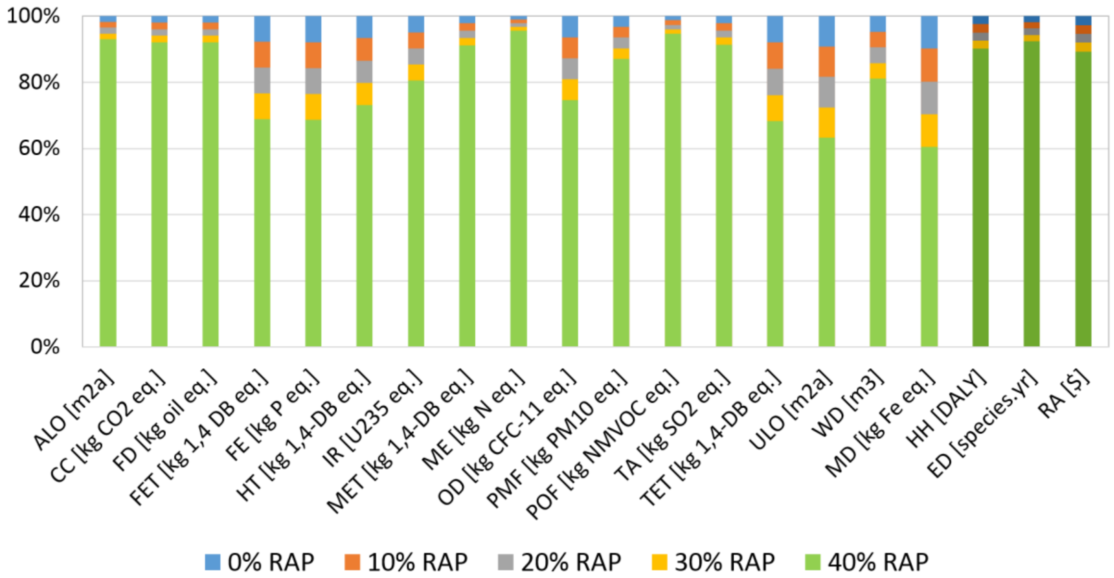


Figure 13. ReCiPe. Total impact. RAP variability.

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).

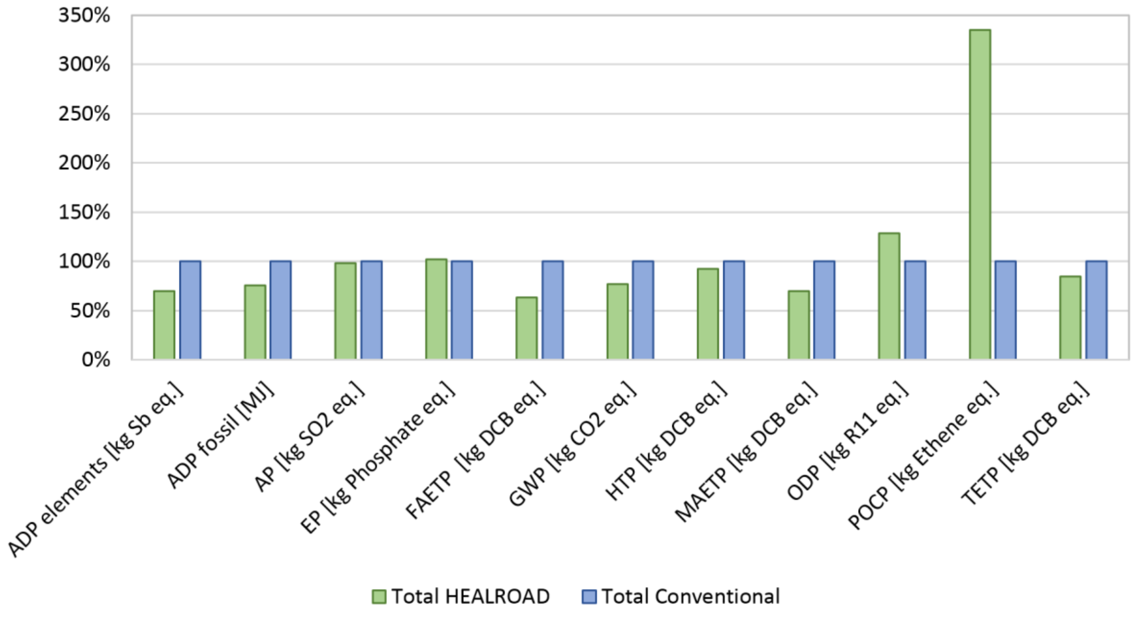


Figure 14. CML 2001 Jan 16. Total impact – Case 1.

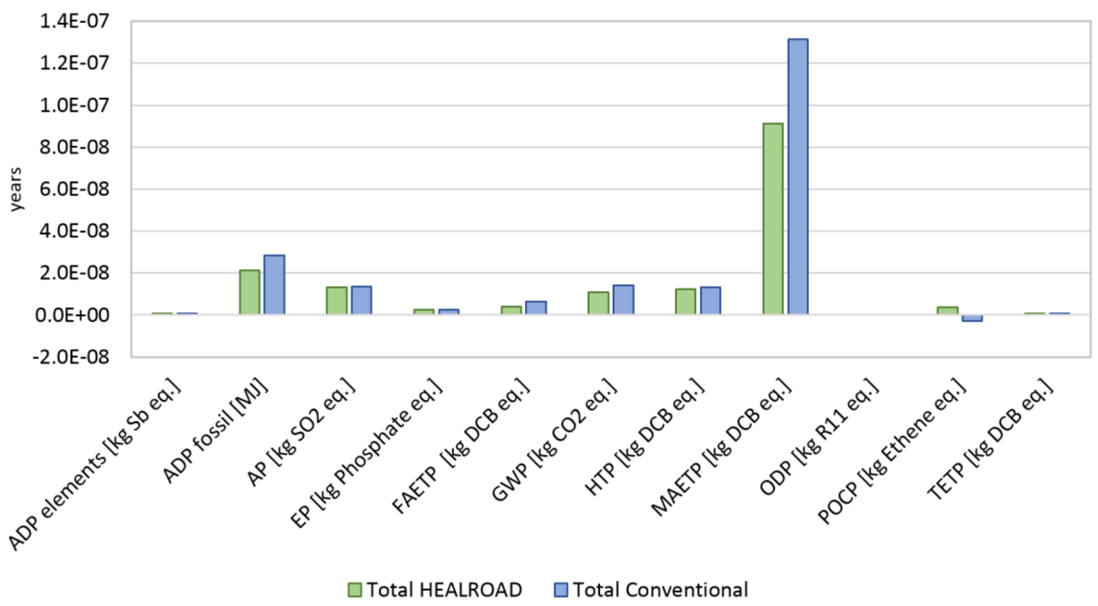


Figure 15. CML 2001 Jan 16. Total impact (Normalised) – Case 1.

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.

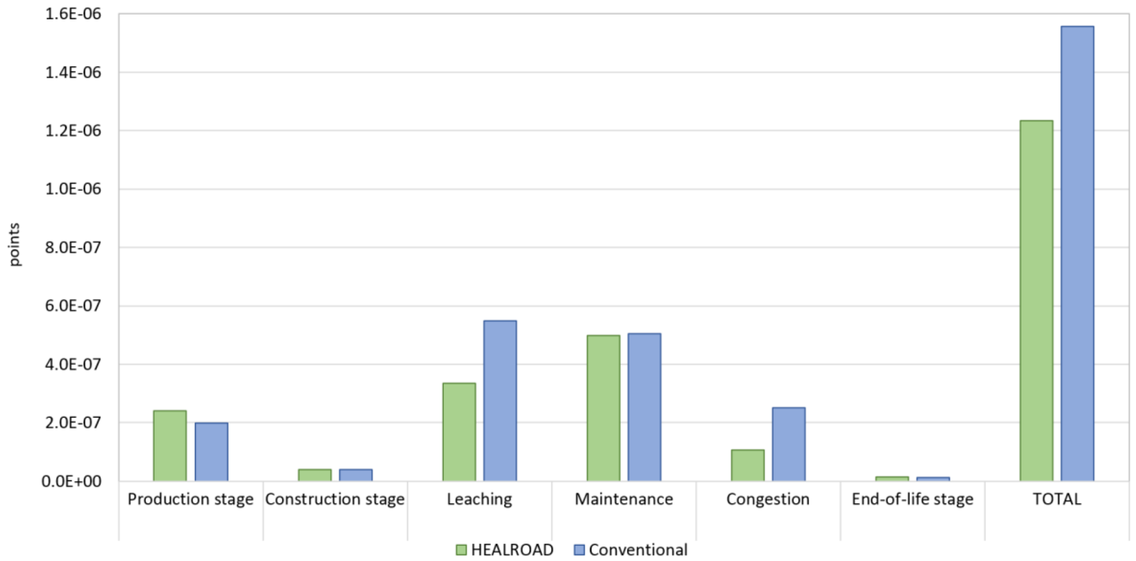


Figure 16. CML 2001 Jan 16. Total impact (Weighted) – Case 1.

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%.

Acknowledgements

This work was supported by the ERA-NET Plus Infravation 2014 Call under grant agreement no. 31109806.0003 – HEALROAD. Funding partners of the Infravation 2014 Call are: Ministerie van Infrastructuur en Milieu, Rijkswaterstaat, Bundesministerium für Verkehr, Bau und Stadtentwicklung, Danish Road Directorate, Statens Vegvesen Vegdirektoratet, Trafickverket-TRV, Vegagerdin, Ministere de l'Ecologie du Developpement Durable et de l'Energie, Centro para el Desarrollo Tecnológico Industrial, Anas S.P.S, Netivei Israel – National Transport Infrastructure Company LTD and Federal Highway Administration USDOT. The HEALROAD project has been carried out by the University of Cantabria, University of Nottingham, German Federal Highways Research Institute (BASt), European Union Road Federation (ERF), Heijmans Integrale projecten B.V. and SGS INTRON B.V. Finally, we express special gratitude to the HEALROAD partners: Alvaro Garcia, Bastian Wacker, Bianca Beatens, Breixo Gómez-Meijide, Gerbert van Bochove and Tobias Panwinkler.

References

Abbe, O., Hamilton, L., 2017. BRE Global Environmental Weighting for Construction Products using Selected Parameters from EN 15804.

Ajam, H., Gómez-Meijide, B., Artamendi, I., Garcia, A., 2018. Mechanical and healing properties of asphalt mixes reinforced with different types of waste and commercial metal particles. J. Clean. Prod.

Ajam, H., Lastra-González, P., Gómez-Meijide, B., Airey, G., Garcia, A., 2017. Self-healing of dense asphalt concrete by two different approaches: Electromagnetic induction and infrared radiation. J. Test. Eval. 45. https://doi.org/10.1520/JTE20160612

Athena, 2005. Cement and Structural Concrete Oroducts: Life Cycle Inventory Update #2,.

Ayar, P., Moreno-Navarro, F., Rubio-Gámez, M.C., 2016. The healing capability of asphalt pavements: a state of the art review. J. Clean. Prod. 113, 28–40. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.12.034

Bueno, M., Arraigada, M., Partl, M.N., 2016. Damage detection and artificial healing of asphalt concrete after trafficking with a load simulator. Mech. Time-Dependent Mater. 20, 265–279. https://doi.org/10.1007/s11043-016-9306-z

Caltrans, 2007. Life-Cycle Cost Analysis Procedures Manual.

ERTRAC, 2011. European Roadmap Climate Resilient Road Transport.

Eurobitume, 2012. The bitumen industry in Europe [WWW Document]. URL http://www.eurobitume.eu/bitumen/industry/ (accessed 12.30.17).

García, Á., Schlangen, E., van de Ven, M., Liu, Q., 2009. Electrical conductivity of asphalt mortar containing conductive fibers and fillers. Constr. Build. Mater. 23, 3175–3181. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2009.06.014

Gómez-Meijide, B., Ajam, H., Lastra-González, P., Garcia, A., 2016. Effect of air voids content on asphalt self-healing via induction and infrared heating. Constr. Build. Mater. 126, 957–966. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.09.115

Häkkinen, T., Mäkelä, K., 1996. Environmental adaption of concrete. Environmental impact of concrete and asphalt pavements. VTT Tied. - Valt. Tek. Tutkimusk.

Horvath, A., Hendrickson, C., 1998. Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements. Transp. Res. Rec. J. Transp. Res. Board 1626, 105–113. https://doi.org/10.3141/1626-13

Huang, Y., 2007. Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements.

Huppes, G., Van Oers, L., 2011. Evaluation of Weighting Methods for Measuring the EU-27 Overall Environmental Impact.

ISO, 2006a. ISO 14040: Environmental Managemen - Life Cycle Assessment - Principles and Framework, 2 end. International Organization for Standarization.

ISO, 2006b. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standarization.

Jeoffroy, E., Bouville, F., Bueno, M., Studart, A.R., Partl, M.N., 2018. Iron-based particles for the magnetically-triggered crack healing of bituminous materials. Constr. Build. Mater. 164, 775–782. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.12.223

Jeoffroy, E., Koulialias, D., Yoon, S., Partl, M.N., Studart, A.R., 2016. Iron oxide nanoparticles for magnetically-triggered healing of bituminous materials. Constr. Build. Mater. 112, 497–505. https://doi.org/10.1016/j.conbuildmat.2016.02.159

Jullien, A., Proust, C., Martaud, T., Rayssac, E., Ropert, C., 2012. Variability in the environmental impacts of aggregate production. Resour. Conserv. Recycl. 62, 1–13. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.02.002

Kucukvar, M., Noori, M., Egilmez, G., Tatari, O., 2014. Stochastic decision modeling for sustainable pavement designs. Int. J. Life Cycle Assess. 19, 1185–1199. https://doi.org/10.1007/s11367-014-0723-4

Marceau, M.L., Nisbet, M. a, Vangeem, M.G., 2007. Life Cycle Inventory of Portland Cement Concrete. Cycle.

Mroueh, U.M., Eskola, P., Laine-Ylijoki, J., Wellman, K., Mäkelä, E., Juvankoski, M., 2000. Life cycle assessment of road construction. Finnra Reports 17/2000.

NAPA, 2016. Product Category Rules (PCR) For Asphalt Mixtures.

NREL [WWW Document], 2012. . U.S. Life Cycle Invent. Database. URL https://www.lcacommons.gov/nrel/search (accessed 11.19.12).

PE International, 2014. Best Practice LCA: Impact Assessment.

Qiu, J., 2012. Self-Healing of Asphalt Mixtures, Towards a Better Understanding.

RE-ROAD, 2012. Life Cycle Assessment of Reclaimed Asphalt.

RIVM, 2016. ReCiPe 2016 V1.1.

Rosemary, A., 2004. Leaching of Alternative Pavement Materials.

Stripple, H., 2001. Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis.

Trupia, L., Parry, T., Neves, L.C., Lo Presti, D., 2017. Rolling resistance contribution to a road pavement life cycle carbon footprint analysis. Int. J. Life Cycle Assess. 22, 972–985. https://doi.org/10.1007/s11367-016-1203-9

UEPG, 2017. European Aggregates Association. A Sustainable Industry for a Sustainable Europe.

UK Department for Transport, 2017. New government proposals to cut congestion on our busiest roads.

UNE-EN, 2012. UNE-EN 15804:2012+A1:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products.

UNE-EN, 2002. UNE-EN 12457-4:2002 Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size re.

UNPG, 2011a. Module d'informations environnementales de la production de granulats issus de roches massives.

UNPG, 2011b. Module d'informations environnementales de la production de granulats issus de roches meubles.

UNPG, 2011c. Module d'informations environnementales de la production de granulats recyclés.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resour. Conserv. Recycl. 74, 101–114. https://doi.org/https://doi.org/10.1016/j.resconrec.2013.02.018

Vila-Cortavitarte, M., Jato-Espino, D., Castro-Fresno, D., Calzada-Pérez, M.Á., 2018. Self-healing capacity of asphalt mixtures including by-products both as aggregates and heating inductors. Materials (Basel). 11. https://doi.org/10.3390/ma11050800

Vila-Cortavitarte, M., Lastra-González, P., Calzada-Pérez, M.Á., Indacoechea-Vega, I., 2018. Analysis of the influence of using recycled polystyrene as a substitute for bitumen in the behaviour of asphalt concrete mixtures. J. Clean. Prod. 170, 1279–1287. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.09.232

World Bank Group, 2000. Roads Works Costs per Km.

Zapata, P., Gambatese, J.A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. J. Infrastruct. Syst. 11, 9–20. https://doi.org/10.1061/(ASCE)1076-0342(2005)11:1(9)

2.2. Artículo Nº2: Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures

Autores: Esther Lizasoain-Arteaga
Pedro Lastra-González
Irune Indacoechea-Vega
Gerardo Flintsch

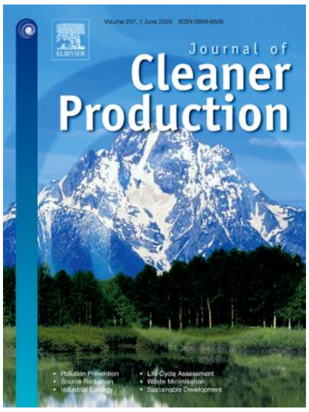
Año: 2020

Revista: Journal of Cleaner Production

Volumen: 275

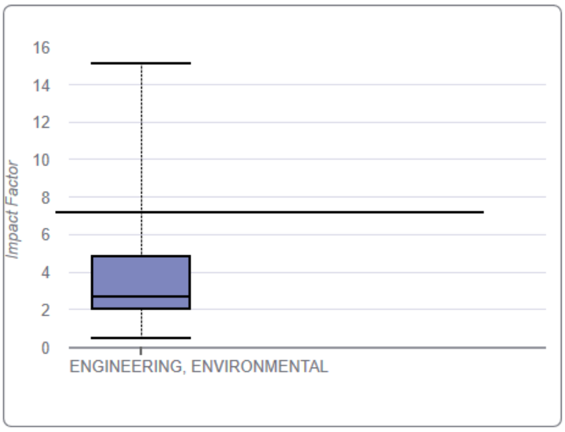
Páginas: 123121

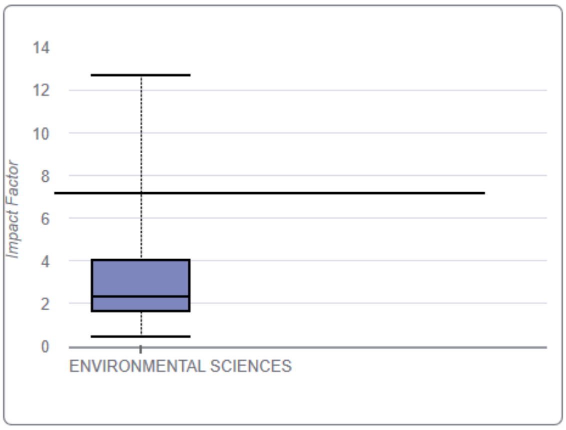
DOI: 10.1016/j.jclepro.2020.123121



Categoría	Año	Ranking	Cuartil	Percentil
Engineering, Environmental	2019	8/53	Q1	85.849
Environmental sciences	2019	19/265	Q1	93.019

Factor de Impacto JCR (2019): 7.246





Author's post-print: E. Lizasoain-Arteaga, P. Lastra-González, I. Indacoechea-Vega, G. Flintsch. "Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures". J. Clean. Prod. 275 (2020), 123121. ISSN: 0959-6526. https://doi.org/10.1016/j.jclepro.2020.123121

Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures

E. Lizasoain-Arteaga[1], P. Lastra-González[1], I. Indacoechea-Vega[1], G. Flintsch[2]

[1]GITECO Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain
[2]Center for Sustainable Transportation Infrastructure, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

Email addresses: lizasoaine@unican.es (E. Lizasoain-Arteaga); pedro.lastragonzalez@unican.es (P. Lastra-González); indacoecheai@unican.es (I. Indacoechea-Vega); flintsch@vt.edu (G. Flintsch)

*Corresponding author. Tel +34942203943; Fax: +34942201703

Abstract

This paper analyses the environmental impact of replacing high-quality coarse aggregates by electric arc furnace (EAF) steel slag. A Life Cycle Assessment (LCA) was performed on three asphalt mixtures containing different aggregates: namely ophite, slag 1 and slag 2. The inventory gaps were filled by performing several laboratory tests and applying theoretical models. Furthermore, the sensitivity of the results when applying several allocation procedures, aggregate moisture content and ophite transport distances was also analysed. The results showed the great importance of both the aggregate absorption rate and, above all, the humidity. Slags can replace ophite located more than 144 km from the asphalt plant.

Keywords

Life cycle assessment; LCA; Environmental impact; Slag; Electric arc furnace; Asphalt mixture

1. Introduction

On September 2015, 193 countries adopted the 17 sustainable development goals, which address "satisfying the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations General Assembly, 1987). These goals are focused on solving three worldwide problems by 2030: extreme poverty, inequality and injustice and environmental deterioration. In particular, goals related to the environment quest for more efficient production and consumption of resources, decrease in waste generation, prevention and reduction in sea pollution and action against desertification and deforestation, among others (United Nations, 2015).

The road industry can contribute significantly to the accomplishment of these global environmental goals. The total European network length is estimated to be 4.9M km, paved roads accounting for 90% (around 4.41M km) (ERF, 2017). Constructing a single kilometre of new road requires the consumption of 30,000 tons of aggregates and around 90 tons of bitumen (UEPG, 2017). This implies not only the consumption of raw materials but also of energy (electricity and fuels), bringing about a great environmental impact. Furthermore, maintaining reliable performance of such a big network required an expenditure of 21,206 million Euros in 2014 (ERF, 2017). However, this figure is expected to increase in the near future since freight traffic is estimated to triple between 2015 and 2050, overloading existing infrastructures and making more frequent maintenance actions necessary (OECD, 2019). Thus, it seems clear that searching for alternative materials for the construction of roads is a must for reducing the economic and environmental loads.

Replacing natural aggregates by wastes and by-products is one of the most widespread techniques used to achieve sustainable roads since it provides a double benefit. On the one hand, the extraction and production of raw materials decrease, reducing the consumption of water, electricity, diesel, and also the production of noise and dust. Moreover, the deposit of wastes in landfill is avoided, extending landfill lifetime and reducing emissions. Electric Arc Furnace (EAF) slag is widely used with this aim. According to the Worldsteel Association (2018), around 168.4 million tons of crude steel were produced in Europe in 2017, around 40% (67.36 million tons) coming from the EAF. Besides, for every ton of steel produced, around 130 kg of EAF slags are generated (Arenal, 2016), thus, 9 million tons of EAF slags were available in Europe that year, 4 million tons of which were used for road construction purposes (EUROSLAG and EUROFER, 2012).

The mechanical performance of EAF slags in asphalt mixtures when they replace natural coarse aggregate has been evaluated in depth obtaining very good results regarding workability, stiffness and resistance to fatigue, moisture damage and permanent deformation (Ameri et al., 2013; Kavussi and Qazizadeh, 2014; Pasetto and Baldo, 2010; Sorlini et al., 2012). However, the environmental aspects have not been studied in such detail.

Most of the environmental analyses of using slags in roads have been focused on Blast Furnace Slags (BFS) used in unbound layers. Mroueh et al. (2001) evaluated the advantages of replacing natural aggregates by coal ash, crushed concrete waste and granulated BFS showing that the last two materials enable the reduction of energy consumption. Sayagh et al. (2010) compared a flexible pavement in which the binder and base layers were manufactured using BFS with a rigid pavement to determine the influence on the results of the waste allocation procedure. Results concluded that considering BFS as a waste or a co-product may affect the decision making tremendously. Huang et al. (2013) also studied the allocation method for BFS, but in this case slags were used in the whole pavement section, corroborating in this way the high variability of the results detected by Sayagh et al. (2010). In contrast, few authors have centred their research on EAF slags used in asphalt layers. Mladenovič et al. (2015) compared the production and construction of two asphalt wearing courses in which siliceous coarse aggregates were replaced by steel slags. Despite the more binder required in the alternative mixture, slags proved the most sustainable option in 4 of the 7 impacts analysed. A year later, Ferreira et al. (2016) performed a similar analysis in which the potential variability of the results depending on the slags' porosity was highlighted. Nevertheless, none of these studies considered important aspects such as leaching of asphalt mixtures, the effects of the specific heat capacity of aggregates or differences in the compaction energy.

The objective of this work is twofold: to provide recommendations for the selection and use of EAF slag in asphalt mixes that ensure environmental improvements and to establish a methodology for performing LCAs of mixtures that incorporate this material. To do so, a comprehensive Life Cycle Assessment (LCA) was carried out following the ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) standards. The inventory gaps were filled by performing several laboratory tests and applying theoretical models. Furthermore, the sensitivity of the results when applying several allocation procedures, aggregate moisture content, transportation distance and two characterization methods (ReCiPe and CML) was also analysed.

2. Goal and scope

This LCA evaluates the environmental impact of replacing ophite (a diabase whose pyroxene has been altered, which is commonly employed in the north of Spain in highly-trafficked roads) by EAF steel slag as high-quality coarse aggregates in asphalt mixtures. As the production process and post-treatment directly influence the final properties, two EAF slags with very different properties were selected for this study. Furthermore, conventional aggregate (limestone) was employed in the filler fraction of the mixes. The characteristics of the aggregates employed in this work can be seen in Table 1 and Table 2.

Table 1. Coarse aggregates' properties.

Test	Standard	Ophite	Slag 1	Slag 2
Specific weight (g/cm^3)	EN 1097-6	2.937	3.735	3.920
Los Angeles coefficient	EN 1097-2	16	18	17
Flakiness index	EN 933-3	8	2	5
Water absorption (8/11.2 fraction)	EN 1097-6	0.60%	0.95%	1.72%
Water absorption (2/4 fraction)	EN 1097-6	0.20%	0.81%	3.09%
Expansiveness index	EN 1744-1	0%	0.6%	<3.5%

Table 2. Fine aggregates' properties.

Test	Standard	Limestone
Specific weight (g/cm^3)	EN 1097-6	2.725
Sand equivalent	EN 933-8	78

The LCA was performed considering a 1-km lane with a width of 3.75 m and a wearing course of 0.04 m thickness as functional unit. An analysis period of 30 years was also selected. Regarding the system boundaries, the material production, construction, use (maintenance and leaching) and end-of-life stages were taken into account. Since this is a simulated road and all the mixtures would undergo the same maintenance activities, congestion was not evaluated despite being a very important stage of a road life-cycle (Lizasoain-Arteaga et al., 2020).

3. Life cycle inventory

This stage consists of creating a consistent database containing all the resources consumed and the emissions produced throughout the road's lifecycle. Although certain processes, especially those related to conventional materials, were studied in more detail by previous researchers (Jullien et al., 2012; Mroueh et al., 2001; Stripple, 2001), a comprehensive study of the slag inventory was necessary. Regarding the electricity generation and fossil fuel production processes (shared by all stages of the LCA), those defined in the Gabi v9.1 database for the European average and in the National Renewable Energy Laboratory database ("NREL," 2012) were used.

3.1. Production stage

This stage includes the extraction and processing of the raw materials (natural aggregates, slags, and bitumen), their transportation to the asphalt plant and the manufacturing of the asphalt mixture.

3.1.1. Mix design

For the analysis, three asphalt concrete mixtures (ref, slag 1 and slag 2) were designed according to the Marshal Design method using a conventional 50/70 penetration grade bitumen. The particle size distribution of the three mixtures was defined following the limits established by the Spanish regulation for pavement design (Dirección General de Carreteras, 2017). However, due to the higher specific weight of slags, the grading size was calculated by volume. As seen in Figure 1, the high specific weight of slags is reflected in the high density of the mixtures. Moreover, slag mixtures improved the stability values of the reference mixture reaching similar or even lower deformation values. Based on the results, mixtures with 5.8% voids were selected for this work, thus ensuring a similar internal structure in all the mixtures.

The percentage of bitumen used in the mixtures is highly influenced by the specific weight of slags and their absorption. In the case of slag 1, with similar absorption to ophite, the percentage of bitumen by weight is reduced compared to the reference mix due to its high specific weight. However, slag 2, which also has a high specific weight, needs a percentage of bitumen closer to the reference mix because of its higher absorption. To eliminate the effect of the specific weight of the material, the dosage was also shown by volume (see Table 3). Comparing the percentages of bitumen by volume, slag 1 mixture needs practically the same amount of bitumen as the reference mix for the same volume of asphalt mixture, while slag 2 requires 32% more.

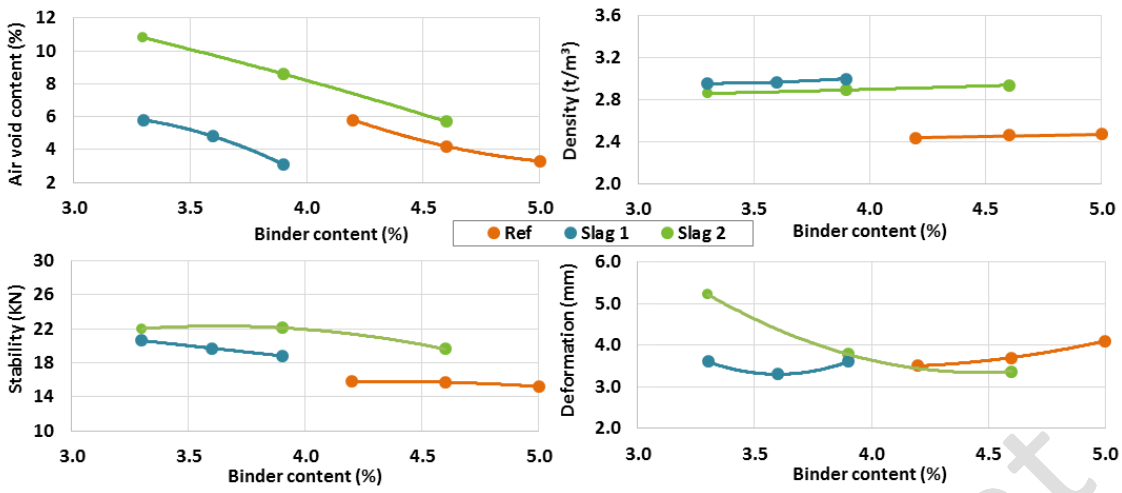


Figure 1. Asphalt mixture design.

Table 3. Asphalt concrete mixture definition.

Details	%w/w			%v/v		
	Ref	**Slag 1**	**Slag 2**	**Ref**	**Slag 1**	**Slag 2**
Ophite	61.60	-	-	56.38	-	-
Limestone	34.20	29.40	29.19	33.69	33.87	33.89
Slag	-	67.30	66.21	-	56.68	53.00
Binder	4.20	3.30	4.60	9.93	9.45	13.11
Density (t/m3)	2.43	2.95	2.94	2.43	2.95	2.94
Voids (%)	-	-	-	5.80	5.80	5.70

3.1.2. EAF slag allocation

To calculate the slag's inventory, the process described in Arenal (2016) was adopted. The steel production process results in the generation of two other materials, black and white slag, about 130 kg and 25 kg of each being produced per ton of steel manufactured. Black slag, once extracted from the furnace, is cooled abruptly by means of a high-pressure water cannon, then being immersed in a pool to continue its cooling. After the cooling process, the remaining steel that might be left in the slag fraction (around 2%) is separated with an overband magnetic separator. Finally, slags are crushed (when needed) and sieved to achieve an adequate size.

There is no consensus about whether slag should be considered as a waste or a by-product. According to some authors (Di Maria et al., 2018; Iacobescu et al., 2016; Mroueh et al., 2001) slag should be considered as waste since it does not completely meet the requirements established in the Waste Framework Directive 200/98/EC (EU, 2008) as its use is not certain and the environmental problems are not sufficiently studied (Di Maria et al., 2018). Consequently, no environmental burden would be assigned to slag. However, other authors claim that from their viewpoint, slags are by-products since those requirements are met (Habert, 2013). This being the case, part of the impact generated during the steel production could be assigned to slags. However, impact allocation is a very controversial issue in LCA (Saade et al., 2013), therefore, even ISO 14044 (ISO, 2006b) recommends avoiding it whenever possible by dividing the unit process into sub-processes or by extending the product system to include the additional functions related to the by-products. Nevertheless, as system expansion seems to be dedicated to the evaluation of main products and it can present inconsistencies when analysing by-products, different approaches emerged (Chen et al., 2010). PE International (2014) and Saade et al. (2013) understand that when a by-product is used to replace another material, the by-product assumes the environmental impact of its own treatment but also receives a credit for the avoided impact. On the other hand, Weidema (2001) states that the environmental burden of the by-product treatment should be assumed by the main product (in this case steel), which also receives the credit for the impacts avoided. Therefore, in order to respect conservation of mass, the by-product assumes the impact of producing the avoided material which was previously subtracted from the main product. However, this would not be appealing to companies that want to use the by-product, as all the environmental advantages go to the main product, leaving the downstream processes of the by-product unaffected. Furthermore, in this case study, subtracting the impact of producing aggregates from that of steel would leave its environmental burden practically unchanged while greatly impairing the use of slags. For this reason, Martin et al. (2015) developed an intermediate approach by dividing the by-product treatment and the credit received between the main product and the by-product with the 50/50 method. However, as proposed by Weidema (2001), the by-product would still assume the impact of producing the displaced product in order to conserve the mass. To analyse the influence of different allocation alternatives, four of them were taken into account in this work (see Figure 2).

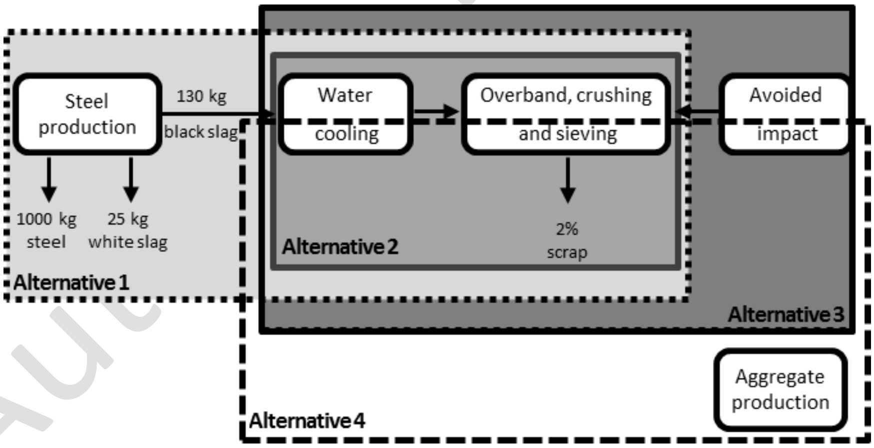


Figure 2. EAF slag allocation alternatives.

Alternative 1 consists of assigning part of the steel production impact to slags, in addition to that generated during their processing (cooling, scrap separation, crushing and sieving). For this purpose, an allocation based on the process's economic profit, combining the mass and economic values of the materials, was applied. LCAs are commonly performed using either one or the other separately. Nevertheless, if one of the materials was produced in a very small quantity but had a very high price, it would not be contemplated. Black slag cost varies on demand, according to the supplier. When a lot of slag is available, it is practically given away. However, in order to cover the expenses, the slag price should be similar to that of limestone. Conservatively, a cost of 10 € has been assumed. In this way, if the allocation were made by mass, slag would receive 11% of the steel production impact, while doing it by cost, it would receive 1.39%. As can be seen in Table 4, with the chosen allocation method, slag would be attributed 0.23% of the steel impact. Therefore, even assuming a high price, the slag assignation used in this work is lower than in the other two options.

Table 4. Allocation coefficients.

Material	Price source	Price (€/t)	Mass (t)	Allocation
Steel	(Maldonado, 2018)	550.00	1.000	99.70%
Black slag	Provider	10.00	0.127	0.23%
White slag	Provider	0.00	0.025	0.00%
Scrap	(Letsrecycle, 2018)	150.00	0.003	0.07%

In Alternative 2, only those processes that are exclusively performed on slags have been included. In this way, slag would be considered as a waste of the steel making industry that will continue to be produced as long as the need for steel remains.

Alternative 3 expands the system boundaries to include the impact that is being avoided by not extracting natural aggregates. The benefit of recycling would only be received by slags to encourage their use. Otherwise steel would be attributed the impact of landfill.

Finally, alternative 4 applies the 50/50 method proposed by Martin et al. (2015) to distribute the benefits between steel and slag but taking into account the mass balance.

The inventory used in each of the alternatives as well as in the processes which allow their calculation is shown in Table 5. The steel production values are a simplification of the inventory available in the GaBi v9.1. Regarding those of natural aggregates, they were calculated in a previous work by combining several studies (Lizasoain-Arteaga et al., 2019). Slag processing was calculated based on the machinery described in Arenal (2016). Finally, although not included in the table, the inventory of bitumen was obtained from Eurobitume (2012).

Table 5. Aggregate inventory.

Inventory	Steel	Aggregates	Alternat. 1	Alternat. 2	Alternat. 3	Alternat. 4
Fossil fuels (MJ/t)	4,745.03	22.06	108.91	22.64	0.58	22.35
Electricity (MJ/t)	1,648.25	19.08	30.22	0.25	-18.83	9.67

3.1.3. Asphalt mixture production

The specific heat capacity of each material affects the asphalt mixture manufacture energy. This is why the differential scanning calorimetry (DSC) technique was used to characterize the three coarse aggregates employed in this work: ophite, slag 1 and slag 2. The analysis was performed to different material fractions (2/4, 4/8, 8/11.2 and 11.2/16) to determine whether the aggregate size influenced the specific heat because of the presence of different compounds in the large and small particles. However, this premise was discarded based on the results shown in Figure 3, according to which, the largest and the smallest material need almost the same energy to increase the temperature 1ºC. The mean and standard deviation of specific heat capacity of each material can be seen in Figure 4. Ophite is the material which requires most energy to be heated, followed by slag 1 and slag 2. Nevertheless, ophite is also the material with the highest standard deviation. In fact, the lowest ophite specific heat is smaller than the highest slag 1 specific heat. Therefore, three specific heat capacity values were considered for each material to evaluate these circumstances (see Table 6).

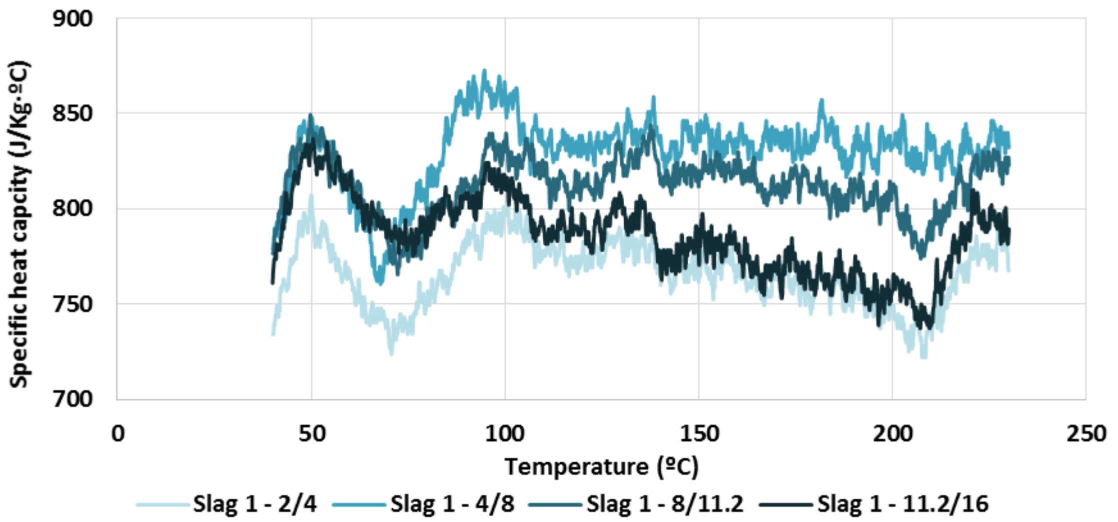


Figure 3. Specific heat capacity of slag 1 distinguishing between different sizes.

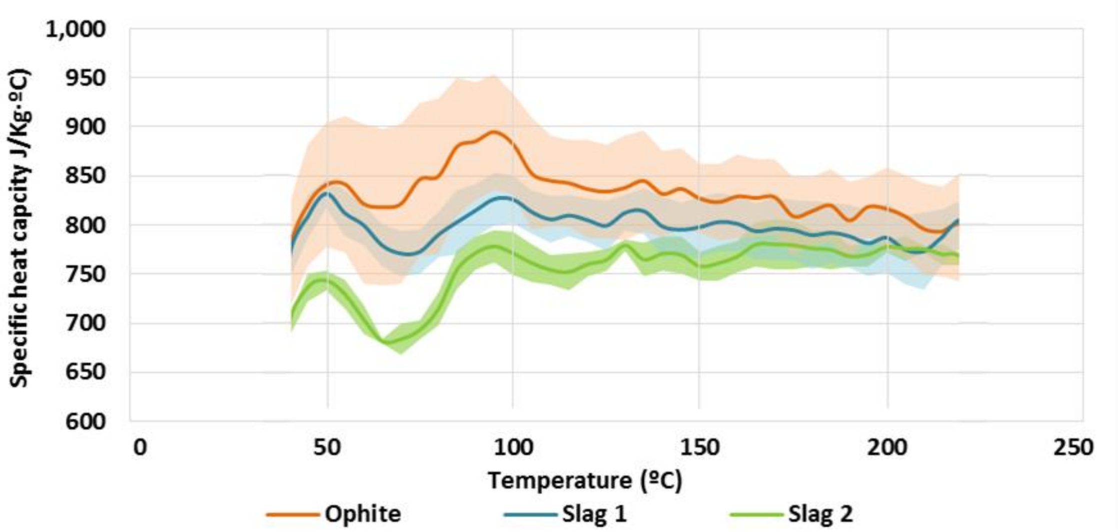


Figure 4. Coarse aggregates specific heat capacity.

Table 6. Specific heat capacity employed.

Material	C Mean (kJ/kg·ºC)	C Min (kJ/kg·ºC)	C Max (kJ/kg·ºC)
Slag 1	0.798	0.768	0.829
Slag 2	0.757	0.726	0.788
Ophite	0.831	0.772	0.889

The water content of the aggregates is another aspect that affects the energy required in producing the asphalt mix. This water content depends on the ambient humidity, on whether the aggregate is covered and its porosity. Moreover, different void geometries could also affect the aggregate drying process since the larger the specific surface area, the greater the heat transfer. To evaluate this aspect, a test was developed in the laboratory. An aggregate sample was saturated for 24 hours and was then placed in a sieve to drain the excess water but, without drying the aggregate surface, thus simulating the worst scenario. The aggregate was then introduced into an oven at 60ºC and the water content was evaluated every 5 minutes to monitor the drying process. The humidity evolution of the aggregate over time can be seen in Figure 5. These results are consistent with the aggregate absorption data (see Table 1). Slag 2, the aggregate with the highest absorption value, requires more drying time than slag 1 and ophite (which have very similar absorption). However, the drying speed is practically the same for all the aggregates (0.07 %/min, 0.08 %/min, 0.10 %/min the ophite, slag 1 and slag 2, respectively). Therefore, at least in this case, the drying time only depends on the amount of water retained in the aggregate. For this reason, three moisture contents were taken into account to evaluate their influence on the asphalt mixture energy consumption: the maximum calculated in the test, 50% of the maximum calculated humidity and 1% in all the materials)

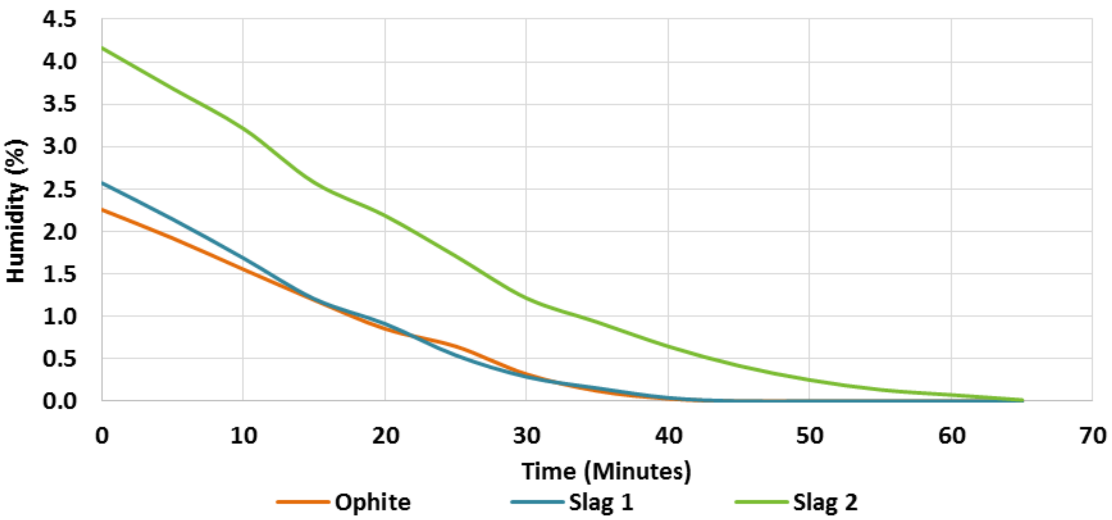


Figure 5. Loss of aggregate moisture over time.

The energy consumed in the asphalt plant was calculated based on the thermodynamic study of an asphalt plant's rotatory dryer carried out by Peinado et al. (2011). However, the model was modified to take into account different types of aggregates. Furthermore, unlike the heavy fuel oil employed in the asphalt plant modelled by Peinado et al. (2011), natural gas was assumed for this work. In addition to this energy, which accounts for 85% of the total consumption of the asphalt plant according to Stotko (2011), 12% of electricity and 3% of diesel have to be added to include other sources of energy consumption such us the bitumen heaters or the drum dryer motor. The parameters needed to feed the model can be seen in Table 7 and the achieved results in Table 8. As the moisture of the aggregate affects the results at least 3 times more than the variation of the specific heat capacity and evaluating all the options would result in a large number of alternatives, the LCA was performed considering only the average specific heat capacity of each aggregate, but several different moisture contents.

Table 7. Parameters of the asphalt plant thermodynamic study.

Parameter	Value
Filler fraction in the solid input (%)	8
Filler fraction retained with solids (%)	1
Ambient temperature (ºC)	15
Solid temperature in the outlet (ºC)	170
Filler temperature in flue gases (ºC)	Air temperature in the outlet
Air temperature in the outlet (ºC)	0.8 * Solid temperature in the outlet (Bueche, 2011)
Reference temperature (ºC)	25
Solid humidity at the inlet (%)	Several
Solid humidity at the outlet (%)	0.5
Stoichiometric ratio	2.25
Humidity ratio, or mass-based absolute humidity	0.0038
Thermal losses (%)	20 (Gillespie, 2012)

Table 8. Asphalt plant energy consumption per ton of asphalt mix.

Energy	Ref			Slag 1			Slag 2		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Maximum humidity									
E. burned (MJ/t)	239.55	231.92	247.05	246.36	242.05	250.81	277.57	273.2	281.95
Electricity (MJ/t)	33.82	32.74	34.88	34.78	34.17	35.41	39.19	38.57	39.81
Diesel (MJ/t)	8.45	8.19	8.72	8.69	8.54	8.85	9.80	9.64	9.95
50% of the maximum humidity									
E. burned (MJ/t)	198.09	190.46	205.59	200.64	196.34	205.28	212.20	207.83	216.58
Electricity (MJ/t)	27.97	26.89	29.03	28.33	27.72	28.95	29.96	29.34	30.58
Diesel (MJ/t)	6.99	6.72	7.26	7.08	6.93	7.24	7.49	7.34	7.64
1% humidity									
E. burned (MJ/t)	193.32	185.69	200.83	191.71	187.40	196.16	183.37	178.99	187.74
Electricity (MJ/t)	27.29	26.21	28.35	27.06	26.46	27.69	25.89	25.27	26.50
Diesel (MJ/t)	6.82	6.55	7.09	6.77	6.61	6.92	6.47	6.32	6.63

3.1.4. Transport distances

The transport distances employed in this work are shown in Table 9. It should be noted that either limestone or slags are considered to be locally used. However, a variable distance was assigned to ophite in order to calculate when replacing natural coarse aggregates by slags becomes preferable.

Table 9. Transport distances.

Material	Transport distance (km)
Ophite	Variable
Limestone	30
Slag	30
Binder	100

3.2. Construction stage

This stage includes the transportation of the asphalt mix from the plant to the roadwork (which is assumed to be 30 km away), as well as the construction of the road. In a previous work (Lizasoain-Arteaga et al., 2019), an industrial partner indicated that 1.56 litres of diesel was required to pave and compact 1 ton of conventional asphalt mix. However, the compaction energy can be affected by the addition of slags. To determine this, the rotatory machine was used to perform compaction tests to the three mixtures (see Figure 6). Results revealed that ophite mixtures need more compaction energy than slag 1 and slag 2. However, the energy calculated in this test cannot be directly correlated to the energy consumed on site. For this reason, the relationship among the energy values obtained were applied to the consumption data available (see Table 10). It should be mentioned that this is a conservative assumption since in addition to an increase in the compaction diesel consumption, an increase in the paving consumption is also assumed.

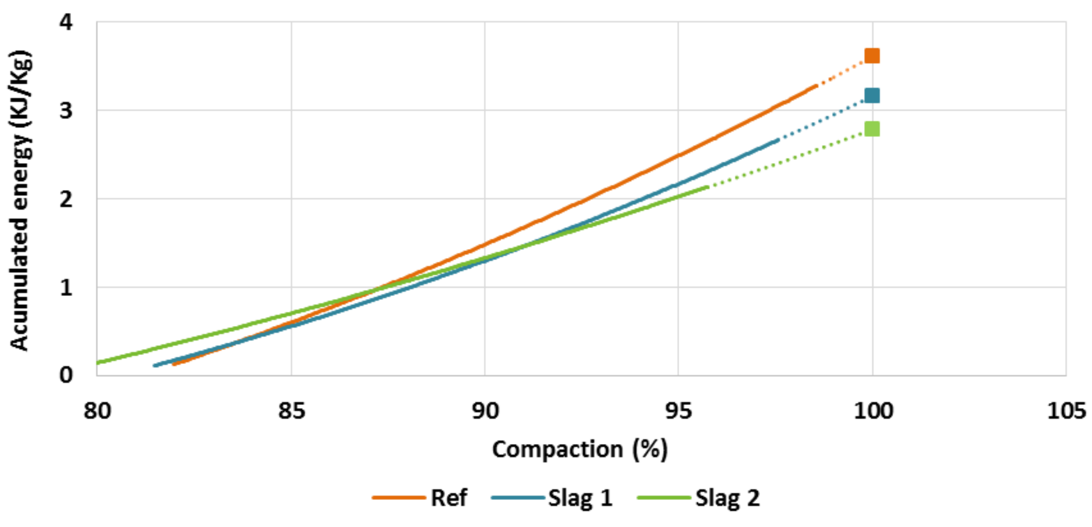


Figure 6. Compaction energy.

Table 10. Paving and compaction diesel consumption.

Results	Ref	Slag 1	Slag 2
Mix density (t/m3)	2.43	2.95	2.94
Compaction energy (test) (KJ/kg)	3.62	3.17	2.78
On-site fuel consumption (l/t)	1.56	1.37	1.20

3.3. Use stage

3.3.1. Leaching

One potential hazard that can arise from the replacement of natural aggregates by slags is an increase in the chemical elements or compounds released to the environment because of contact with rainwater. However, when they are used as aggregates in asphalt mixtures this contact could decrease because of the coating that bitumen provides. To take this effect into account, the test defined in the standard EN 12457-4:2002 (UNE-EN, 2002), was used. This test is commonly used to analyse the environmental behaviour of granular waste materials. Nevertheless, in this case, it was also applied to the loose asphalt mixtures in order to evaluate their leaching in a more realistic way.

Figure 7 shows the relationship between the leachate generated by slag 1 when analysed as a granular material and embedded within the asphalt mixture. In general, the amount of chemical elements released to the environment decrease due to bitumen and only those below the detection limit remain unchanged. Still, 3 of the 18 substances analysed increase: dissolved organic carbon (DOC), nitrates (NO_3^-) and copper (Cu). However, this increase could be caused by the limestone and/or the bitumen contained in the mixture. In fact, the amount of these compounds is higher in the reference mixture than in those containing EAF slags (see Table 11). The leachate values used for each of the mixtures are shown in Table 11. It should be noted that beryllium (Be), cobalt (Co), cadmium (Cd) and mercury (Hg) were considered to be zero since they were below the detection limit in all the samples despite the high accuracy of the equipment employed to perform the tests.

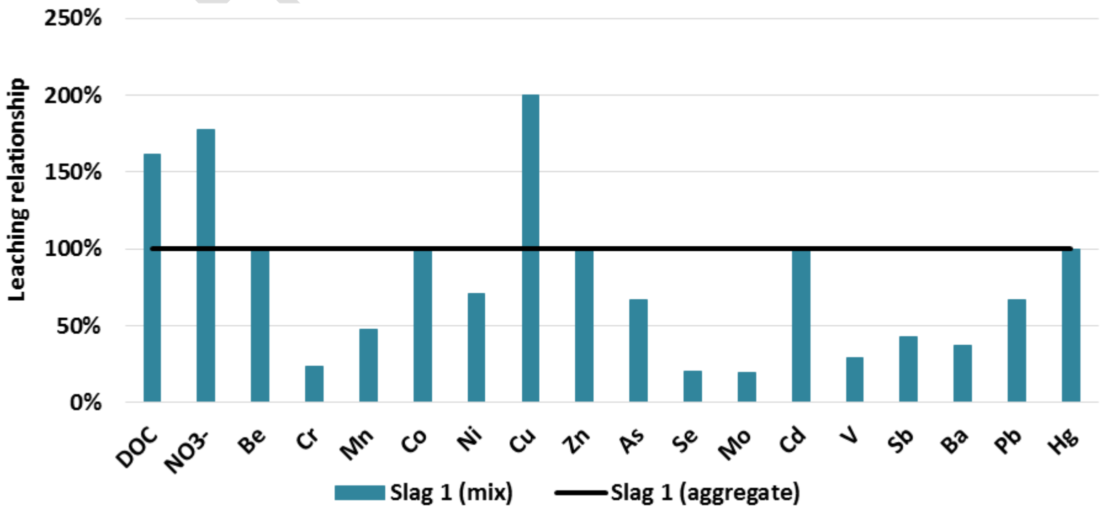


Figure 7. Effect of bitumen in asphalt mixture leachates.

Table 11. Leaching results per kg of loose asphalt mixture.

Mix	DOC	NO_3-	Cr	Mn	Ni	Cu	Zn	As	Se	Mo	V	Sb	Ba	Pb
Ref	31.6	1.3	0.009	0.001	0.003	0.005	0.066	0.001	0.006	0.022	0.033	0.002	0.025	0.001
Slag 1	25.1	0.6	0.01	0.002	0.002	0.002	0.001	0.001	0.002	0.018	1.246	0.001	0.218	0.001
Slag 2	19.2	0.25	0.016	0.002	0.001	0.001	0.001	0.001	0.004	0.048	1.006	0.005	0.312	0.001

3.3.2. Maintenance

Maintenance activities involve milling the deteriorated layer (which consumes 0.41 l/t (Lizasoain-Arteaga et al., 2019)), transporting the reclaimed asphalt to the recovery centre (located 30 km away) and producing and constructing a new layer. According to experience, 15 years' durability can be expected for an AC mix (EAPA, 2007; Nicholls et al., 2010). Therefore, taking into account the 30-year analysis period selected for this work, only 1 mill and overlay action would be performed. Furthermore, the same durability was assumed for all mixes.

3.4. End-of-life stage

This stage includes the milling of the asphalt layer and the transportation of the reclaimed asphalt to the recovery centre. The same consumption and distances assumed in the maintenance modules were applied.

4. Life Cycle Impact Assessment

To convert emissions into impacts, the ReCiPe 2016 Hierarchical characterization method was selected (RIVM, 2016). This method enables the transformation of the 18 midpoint impacts, which are focused on single environmental problems, into 3 endpoint impacts which represent the damage to the three areas of protection (damage to human health, HH; damage to ecosystem diversity, ED; and damage to resource availability, RA) based on cause-effect pathway.

An LCA of the 3 mixtures was carried out taking into account the 4 allocation procedures and different ophite transport distances. In addition, the aggregates were considered to have the highest moisture content (2.26%, 2.57% and 4.16% the ophite, slag 1 and slag 2, respectively). The results of comparing the impacts of slag mixtures with the reference mixture are shown in Figure 8. The x-axis represents the transport distance of ophite while the y-axis represents the increase or decrease of the slag mixtures' environmental impact with respect to the reference mix.

Results show that alternatives 2 and 4 produce very similar values for HH and ED impacts. In fact, for the same ophite transport distance, alternative 2 produces only around 1.3% more environmental impact than alternative 4. Alternative 1, assuming part of the environmental loads associated with the steel manufacturing process, produces 13.0% more environmental impact than alternative 2. However, as alternative 3 benefits from the credit received for the avoided impact without taking into account the conservation of mass, 7.8% reduction is achieved. However, these relationships are not maintained in the RA impact, which is clearly affected by the consideration or not of the avoided impact as well as by the conservation of mass. This makes alternative 4 the most detrimental allocation method and alternative 3 the most beneficial, leaving alternative 1 and 2 with very similar results. Therefore, it seems that alternative 2 always remains in a middle position between the other methods. Moreover, this alternative has the advantage of directly fulfilling the mass conservation and not requiring debate about future potential uses or the product which should receive the credit. Consequently, alternative 2 was selected for the rest of the work.

When comparing the two slags, the better performance of slag 1 can be seen due to the higher absorption rate of slag 2, which increases the amount of bitumen needed as well as the aggregate water content. In fact, while slag 1 could replace ophite aggregate located 177 km away, achieving improvements in the HH and ED impacts, slag 2 could replace those located more than 296 km away. Regarding the RA impact, the results do not seem to vary too much despite changing the ophite transport distance. In fact, slag 1 always proves to be a good alternative to ophite while slag 2 always produces a greater impact.

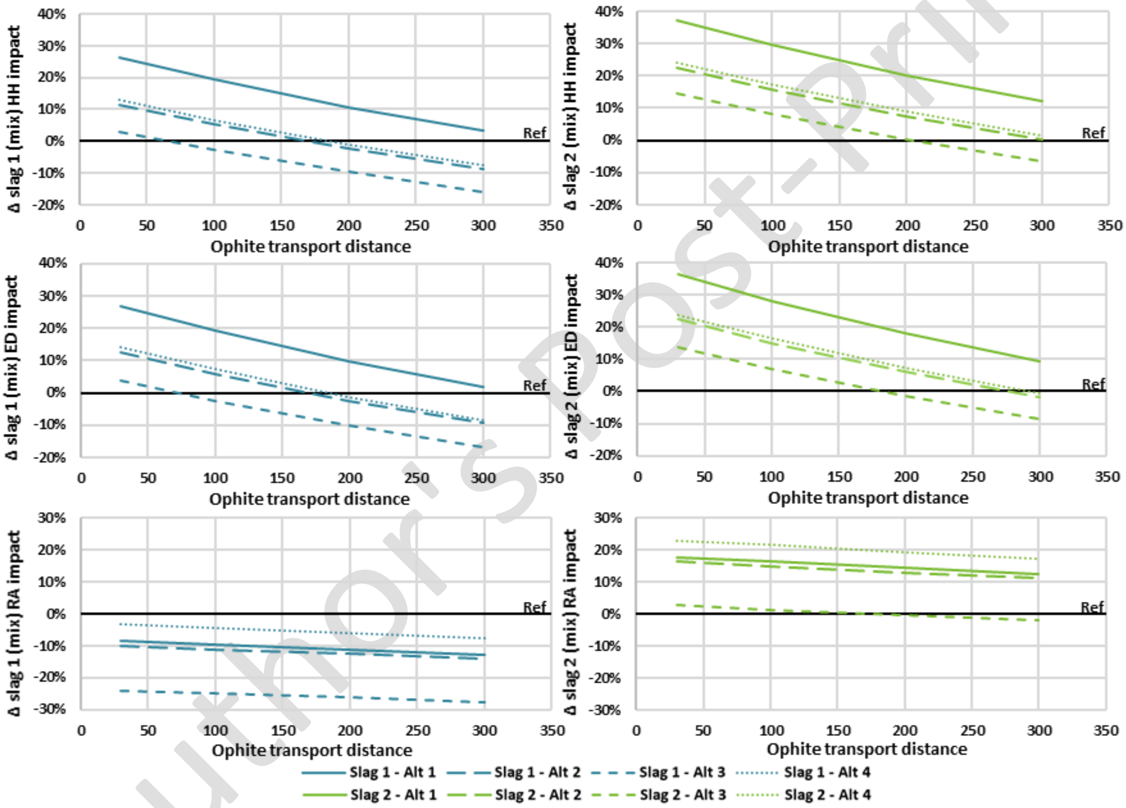


Figure 8. LCA considering 4 allocation procedures and maximum aggregate humidity.

To further understand these results, the process's contribution to the LCA results were evaluated focussing on a specific case in which the ophite transportation distance was assumed to be 200 km (see Figure 9).

As expected, the asphalt mixture production is the process that contributes most to the HH and ED impacts, its relevance being greater in slag 2 due to the higher aggregate humidity. This process is followed for the bitumen production in the slag 2 mixture and the construction activities in slag 1 mixture. It should be remembered that the slag 2 mixture needs a greater percentage of bitumen. Furthermore, the selection of 200 km as the ophite transportation distance increases transport relevance in the reference mix up to 24% of the total impact.

Regarding RA impact, the transportation activities barely affect the results. In fact, in the reference mix it only accounts for 6% of the total impact. In contrast, bitumen is the most important process meaning 67%, 73% and 79% in the reference, slag 1 and slag 2 mixes, respectively. This explains the results observed in Figure 8. Slag 1, needing the least bitumen, always produces less RA impact than ophite. However, slag 2, containing more bitumen, always produces more RA impact.

Finally, leachate is negligible in all the three endpoint categories, representing less than 0.2%.

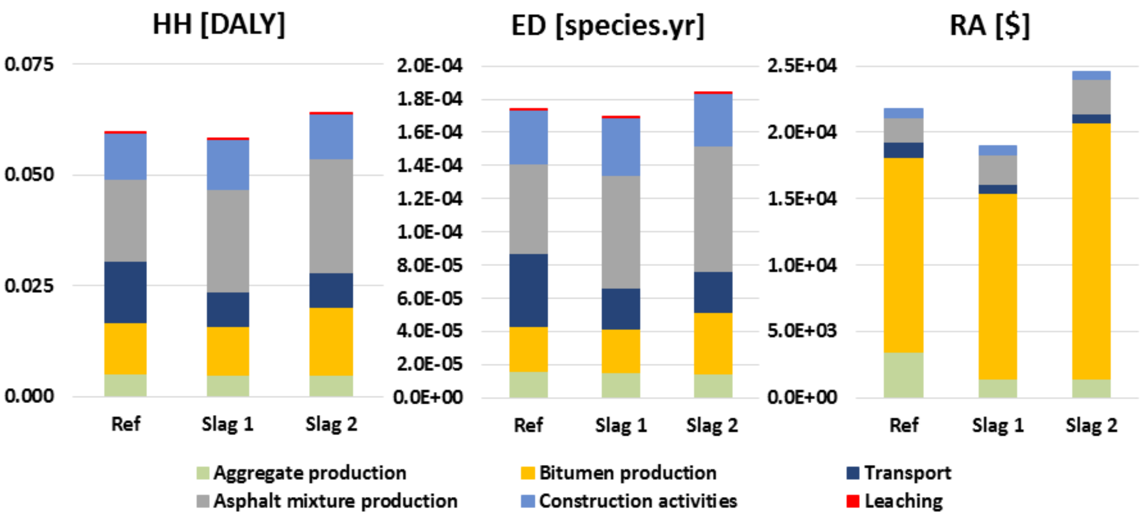


Figure 9. Process contribution to the LCA results. Allocation method: Alternative 2. Transport distance: 200 km.

Considering the great importance of the asphalt mix production in the HH and ED impacts and the possible reduction of the aggregates' moisture with their covering, the distance from which using slag is beneficial was re-evaluated. In this sense, the analysis was repeated considering 50% of the humidity employed before (1.13%, 1.29% and 2.08%). Results show that slag 1 and slag 2 could replace natural aggregates located 149 km and 235 km away, respectively, what implies a reduction of around 30 km and 60 km with respect to the distance previously calculated when the maximum humidity was used. However, despite this 50% decrease in the moisture content, slag 2 would still have much more water than slag 1 and ophite. In fact, even considering the same percentage of moisture for all the aggregates, slags would still have more water than ophite due to their higher specific weight. Therefore, to evaluate the results under more similar conditions, 1% moisture in all the aggregates was also assumed. This percentage, which is similar to the absorption rate, is only slightly lower than that already considered for ophite and slag 1, so the distance is practically unaffected. However, it makes a big change for slag 2, which could even replace ophite 190 km away. Nevertheless, it would still produce between 9% and 14% more RA impact than the reference mix due to its higher bitumen content (see Figure 10).

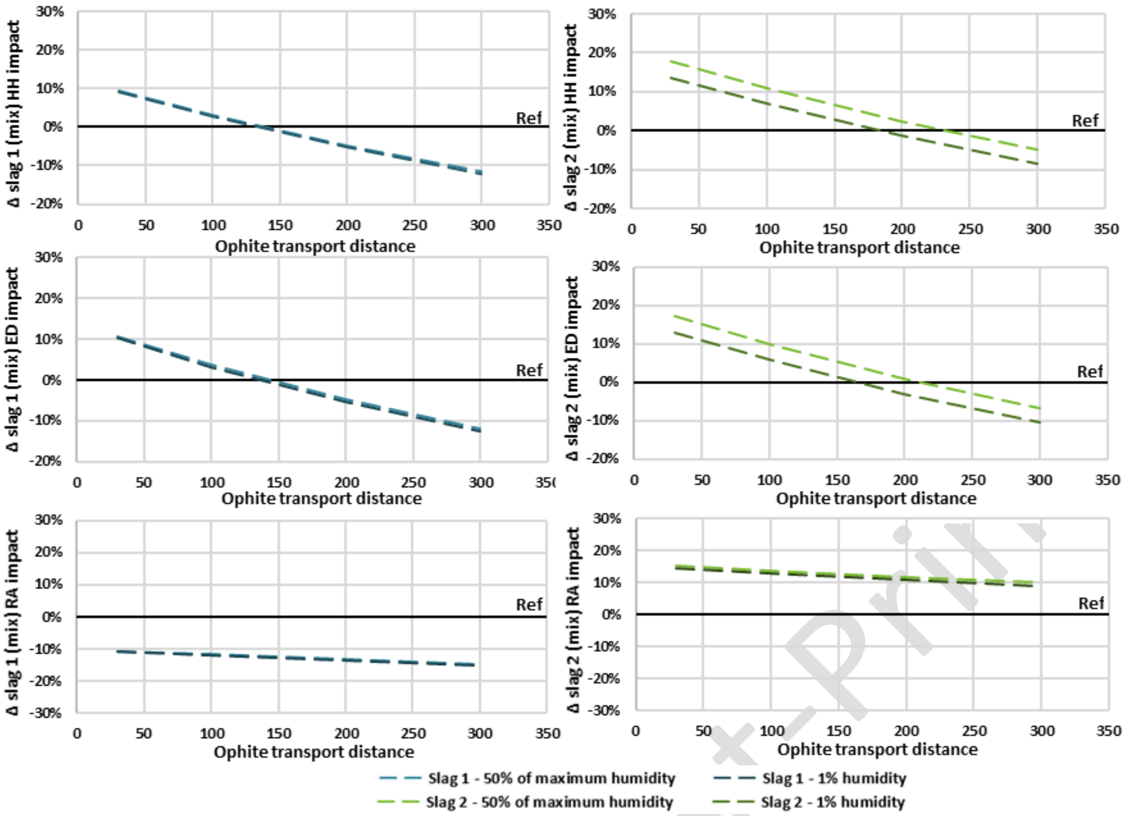


Figure 10. LCA considering alternative 2 allocation procedure and 2 moisture content.

Finally, the sensitivity of the analysis was studied by applying the CML 2001 characterization method (January 2016 update). This method is recommended to develop Environmental Product Declarations of construction products, services and processes and enables the calculation of mid-point impacts. However, to obtain a single value for every mix, normalization and weighting processes are required, which do not have a scientific basis and are not recommended in ISO 14044 (ISO, 2006b) in comparative assertions intended to be disclosed to the public. The analysis was performed to the specific case described above where the maximum humidity of the aggregates and 200 km transport distance was selected. Furthermore, the impacts where normalized by dividing the scores by the impact produced by the 28 member states of the European Union in 2000 and they were weighted using the factors described in Lizasoain-Arteaga et al. (2019).

Table 12 shows the relationship between the impacts produced by the slag and the reference mixtures when both characterisation methods are applied. ReCiPe studies more environmental impacts than CML and of those common to both methods, the former provides a greater difference in the metal depletion impacts while CML calculates grater freshwater ecotoxicity, human toxicity and photochemical ozone formation potential. However, the greatest differences occur when comparing ReCiPe's end-point impacts with the normalized and weighted impacts of CML: while ReCiPe calculates similar impacts for slag and reference mixtures, CML predicts 145% and 137% higher impacts for slag 1 and 2 mixtures, respectively.

Table 12. Slag and reference mixture impact relationship using ReCiPe and CML characterization methods.

Impact	Abbr.	ReCiPe		CML	
		Slag 1	**Slag 2**	**Slag 1**	**Slag 2**
		Mid-point impacts			
Climate change, excl biogenic carbon	GWP	-1%	10%	-1%	10%
Fine Particulate Matter Formation	PMFP	-6%	3%		
Fossil depletion	FD	-3%	26%	-3%	26%
Freshwater Consumption	WCP	89%	94%		
Freshwater ecotoxicity	FETP	936%	745%	2,715%	2,178%
Freshwater Eutrophication	FEP	-7%	24%		
Human toxicity, cancer	HTPc	-7%	-7%	110%	100%
Human toxicity, non-cancer	HTPnc	2%	-5%		
Ionizing Radiation	IRP	-6%	3%		
Land use	LU	-17%	-17%		
Marine ecotoxicity	METP	787%	626%	815%	670%
Marine Eutrophication	MEP	-18%	-18%	-5%	-3%
Metal depletion	MD	-63%	-63%	-6%	0%
Photochemical Ozone Formation, Ecos.	EOFP	-5%	-3%	-245%	-294%
Photochemical Ozone Formation, HH	HOFP	-5%	-3%		
Stratospheric Ozone Depletion	ODP	-8%	-4%	-6%	3%
Terrestrial Acidification	TAP	-5%	4%	-5%	4%
Terrestrial ecotoxicity	TETP	-8%	-2%	-16%	-16%
Impact	**Abbr.**	**End-point impacts**		**Normalized and weighted**	
Damage to human health	HH	-2%	7%		
Damage to ecosystem diversity	ED	-2%	6%	145%	137%
Damage to resource availability	RA	-13%	13%		

When the contribution of each process to the total LCA impact is analysed, the difference between the two methods can be seen (Figure 11). Leaching, which was negligible according to the ReCiPe method, accounts for 61% and 53% of the total impact in slag 1 and 2 mixtures. Over 90% of this impact is caused by vanadium, a chemical element that is only included in the leaching limit standards for waste-derived aggregates of 4 of the 10 countries studied in Saveyn et al. (2014). In fact, the asphalt mixtures under study fulfil those 4 legislations. Therefore, taking into account that when comparing the midpoint impacts with both methods the results are not so different, the variation of the final results may be caused by the way these impacts are aggregated, in other words, by the normalization and weighting.

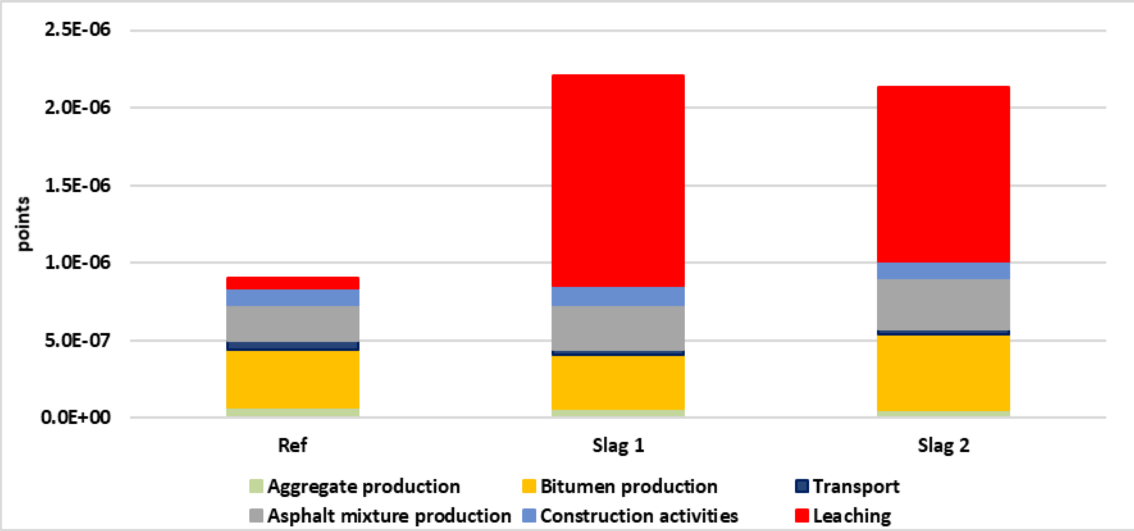


Figure 11. Process contribution to the LCA results. Transport distance: 200 km. CML characterization method. Total impact (normalised and weighted.

5. Conclusions

In this study, the environmental impact of replacing high-quality coarse aggregates by EAF steel slag was assessed. A 30-year LCA was performed on three different asphalt mixtures (reference, slag 1 and slag 2) considering several aggregate moisture contents, ophite transport distances and allocation methods. After the analysis, the following conclusions can be drawn:

- Alternative 2, which only takes into account those processes that are exclusively performed on slags, is the most reasonable allocation method. Assigning part of the steel-making process impact to slags makes this material unattractive while including a credit for the avoided impact creates problems regarding the mass conservation and the industry that should receive the benefit.
- The absorption rate of slags strongly affects the LCA results, increasing the binder content of the mixture as well as the aggregate humidity. However, depending on the production process, it is possible to find slags with a porosity similar to natural aggregates.
- The aggregate moisture is crucial in the LCA of a road. Slags with low absorption rate can replace high-quality aggregates located more than 144 km away when they are covered, this distance increasing to 177 km when the humidity is higher. Similarly, slags with high absorption rate can replace aggregates located between 190 km and 296 km away depending on their moisture content. However, if the water absorption is too high, as in the case of slag 2, the higher binder content could impede slags improving the RA impact.
- Bitumen coating reduces most of the chemical elements leached by the asphalt mixtures, thus, making this stage negligible when the ReCiPe characterization method is employed.
- Although similar trends are observed with ReCiPe and CML mid-point impact categories, results calculated by normalising and weighting the CML impacts differ greatly from those obtained applying ReCiPe. Considering the high

subjectivity and variability of the normalisation and weighting processes, using ReCiPE's endpoint impacts is recommended when it is necessary to reduce the number of impacts to make comparative assertions.

Acknowledgements

This work has been funded by the doctoral CVE-2006-11670 studentship program from the University of Cantabria, co-financed by the Government of Cantabria.

References

Ameri, M., Hesami, S., Goli, H., 2013. Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag. Constr. Build. Mater. 49, 611–617. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.08.034

Arenal, J.R., 2016. Estudio, análisis y diseño de aplicaciones de áridos procedentes de la valorización de residuos industriales : firmes de carreteras y hormigones.

Bueche, N., 2011. Évaluation des performances et des impacts des enrobés bitumineux tièdes. EPFL PP - Lausanne. https://doi.org/10.5075/epfl-thesis-5169

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour. Conserv. Recycl. 54, 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001

Di Maria, A., Salman, M., Dubois, M., Van Acker, K., 2018. Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag. Int. J. Life Cycle Assess. 23, 2091–2109. https://doi.org/10.1007/s11367-018-1440-1

Dirección General de Carreteras, 2017. Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Spanish General Technical Specifications for Roads and Bridge Works, PG-3).

EAPA, 2007. Long-Life Asphalt Pavements. Technical version.

ERF, 2017. Road [WWW Document]. Road Netw. 2017. URL http://erf.be/statistics/road-network-2017/

EU, 2008. Directive 2008/98/EC of the European parliament and of the council on waste and repealing certain directives.

Eurobitume, 2012. The bitumen industry in Europe [WWW Document]. URL http://www.eurobitume.eu/bitumen/industry/ (accessed 12.30.17).

EUROSLAG, EUROFER, 2012. Position paper on the status of ferrous slag complying with the Waste Framework Directive (Articles 5/6) and the REACH Regulation.

Ferreira, V.J., Sáez-De-Guinoa Vilaplana, A., García-Armingol, T., Aranda-Usón, A., Lausín-González, C., López-Sabirón, A.M., Ferreira, G., 2016. Evaluation of the steel slag incorporation as coarse aggregate for road construction: technical requirements and environmental impact assessment. J. Clean. Prod. 130, 175–186. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.08.094

Gillespie, I., 2012. Quantifying the Energy Used in an Asphalt Coating Plant 164.

Habert, G., 2013. A method for allocation according to the economic behaviour in the EU-ETS for by-products used in cement industry. Int. J. Life Cycle Assess. 18, 113–126. https://doi.org/10.1007/s11367-012-0464-1

Huang, Y., Spray, A., Parry, T., 2013. Sensitivity analysis of methodological choices in road pavement LCA. Int. J. Life Cycle Assess. 18, 93–101. https://doi.org/10.1007/s11367-012-0450-7

Iacobescu, R.I., Angelopoulos, G.N., Jones, P.T., Blanpain, B., Pontikes, Y., 2016. Ladle metallurgy stainless steel slag as a raw material in Ordinary Portland Cement production: a possibility for industrial symbiosis. J. Clean. Prod. 112, 872–881. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.06.006

ISO, 2006a. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework, 2 nd. International Organization for Standardization.

ISO, 2006b. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standardization.

Jullien, A., Proust, C., Martaud, T., Rayssac, E., Ropert, C., 2012. Variability in the environmental impacts of aggregate production. Resour. Conserv. Recycl. 62, 1–13. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.02.002

Kavussi, A., Qazizadeh, M.J., 2014. Fatigue characterization of asphalt mixes containing electric arc furnace (EAF) steel slag subjected to long term aging. Constr. Build. Mater. 72, 158–166. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.08.052

Letsrecycle, 2018. Ferrous scrap metal prices [WWW Document]. URL https://www.letsrecycle.com/prices/metals/ferrous-metal-prices/ferrous-scrap-metal-prices-2018/

Lizasoain-Arteaga, E., Indacoechea-Vega, I., Alonso, B., Castro-Fresno, D., 2020. Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road. J. Clean. Prod. 253. https://doi.org/10.1016/j.jclepro.2020.120050

Lizasoain-Arteaga, E., Indacoechea-Vega, I., Pascual-Muñoz, P., Castro-Fresno, D., 2019. Environmental impact assessment of induction-healed asphalt mixtures. J. Clean. Prod. 208. https://doi.org/10.1016/j.jclepro.2018.10.223

Maldonado, M., 2018. Suben los precios del alambrón en el sur de Europa [WWW Document]. URL https://es.linkedin.com/pulse/suben-precios-del-alambrón-en-el-sur-de-europa-manuel-maldonado

Martin, M., Svensson, N., Eklund, M., 2015. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. J. Clean. Prod. 98, 263–271. https://doi.org/10.1016/j.jclepro.2013.06.024

Mladenovič, A., Turk, J., Kovač, J., Mauko, A., Cotič, Z., 2015. Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses. J. Clean. Prod. 87, 683–691. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.10.013

Mroueh, U.-M., Eskola, P., Laine-Ylijoki, J., 2001. Life-cycle impacts of the use of industrial by-products in road and earth construction. Waste Manag. 21, 271–277. https://doi.org/https://doi.org/10.1016/S0956-053X(00)00100-8

Nicholls, J.., Carswell, I., Thomas, C., Sexton, B., 2010. Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring. 674 TRL Rep.

NREL [WWW Document], 2012. . U.S. Life Cycle Invent. Database. URL https://www.lcacommons.gov/nrel/search (accessed 11.19.12).

OECD, 2019. TF Transport Outlook 2019.

Pasetto, M., Baldo, N., 2010. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. J. Hazard. Mater. 181, 938–948. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.05.104

PE International, 2014. Harmonization of LCA Methodologies for Metals.

Peinado, D., de Vega, M., García-Hernando, N., Marugán-Cruz, C., 2011. Energy and exergy analysis in an asphalt plant's rotary dryer. Appl. Therm. Eng. 31, 1039–1049. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.11.029

RIVM, 2016. ReCiPe 2016 V1.1.

Saade, M., Silva, M., Silva, V., 2013. Environmental impact allocation methods and their reflection on the attractiveness of blast furnace slag in cement industry.

Saveyn, H., Eder, P., Garbarino, E., Muchova, L., Hjelmar, O., van der Sloot, H., Comans, R., van Zomeren, A., Hyks, J., Oberender, A., 2014. Study on methodological aspects regarding limit values for pollutants in aggregates in the context of the possible development of end-of-waste criteria under the EU Waste Framework Directive, Report EUR 26769 EN. https://doi.org/10.2791/1125

Sayagh, S., Ventura, A., Hoang, T., François, D., Jullien, A., 2010. Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures. Resour. Conserv. Recycl. 54, 348–358. https://doi.org/https://doi.org/10.1016/j.resconrec.2009.08.011

Sorlini, S., Sanzeni, A., Rondi, L., 2012. Reuse of steel slag in bituminous paving mixtures. J. Hazard. Mater. 209–210, 84–91. https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.12.066

Stotko, O., 2011. Energy and Related Carbon Emission Reduction Technologies for Hot Mix Asphalt Plants. 10th Conf. Asph. Pavements South. Africa - CAPSA 8000, 1–9.

Stripple, H., 2001. Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis.

UEPG, 2017. European Aggregates Association. A Sustainable Industry for a Sustainable Europe.

UNE-EN, 2002. UNE-EN 12457-4:2002 Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size re.

United Nations, 2015. Sustainable Development Goals [WWW Document]. URL https://www.un.org/sustainabledevelopment/sustainable-development-goals/

United Nations General Assembly, 1987. Report of the world commission on environment and development: Our common future.

Weidema, B., 2001. Avoiding Co-Product Allocation in Life-Cycle Assessment 4.

Worldsteel Association, 2018. World Steel in Figures 2018

2.3. Artículo Nº3: Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures

Autores: Israel Rodríguez-Fernández
Esther Lizasoain-Arteaga
Pedro Lastra-González
Daniel Castro-Fresno

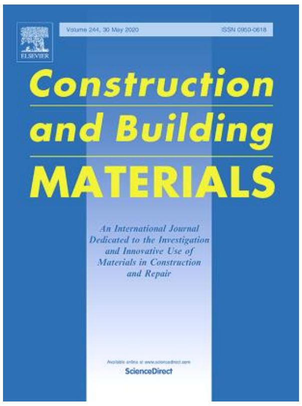
Año: 2020

Revista: Construction and Building Materials

Volumen: 251

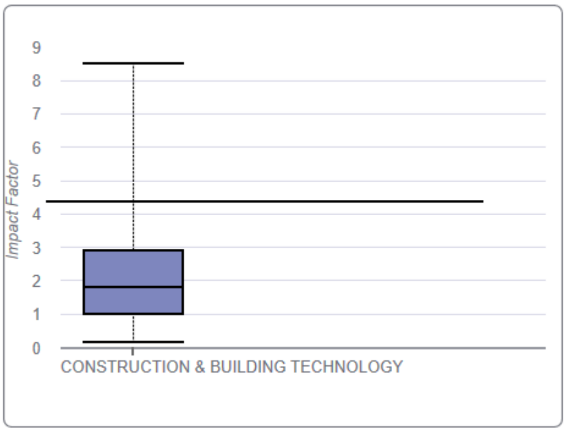
Páginas: 118982

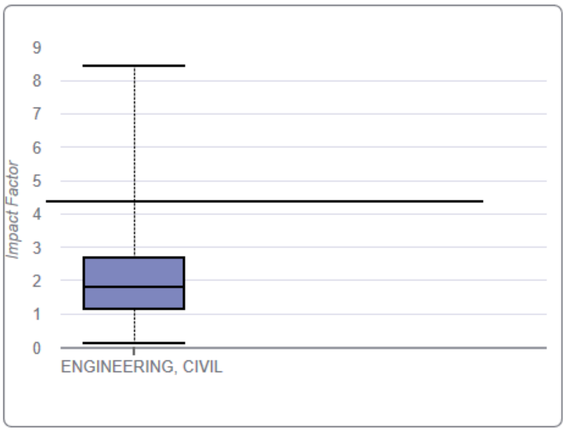
DOI: 10.1016/j.conbuildmat.2020.118982



Categoría	Año	Ranking	Cuartil	Percentil
Construction and building technology	2019	10/63	Q1	84.921
Engineering, civil	2019	11/134	Q1	92.164

Factor de Impacto JCR (2019): 4.419





Author's post-print: I. Rodríguez-Fernández, E. Lizasoain-Arteaga, P. Lastra-González, D. Castro-Fresno. "Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures". Construction and Building Materials, 251 (2020), 118982. ISSN: 0950-0618. https://doi.org/10.1016/j.conbuildmat.2020.118982

Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures

I. Rodríguez-Fernández[1], E. Lizasoain-Arteaga[1], P. Lastra-González[1], D. Castro-Fresno[1*]

[1]GITECO Research Group, University of Cantabria, Santander, Spain

Email addresses: israel.rodriguez@unican.es (I. Rodriguez-Fernández); lizasoaine@unican.es (E. Lizasoain-Arteaga); pedro.lastragonzalez@unican.es (P. Lastra-González); castrod@unican.es (D. Castro-Fresno)

*Corresponding author. Tel +34942201753; Fax: +34942201703

Abstract

Road infrastructure plays a crucial role in the social and economic development of nations but also generates several environmental problems. To deal with these, three technologies were combined to produce highly sustainable porous asphalt mixtures: namely replacement of natural aggregates, reduction in manufacturing temperature and use of a nano-modified binder. The feasibility of the mixtures was evaluated by applying mechanical tests and performing a life-cycle assessment (LCA) and life-cycle cost analysis (LCCA). The results demonstrated the good behaviour of these sustainable mixes, enabling more than 12% and 15% reduction in the environmental and economic impacts of the road.

Keywords

Carbon black; Evotherm; Porous asphalt; Electric arc furnace slag; Reclaimed asphalt

1. Introduction

Road infrastructure is vital for social and economic development of nations by enabling the transportation of valuable resources such as wood, minerals and petroleum and also by boosting trade between regions. However, it also generates several environmental problems which worsen as the transport network grows. The length of roads is expected to increase by at least 25 million kilometres by 2050 (60% more traffic than in 2010), thus affecting areas with exceptional biodiversity [1]. Therefore, there is a need to implement new technologies that reduce the impact of these infrastructures.

One of the main technologies used to reduce the environmental impact of roads is the replacement of natural aggregates by wastes and by-products [1–5]. For instance, slags generated during steel production, and in particular, those generated in electric arc furnaces (EAF) are a very promising material for use in asphalt pavements due to their good behaviour regarding plastic deformation, durability, stiffness and fatigue resistance

[6]. They are especially suitable as coarse aggregates, given that they form a very stable mineral skeleton [7]. Furthermore, their resistance to polishing and abrasion and their toughness make EAF slags an appropriate material for use in surface layers [8].

Another alternative for replacement of natural aggregates is the use of by-products generated by the construction industry, reclaimed asphalt pavement (RAP) being the most common material. Traditionally, RAP has been treated as a black rock, meaning that the binder linked to the aggregates was supposed not to mix with the new binder, and therefore, no savings of virgin binder were considered. However, several authors state that the residual bitumen blends, so both materials (aggregates and binder) can be recovered [9,10]. Consequently, when RAP is used in unbound layers (a common practice nowadays), the full potential of the material is not reached.

In addition to the replacement of natural aggregates, warm mix asphalt technology (WMA) is also a good option to palliate the environmental impact produced by roads. The WMA concept relies on reducing the hot mix asphalt's (HMA) manufacturing temperature by 20-40°C while maintaining a similar mechanical performance [11]. To achieve this temperature reduction, the binder viscosity has to be modified by using, among other methods, additives (organic or chemical) and foamed binder. Considering that around 48% of the energy consumed during the materials' production and road construction occurs in the asphalt plant, several benefits (such as the reduction in the CO2 emissions, energy consumption or costs) can be achieved by using these asphalt mixtures [12].

Recently, researchers have also focused on increasing the durability of the pavements to amortize the environmental impacts and cost incurred during the production of asphalt mixtures [13–15]. In this sense, there is a trend toward incorporating nano-materials such as carbon black (CB) or graphite as additives to modify the binder, trying to improve its thermal properties, plastic deformation or elasticity [16,17].

The aim of this paper is to attempt to reduce as far as possible the environmental impact of asphalt mixtures without compromising their economic and mechanical performance. With this in mind, this research entirely replaced the natural aggregates commonly used in asphalt mixtures by adding RAP and EAF slag. Then, the effect of incorporating a temperature reduction additive and also using a new nano-modified binder instead of traditional polymer-modified bitumen (PMB) was analysed. The feasibility of combining all the technologies to produce highly sustainable asphalt mixtures was evaluated by applying mechanical tests and life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) methodologies.

2. Materials and methodology

2.1. Experimental design

Three mixtures were developed to evaluate the technical, economic and environmental feasibility of applying three technologies (replacement of virgin materials, warm mix asphalt and nano-modified binder) in a porous asphalt (PA) mixture. This type of mixture already has some advantages over asphalt concrete (AC) mixtures since its high void content (more than 20%) improves the water runoff, heat island effect and noise pollution of roads [14]. However, its impact could be even smaller after applying the aforementioned measures. With this in mind, the mixtures were developed introducing changes sequentially: firstly, a HMA was designed containing EAF and RAP and using a PMB 45/80-65 bitumen; then, a WMA was manufactured incorporating Evotherm into the previous mix to reduce the production temperature; and finally, a nano-modified binder (NB) developed by ACCIONA Infrastructure [16] containing carbon black (CB) and styrene-butadiene-styrene (SBS) was used instead of the PMB to produce another WMA. It should be noted that the percentages of EAF slag, RAP and binder content remain unaltered in the different stages of the mix design. Furthermore, the mixes only employed conventional aggregates (limestone) in the filler fraction since the filler contained in the RAP was not enough to accomplish the requirements of this type of mixes.

As mentioned previously in the introduction, EAF slags present good characteristics for use as coarse aggregates, as is demonstrated by several studies. The properties of both EAF slag and conventional aggregates are summarized in Table 1.

Table 1. Aggregate properties

Test	Standard	EAF slag	Limestone
Specific weight (g/cm^3)	EN 1097-6	3.735	2.725
Los Angeles coefficient	EN 1097-2	18	-
Flakiness index	EN 933-3	2	-
Polished stone value	EN 1097-8	> 59	-
Sand equivalent	EN 933-8	-	78
Maximum particle size (mm)	-	16	2
Minimum particle size (mm)	-	2	< 0.063

The RAP used in this study comes from a road located in Cantabria (Spain) and no information regarding its original properties is available. Therefore, in order to characterize it, basic laboratory tests were done. The RAP binder content was determined according to the standard EN 12697-1 and the residual binder content was recovered following the methodology proposed by the standard ASTM D5404. In Table 2, the main properties of the RAP aggregates and binder are shown, while the particle size distributions of the RAP and the recovered aggregates can be verified in Figure 1.

Table 2. RAP properties

Test	Standard	Result
Specific weight	EN 1097-6	2.502 g/cm^3
Los Angeles coefficient (recovered aggregate)	EN 1097-2	24
Flakiness index (recovered aggregate)	EN 933-3	11
Residual binder content (from mass of mixture)	EN 12697-39	4.0%
Softening point of residual binder	EN 1427	76.1°C
Penetration of residual binder	EN 1426	13 (0.1mm)
Penetration index	EN 12591	0.9

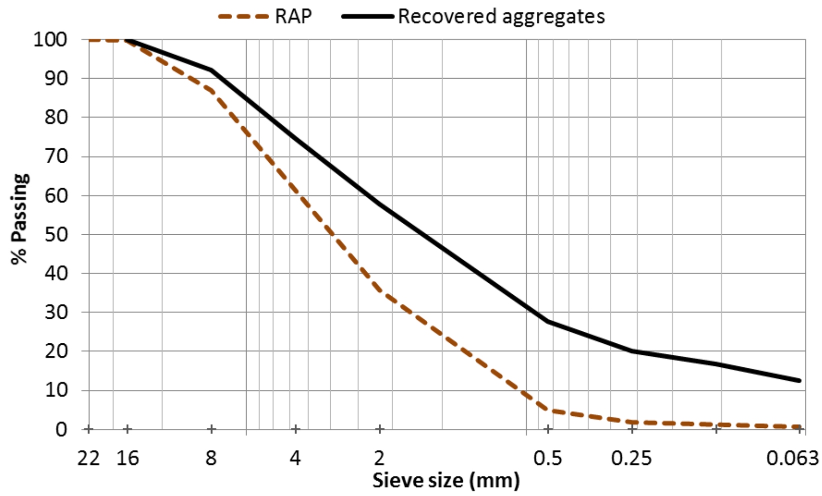


Figure 1. Particle size distribution of RAP

The two binders selected for this study are a polymeric modified binder (PMB 45/80-65) and a nano-modified binder produced by mixing carbon black (CB) and styrene-butadiene-styrene (SBS) [16]. The basic properties of these binders are shown in the Table 3.

Table 3. Binder properties

Test	Standard	PMB 45/80-65	NB
Softening point	EN 1427	74.1°C	71.0°C
Penetration at 25°C	EN 1426	55 (0.1mm)	45.3 (0.1mm)
Fraass breaking point (ºC)	EN 12593	-13	-12
Elastic recovery	EN 13398	92%	91%

Once the materials were selected, the next step was the asphalt mixture design. The specimens were compacted with 50 blows on each side, following the indications of the Spanish standard [18]. Given that the compaction energy is fixed, there are three main variables which determine the volumetric properties of the mixture: the particle size distribution, the binder content and the compaction temperature.

The particle size distribution of the PA mixture (see Figure 2b) was defined considering the limits established by the Spanish regulation for pavement design [18]. However, in this study the passing percentages were specified by volume instead of by weight due to the high specific weight of EAF slags. In this way, the same volumetric characteristics for all the mixtures' aggregates was ensured, and as a result, the asphalt mixture aggregate composition shown in Figure 2a was obtained.

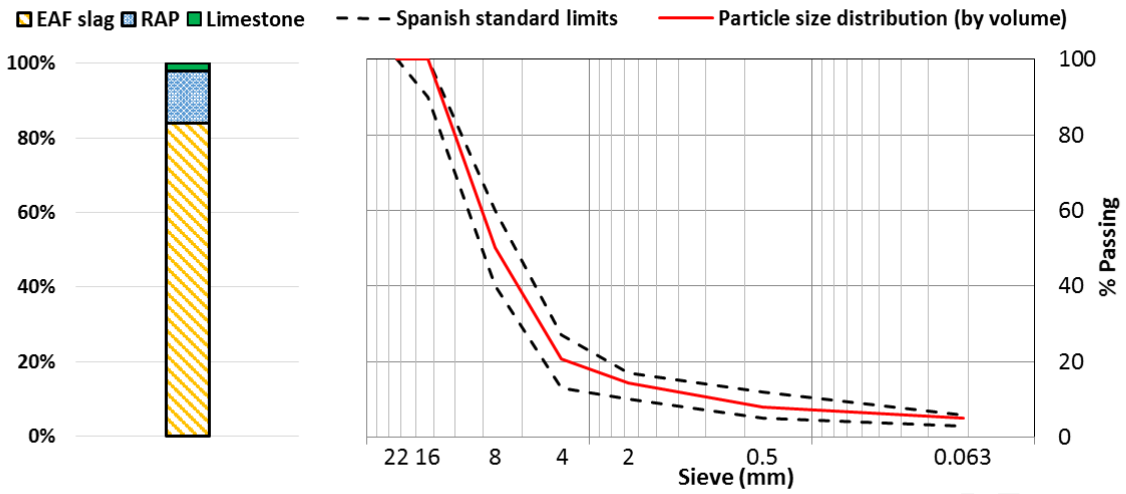


Figure 2. a) Aggregate composition (%w/w); b) Particle size distribution (%v/v)

The binder content employed in the mixtures was determined based on the air void content, which was fixed, in turn, according to the Spanish regulation for pavement design [18]. This standard stipulates the minimum air void content that every type of mixture should have: 20% regarding the PA mix. However, a maximum value is not specified. Taking these requirements into account, the binder content (expressed by weight) selected is shown in Table 4. It should be noted that the residual binder of RAP was assumed to blend and mix with the virgin binder. Therefore, the total amount of binder is the combination of both binders.

Table 4. Binder content of PA mix (%w/w)

Virgin Binder	RAP Binder	Total binder
3.55%	0.55%	4.10%

To achieve the temperature reduction in the WMA, the commercial additive Evotherm was used following the indications of the manufacturer, who stated that a 0.5% of additive by weight of virgin binder was needed due to the characteristics of the binder. This additive, which is in liquid state at room temperature, was added to the preheated virgin binder at mixing temperature and was then blended at 5,000 rpm during 5 min using a high shear mixer.

Regarding the manufacturing temperatures, HMA samples were mixed at around 165°C and compacted at 155°C, following the indications of the binder manufacturer. Once the temperature and the particle size distribution were fixed, the optimum binder content was obtained by testing different quantities of bitumen until the desired percentage of air void content was achieved. In contrast, WMA was designed using the same binder content as the HMA but varying the manufacturing and compaction temperatures until the same air void content as the HMA mixture was reached. Table 5 shows the temperatures used for each phase.

Table 5. Manufacturing temperatures (ºC)

Mix	Mixing Temp	Compaction Temp	Aggregates Temp	Binder Temp	RAP Temp
HMA – PMB	165	155	195	165	110
WMA – PMB	145	135	175	145	110
WMA – NB	155	145	185	155	110

Once the asphalt mixtures' composition was defined, the mechanical performance of the mixtures was evaluated using the mechanical tests required by the European standards: Maximum density (EN 12697-5 procedure C), bulk density (EN 12697-6 procedure D), air void content (EN 12697-8), Particle loss test (EN 12697-17), water sensitivity test (EN 12697-12) and indirect traction test EN 12697-23. Dynamic tests were also conducted: stiffness test (EN 12697-26) and the resistance to fatigue test (EN 12697-24).

The results were statistically analysed and interpreted with Minitab statistical software. Firstly, the Shapiro-Wilk normality test was performed. Secondly, the One-Way Analysis of Variance (ANOVA) was carried out since a normal distribution was observed in all the samples analysed. The Tukey test was used to determine the differences between the asphalt mixtures' means. In all cases, the influence of the different factors has been determined applying a 95% confidence interval, thus the results are significantly different when the p-value is less than 0.05.

2.2. Life cycle assessment (LCA) and life cycle cost analysis (LCCA)

LCA is a methodology which enables the calculation of the potential environmental impact of a product throughout its life cycle. Standardised by the ISO 14040:2006 [19] and 14044:2006 [20], the LCA methodology consists in the application of 4 interrelated stages: goal and scope definition, inventory analysis, impact assessment and interpretation of the results.

As mentioned before, the main goal of this paper is to attempt to reduce as far as possible the environmental impact of asphalt mixtures without compromising their economic and mechanical performance, consequently achieving more sustainable infrastructures. With this in mind, the analysis was performed considering as a reference unit a 1-km lane with a width of 3.5 m and a pavement thickness of 25 cm (5 cm wearing course, 10 cm binder course and 10 cm base layer).

The selection of the system boundaries was based on the stages defined in the standard UNE-EN 15804:2012 [21]. In this sense, the material, construction, maintenance, use (leaching) and end-of life stages were included in the analysis and the inventory defined in a previous work [22] was also used here. However, the following aspects need to be specified:

- The production of CB was obtained from the database available in Gabi.
- The nano-modified binder developed by ACCIONA Infrastructure was calculated by combining the inventory of a polymer-modified bitumen [23] and CB.
- The environmental impact of producing Evotherm was excluded due to the lack of data and the little amount added to the mixture (0.018%) [21]. However, it was considered in the economic analysis.

- The impact of generating slags includes the valorisation process described by Arenal (2016) [24].
- Slags and Evotherm were assumed to be transported 30 km and 100 km, respectively, from the factory to the asphalt plant.
- WMA-PMB and WMA-NB were assumed to reduce 8.8% and 4.4%, respectively, the manufacturing energy of a HMA according to the model developed by Peinado et al. (2011) [25] despite reducing the temperature 12% and 6%. It should be noted that a certain amount of energy is consumed drying the aggregates.
- Although a mixture containing slag leaches less than the slag itself due to the impermeability provided by the bitumen, in this case, the same leaching rate has been assumed.
- The analysis was performed considering different service life extensions for the WMA-PMB and WMA-NB pavements.

Impacts were calculated using the ReCiPe 2016 characterization method. Developed by the University of Leiden, this method enables the calculation of the damage caused by a product to the three protection areas: human health (HH), ecosystem diversity (ED) and resource availability (RA). However, to compare the results when different service life extensions are assumed, results need to be annualized dividing them by the road service life. LCCA is a similar methodology but applying an economic point of view, that is to say, quantifying agency and user cost. The former includes the expenditures that the owner of the road bears whereas the latter refers to the cost that the road users incur. It should be noted that the value of money does not remain constant over time, thus, a discount rate needs to be applied to calculate the present value of future costs [26]. In this analysis, only the agency costs were considered due to the boundaries defined above and the 4% discount rate recommended by the European commission was selected. The cost data employed in the analysis as well as the sources are shown in Table 6.

Table 6. Costs database

Material/process	Units	Costs	Source
PMB	€/t	540.00	[27]
NB	€/t	704.00	Calculated
Coarse and fine aggregates	€/t	7.50	Provider
RAP	€/t	4.65	PaLaTe v2.0
Slags	€/t	10.00	Waste manager
Filler	€/t	41.36	[28]
Evotherm	€/t	6,200.00	ACCIONA Infrastructure
Asphalt plant HMA	€/t	8.16	[28]
Asphalt plant WMA-PMB	€/t	7.56	Calculated
Asphalt plant WMA-NB	€/t	7.86	Calculated
Construction	€/t	4.74	[28]
Milling	€/t	29.30	[28]
Transportation	€/(t*km)	0.10	[28]

Finally, as the sustainability results are highly dependent on the service life of the road, a simulation of the pavement performance was carried out. The main failure mechanism of the binder and base layers is fatigue damage and ravelling is the most common failure of porous mixtures. The Cantabro test can shed light on the particle loss that a porous mixture could undergo in the future. However, a direct correlation between the laboratory test results and the durability of the mixture does not exist. Therefore, the pavement was assumed to fail by fatigue cracking and it was simulated using two software packages: Alize and 3D-Move. Alize is software developed by the French organization LCPC and SETRA, which calculates the response of a pavement to truck loads considering an isotropic linear elastic behaviour [29]. In contrast, 3D-Move uses a continuum-based finite layer approach accounting for a viscoelastic performance of the layers [30]. In both cases, a single axle dual tire was selected to load the pavement: tire pressure of 900 kPa, tire load of 32 KN, tire radius of 0.106 m and centre to centre tyre spacing of 0.3192 m.

3. Results and discussion.

3.1. Mechanical results

The volumetric properties of the three PA mixtures are shown in Table 7. 4 samples were used for each test, except for the water sensitivity test, where 4 samples for each condition (wet and dry) were employed.

Table 7. Mechanical properties of PA mixes

Results		HMA - PMB	WMA - PMB	WMA - NB
Voids test (EN 12697 – 8)				
Total binder (%)		4.1	4.1	4.1
Raw binder (%)		3.55	3.55	3.55
Bulk density (g/cm^3)		2.554	2.555	2.539
Voids (%)		20.8	20.7	21.1
Particle loss test (EN 12697-17)				
Loss particle (%)		15.5	12.1	18.3
Water sensitivity test (EN 12697 – 12)				
I.T.S.	Dry (KPa)	1022.6	1502.6	1203.9
	Wet (KPa)	896.6	1408.3	1197.5
I.T.S.R. (%)		88	94	99

As can be observed, all the mixtures have very similar volumetric characteristics and the minimum air void content of 20% considered as adequate for porous asphalt mixes was accomplished. In fact, the differences among the mixtures on this point are not statically significant according to the statistical analysis performed at 95% confidence level (Table 8). This is reasonable considering that it was a requirement decided during the mixtures' design.

Table 8. Mechanical properties. Statistical analysis

Difference of Levels	Difference of means	95% CI	Adjusted P-Value
	Voids test (EN 12697 – 8)		
WMA-PMB – HMA-PMB	0.0016	-0.0247; 0.0280	0.987
WMA-NB – HMA-PMB	-0.0146	-0.0409; 0.0117	0.374
WMA-NB – WMA-PMB	-0.0162	-0.0435; 0.0111	0.324
	Particle loss test (EN 12697-17)		
WMA-PMB – HMA-PMB	-3.4	-7.7; 0.9	0.121
WMA-NB – HMA-PMB	2.8	-1.4; 7.1	0.212
WMA-NB – WMA-PMB	6.2	1.9; 10.5	0.007
	ITS values for unconditioned samples (kPa)		
WMA-PMB – HMA-PMB	479.9	286.0; 673.8	0.000
WMA-NB – HMA-PMB	181.3	-12.6; 375.2	0.066
WMA-NB – WMA-PMB	-298.6	-478.1; -119.1	0.004
	ITS values for conditioned samples (kPa)		
WMA-PMB – HMA-PMB	511.7	352.2; 671.1	0.000
WMA-NB – HMA-PMB	300.9	151.7; 450.0	0.001
WMA-NB – WMA-PMB	-210.8	-360.0; -61.6	0.010

Even though achieving a very similar air void content in all the mixtures seems to indicate that no differences exist among the compaction energies required by each mix, the workability test (EN 12697-31) was carried out to 2 samples to corroborate this. The relationship between the air void content and the number of gyrations applied was analysed (Figure 3). These results agree with the values obtained above for the volumetric properties. The temperature reduction in WMA mixtures does not affect the mix's workability, the three asphalt mixtures demonstrating very similar results in this test.

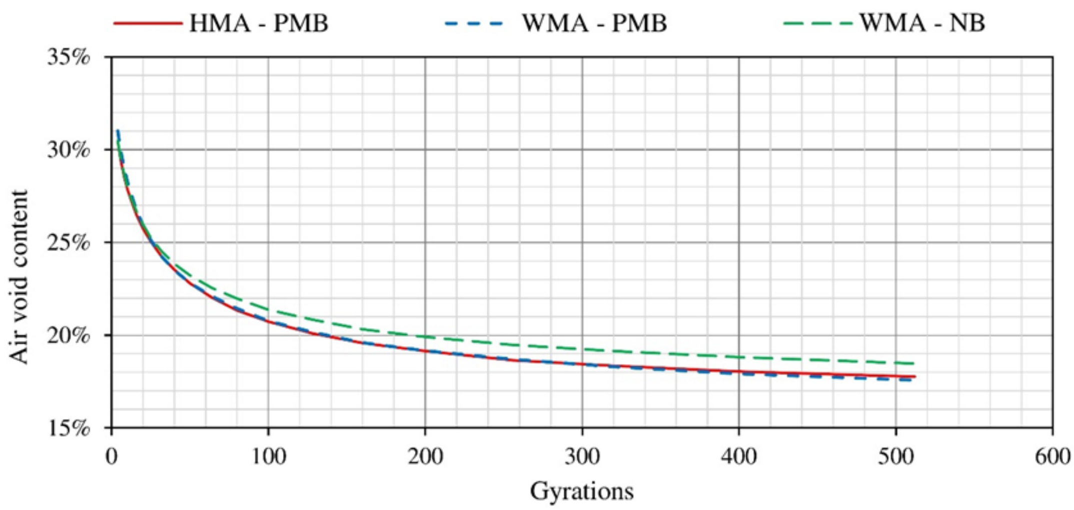


Figure 3. Workability test results

As raveling is the main failure mechanism of porous mixtures, the cohesion of the three mixtures under study needs to be analysed by means of the Cantabro test (EN 12697-17) (Table 7).

To evaluate whether the results are adequate or not, the limit established by the Spanish regulation for pavement design [18] can be considered. This standard establishes a maximum value for particle loss of 20%. Therefore, it is possible to state that all the mixtures show an adequate performance. However, some conclusions can be drawn by comparing the different mixtures.

Firstly, the use of the experimental NB leads to lower mixture cohesion. This fact is clearly shown when comparing the two WMAs, which only differ in the type of binder and production temperature. In this sense, the WMA with NB undergoes more particle loss than the mixture with PMB. However, no significant differences are observed when the mixture is compared to the HMA mix (see Table 8).

Another conclusion is related to the use of Evotherm, or in other words, with the temperature reduction. Comparing the WMA and the HMA, both with the PMB, it can be stated that using Evotherm does not produce any problem in terms of mixture cohesion. In fact, the WMA results are slightly better than HMA results although these differences are not statistically significant.

The moisture susceptibility of the asphalt mixes was evaluated by performing the water sensitivity test (EN 12697-12). This test provides a good indicator of the adhesiveness between binder and aggregates in an asphalt mix. The ITS values of both conditioned and unconditioned groups of specimens as well as the Indirect Tensile Strength Ratio (ITSR) are shown in Table 7 and the statistical analysis is shown in Table 8.

The good performance of the three mixtures regarding indirect traction can be observed when analysing the results. In this sense, the addition of Evotherm produces a significant increment in the ITS values (whether unconditioned or conditioned), WMA-PMB surpassing the HMA results by more than 50%. These results corroborate other studies' findings which concluded that using Evotherm has a positive effect on the moisture performance of the mixtures [31,32].

On the other hand, when the NB is used instead of the PMB, a median value between the other two mixtures is observed, what implies a 25% increment in the HMA results. Furthermore, WMA-NB reaches 99% in the ITSR and therefore, it undergoes less damage due to moisture effects.

The dynamic performance of the PA mixes was evaluated through the stiffness (EN 12697-26) and resistance to fatigue (EN 12697-24) tests. 3 and 12 samples were used, respectively, in this case. The dynamic modulus of the three asphalt mixtures at different frequencies are shown in Figure 4 and 2 examples of the statistical analysis can be seen in Table 9.

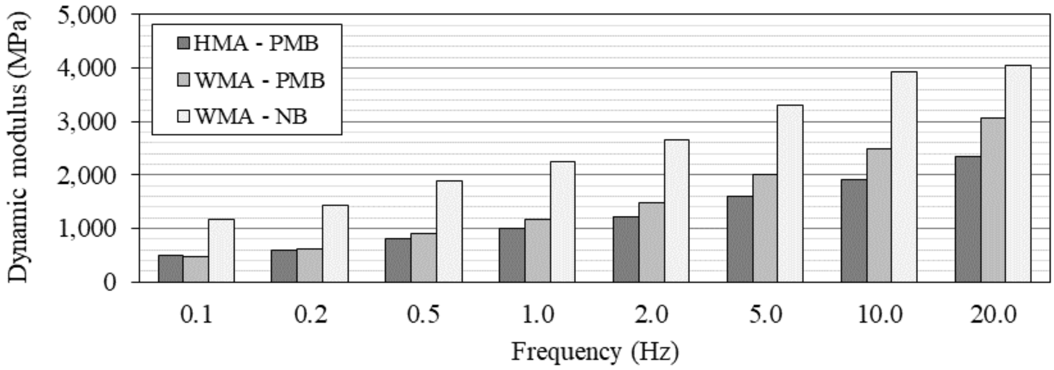


Figure 4. Dynamic modulus test results of PA mixtures

The WMA with NB shows higher stiffness at all frequencies in comparison with the rest of the mixtures. In fact, the higher the frequency, the higher the difference between the dynamic modulus of the WMA-NB and the other two mixes, especially when compared to the HMA. Therefore, it seems that NB could be stiffer than the conventional polymeric modified binder.

Regarding the WMA-PMB, its behaviour is very similar to the HMA mix in the lower range of the graph. However, over 2 Hz the difference between WMA-PMB and the HMA mix becomes significant, demonstrating the capability of Evotherm to increase the mixture stiffness.

Table 9. Dynamic modulus (MPa). Statistical analysis

Difference of Levels	Difference of means	95% CI	Adjusted P-Value
	0.1 Hz		
WMA-PMB – HMA-PMB	-2.3	-137.0; 132.5	0.999
WMA-NB – HMA-PMB	673.9	529.9; 818.0	0.000
WMA-NB – WMA-PMB	676.2	541.5; 810.9	0.000
	20 Hz		
WMA-PMB – HMA-PMB	714	359; 1068	0.001
WMA-NB – HMA-PMB	1695	1316; 2074	0.000
WMA-NB – WMA-PMB	981	626; 1335	0.000

Fatigue test results, expressed using the two most common parameters, are shown in Table 10 and Figure 5. The strain characteristic represents the strain which causes the mixture failure after a million cycles while N100 indicates the number of cycles at which a mixture fails when a strain of 100 microstrains is fixed.

The results obtained during the development of the fatigue test are coherent with the stiffness values. The two mixtures that uses PMB show a very similar stress-cycle (S-N) curve. However, the higher stiffness of the WMA mixture displaces the fatigue law trace downwards, WMA suffering a higher stress under the same strain conditions.

Regarding the WMA-NB, it presents a similar performance to the WMA-PMB at high strain levels (350-500µm/m). However, as the deformation decreases the performance of this mixture gets worse.

It is important to mention that the real fatigue performance is directly influenced by the material stiffness. For the same traffic loads, the response of the pavement will be different depending on the stiffness of the materials used for each layer. In this case, the differences shown in the fatigue test between the WMA-NB and the rest of the mixtures will be reduced under real pavement conditions due to the positive effect caused by the higher stiffness of the new binder. Finally, it is necessary to consider that these types of mixtures are usually employed in surface layers, where the damage caused by fatigue is not as important as in the bottom layers. In any case, the results obtained in terms of dynamic performance are adequate for this type of asphalt mixtures.

Table 10. Fatigue test results of PA mixes

Mix	**Binder**	**Strain characteristic (µm/m)**	**N_{100} (cycles)**	**Fatigue law**	**R^2**
HMA	PMB 45/80-65	222.1	1.02E+08	$\ln(N)=45.1 -5.79\times\ln(\varepsilon)$	0.90
WMA	PMB 45/80-65	185.7	3.03E+07	$\ln(N)=42.6 -5.51\times\ln(\varepsilon)$	0.88
WMA	NB	126.4	1.89E+06	$\ln(N)=30.7 -3.54\times\ln(\varepsilon)$	0.92

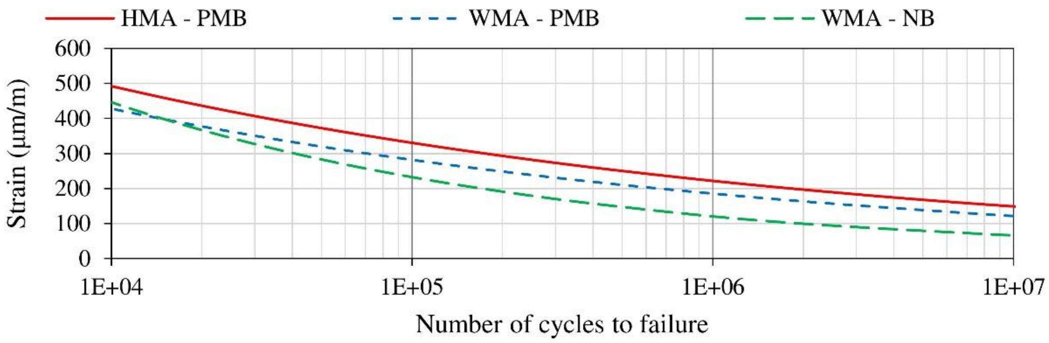


Figure 5. Fatigue test results of PA mixes

3.2. LCA and LCCA results

Results after comparing the LCA and LCCA of both WMA with the HMA are shown in Figure 6 and Figure 7. As is obvious, the greater the service life of the road, the smaller the economic and environmental impacts.

When the analysis is performed considering only the wearing course (Figure 6), the differences between the mixtures are more obvious. The 20ºC reduction in the manufacturing temperature of the WMA-PMB leads to a decrease of 1.0%, 2.9% and 3.3% in the RA, HH and ED impacts, respectively when no service life extension is considered. However, the addition of Evotherm increases the cost of the mixture, WMA-PMB needing 0.5% life extension to equalize the HMA cost.

Regarding WMA-NB, the addition of nano-technology results in a higher environmental and economic impact if no service life extension takes place. Again, the economic impact is the most restrictive one with 8.8% higher cost than the HMA. This impact is followed by HH, which is 4.6% higher than in the HMA, RA having the lowest impact with an increment of 0.5%. Nevertheless, as calculating the durability of porous asphalt mixtures is not possible with the tools that are currently available (at least at laboratory level), the analysis was performed applying the LCA and LCCA methodology to the whole pavement assuming fatigue failure.

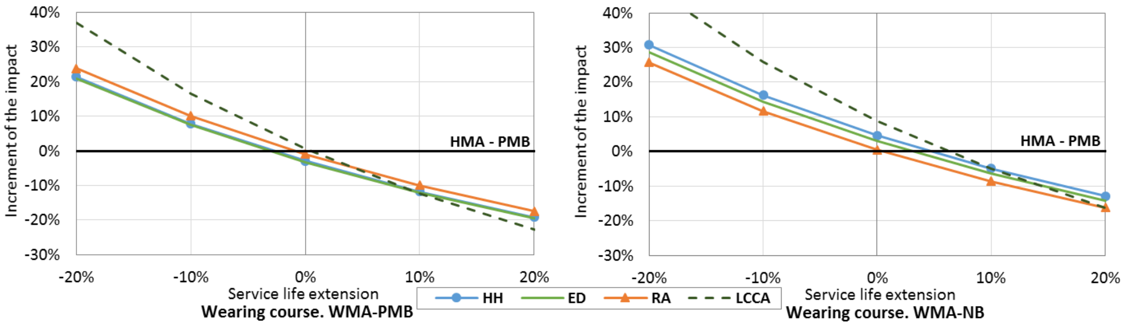


Figure 6. LCA and LCCA result comparison. Wearing course.

The durability of the asphalt pavements calculated with Alize and 3D-Move as well as their relationship (in percentage) can be seen in Table 11. When a static approach is applied, Alize provides more conservative results than 3D-Moves due to intrinsic variables of the software (such as the adherence between the layers). However, the relationship between the mixtures durability is very similar whichever software is used. In this sense, WMA-PMB and WMA-NB increase the durability of HMA by around 5% and 17%. On the other hand, the effect of vehicle speed on the pavement deterioration can be clearly observed when the dynamic analysis is carried out: the lower the speed, the greater the damage. Nevertheless, as the relationship between the mixtures' durability is barely affected by the speed selected, the service life increase of the WMA-PMB and WMA-MB is 4% and 11%. Therefore, smaller increments in the service life are calculated when performing a dynamic analysis.

Table 11. PA mixture durability

Mix	Alize Static	3D-MOVE					Static (mean	Dynamic (mean)
		Static	10 km/h	20 km/h	60 km/h	100 km/h		
Absolute value (years)								
HMA-PMB	11.8	15.3	10.0	14.2	23.8	29.2	-	-
WMA-PMB	12.5	16.1	10.3	14.8	24.9	30.5	-	-
WMA-NB	13.9	17.8	11.1	15.9	26.4	32.2	-	-
Durability increase compared to the HMA-PMB mix (%)								
HMA-PMB	0%	0%	0%	0%	0%	0%	0%	0%
WMA-PMB	6%	5%	3%	4%	5%	5%	5%	4%
WMA-NB	17%	16%	12%	12%	11%	11%	17%	11%

When the whole pavement section is included in the LCA and LCCA system boundaries (see Figure 7), the effect of the technology is attenuated. In this sense, the economic aspect is still the most restrictive impact, WMA-PMB needing 0.2% service life extensions to be considered as profitable, whereas the WMA-NB needs at least a 3.0% increase. On the other hand, when the environmental point of view is taken into account, the benefits of using WMA-PMB technology can be observed even when the pavement lasts 1.4% less than the HMA pavement, the pavement needing -0.3% life extension to improve the three environmental impacts. However, WMA-NB starts showing benefits when 0.2% service life increase is achieved and requires 2.3% increase to be considered as environmentally friendly due to the HH impact generated during the CB production.

Considering the service life extension calculated with the software, significant improvements are obtained with both mixes. WMA-PMB, achieving a smaller increment in the service life, enables a reduction between 5.2% and 6.3% in the environmental impact when the static approach is applied and between 4.1% and 5.2% with the dynamic analysis. Bigger improvements are achieved with the nano-modified binder. When the dynamic analysis is carried out, reductions of 8.2%, 8.9 and 10.0% in the HH, ED and RA impacts are possible. Furthermore, if the static analysis is performed, these three environmental impacts can be reduced 12.3%, 13.0% and 14.0% respectively.

Economic advantages are also obtained with these technologies and again, WMA-NB is the most profitable pavement. When an optimistic service life extension is assumed, WMA-NB achieves 15.0% cost reduction while WMA-PMB achieves 5.9%. Considering a more conservative scenario, WMA-NB can reduce 9.8% the agency costs whereas WMA-PMB only reduces them 4.5%.

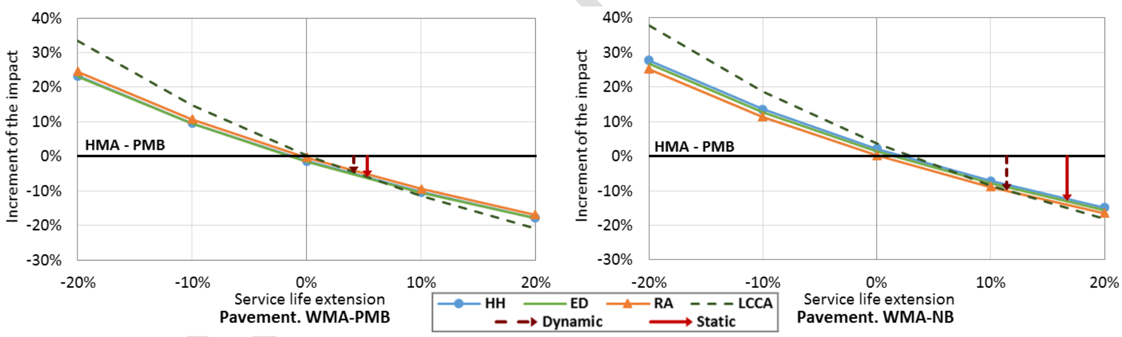


Figure 7. LCA and LCCA result comparison. Pavement.

4. Conclusions.

Three porous asphalt mixtures which combine the most common techniques to reduce the environmental impact of roads (the replacement of natural aggregates, the reduction of the manufacturing temperature and the use of a nano-modified binder) were designed in this paper. All the mixtures were dosed using EAF slag (80.4%) and RAP (14.0%), the addition of limestone (natural aggregates) being necessary in the filler fraction (2.0%). Evotherm was used as the additive to reduce the WMA temperature and CB was used by ACCIONA Infrastructure to develop a nano-modified bitumen.

After performing several mechanical tests in the laboratory as well as applying the LCA and LCCA methodologies, several conclusions can be drawn:

- The technical feasibility of producing highly sustainable PA mixtures which combine the three technologies was demonstrated at laboratory level.
- Evotherm ends up being a good additive to produce WMA. Adding 5% of Evotherm by weight of virgin binder leads to a decrease of 20ºC in the manufacturing temperature in porous asphalt mixes without affecting the compaction energy.
- Using Evotherm has a positive influence on the mechanical performance of the mixtures. WMA-PMB presents less particle loss than HMA and achieves the highest values of ITS. Furthermore, Evotherm tends to increase the stiffness of the mixture.
- The mixtures with the experimental binder show the lowest water susceptibility. In contrast, despite accomplishing the standards and the differences not being statistically significant, WMA-NB presents the worst results in the particle loss test. In terms of dynamic performance, WMA-NB shows worse fatigue performance than the mixture with PMB. However, its higher dynamic modulus would reduce the differences between the mixtures' behaviour under real pavement conditions.
- In general, static simulations provide more conservative results than dynamic analysis when they are expressed in absolute terms. However, comparing the durability of the pavements percentage-wise, static simulations calculates larger service life increases.
- Alize and 3D-Move can be used interchangeable to calculate the relationship between the pavements durability in a static way. However, the absolute value is different due to intrinsic characteristics of the software. This is also observed in the dynamic analysis when several traffic speeds are simulated. Although the absolute values of durability differ, any speed can be selected as long as the analysis is being performed for comparative purposes.
- Both WMA technologies improve the environmental and economic impacts. Nevertheless, using nano-modified binder provides the most promising results. When the best durability scenario is considered, more than 12% and 15% reductions in the environmental and economic impacts can be achieved.
- The incorporation of the whole pavement within the system boundaries when the technology is only applied in the wearing course attenuates the LCA and LCCA results. However, there is a need to develop tools which enable the prediction of porous asphalt mixture service life.
- The experimental binder shows an adequate performance for use in PA mixes. However, considering the failure mechanism of this type of mixtures and the behaviour detected during this research, the benefits of this NB could be maximized by its application in asphalt concrete mixes.

Acknowledgements

This work was supported by the European Union's Seventh Framework Programme for research, technological development and demonstration [Grant Agreement n° 605404], the FPU Programme of the Spanish Ministry of Education, Culture and Sport [grant number FPU-1/06997] and the doctoral studentship programme of the University of Cantabria, co-financed by the Government of Cantabria.

References

[1] W.F. Laurance, G.R. Clements, S. Sloan, C.S. O'Connell, N.D. Mueller, M. Goosem, O. Venter, D.P. Edwards, B. Phalan, A. Balmford, R. Van Der Ree, I.B. Arrea, A global strategy for road building, Nature. 513 (2014) 229–232. https://doi.org/10.1038/nature13717.

[2] P. Ahmedzade, B. Sengoz, Evaluation of steel slag coarse aggregate in hot mix asphalt concrete, J. Hazard. Mater. 165 (2009) 300–305. https://doi.org/10.1016/J.JHAZMAT.2008.09.105.

[3] S. Sorlini, A. Sanzeni, L. Rondi, Reuse of steel slag in bituminous paving mixtures, J. Hazard. Mater. 209–210 (2012) 84–91. https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.12.066.

[4] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Constr. Build. Mater. 49 (2013) 611–617. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.08.034.

[5] D. Movilla-Quesada, A.C. Raposeiras, O. Muñoz, D. Castro-Fresno, Reduction in the use of mineral aggregate by recycling cellulose ashes to decrease the aging of hot asphalt mixtures, Constr. Build. Mater. 143 (2017) 547–557. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.03.154.

[6] M. Pasetto, N. Baldo, Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags, J. Hazard. Mater. 181 (2010) 938–948. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.05.104.

[7] A. Behnood, M. Ameri, Experimental investigation of stone matrix asphalt mixtures containing steel slag, Sci. Iran. 19 (2012) 1214–1219. https://doi.org/10.1016/j.scient.2012.07.007.

[8] M. Skaf, J.M. Manso, Á. Aragón, J.A. Fuente-Alonso, V. Ortega-López, EAF slag in asphalt mixes: A brief review of its possible re-use, Resour. Conserv. Recycl. 120 (2017) 176–185. https://doi.org/10.1016/j.resconrec.2016.12.009.

[9] H.M.R.D. Silva, J.R.M. Oliveira, C.M.G. Jesus, Are totally recycled hot mix asphalts a sustainable alternative for road paving?, Resour. Conserv. Recycl. 60 (2012) 38–48. https://doi.org/10.1016/J.RESCONREC.2011.11.013.

[10] M. Zaumanis, R.B. Mallick, R. Frank, 100% recycled hot mix asphalt: A review and analysis, Resour. Conserv. Recycl. 92 (2014) 230–245. https://doi.org/10.1016/J.RESCONREC.2014.07.007.

[11] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm Mix Asphalt: An overview, J. Clean. Prod. 24 (2012) 76–84. https://doi.org/10.1016/j.jclepro.2011.11.053.

[12] A. Almeida-Costa, A. Benta, Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt, J. Clean. Prod. 112 (2016) 2308–2317. https://doi.org/10.1016/j.jclepro.2015.10.077.

[13] H. Ajam, P. Lastra-González, B. Gómez-Meijide, G. Airey, A. Garcia, Self-healing of dense asphalt concrete by two different approaches: Electromagnetic induction and infrared radiation, J. Test. Eval. 45 (2017). https://doi.org/10.1520/JTE20160612.

[14] C.J. Slebi-Acevedo, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers, Constr. Build. Mater. 234 (2020) 117224. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.117224.

[15] S. Eskandarsefat, G. Dondi, C. Sangiorgi, Recycled and rubberized SMA modified mixtures: A comparison between polymer modified bitumen and modified fibres, Constr. Build. Mater. 202 (2019) 681–691. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.01.045.

[16] R. Casado-Barrasa, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Assessment of carbon black modified binder in a sustainable asphalt concrete mixture, Constr. Build. Mater. 211 (2019) 363–370. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.03.255.

[17] F. Moreno-Navarro, M. Sol-Sánchez, F. Gámiz, M.C. Rubio-Gámez, Mechanical and thermal properties of graphene modified asphalt binders, Constr. Build. Mater. 180 (2018) 265–274. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2018.05.259.

[18] Dirección General de Carreteras, Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Spanish General Technical Specifications for Roads and Bridge Works, PG-3), 2017. https://fomento.gob.es/NR/rdonlyres/7E090150-7354-4F83-8D4E-E4BA2BE70717/141045/PG3_PARTE_5.pdf.

[19] ISO, ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework, 2 nd. International Organization for Standardization, 2006.

[20] ISO, ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standardization, 2006.

[21] UNE-EN, UNE-EN 15804:2012+A1:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2012.

[22] E. Lizasoain-Arteaga, I. Indacoechea-Vega, P. Pascual-Muñoz, D. Castro-Fresno, Environmental impact assessment of induction-healed asphalt mixtures, J. Clean. Prod. 208 (2019). https://doi.org/10.1016/j.jclepro.2018.10.223.

[23] Eurobitume, The bitumen industry in Europe, (2012). http://www.eurobitume.eu/bitumen/industry/ (accessed December 30, 2017).

[24] J.R. Arenal, Estudio, análisis y diseño de aplicaciones de áridos procedentes de la valorización de residuos industriales : firmes de carreteras y hormigones, 2016. https://repositorio.unican.es/xmlui/handle/10902/8293.

[25] D. Peinado, M. de Vega, N. García-Hernando, C. Marugán-Cruz, Energy and exergy analysis in an asphalt plant's rotary dryer, Appl. Therm. Eng. 31 (2011) 1039–1049. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.11.029.

[26] European Commission, Guide to Cost-Benefit Analysis of Investment Projects, 2014.

[27] M. de Fomento, Ordin Circular 37/2016. Base de precios de referencia de la Dirección General de Carreteras., 2016.

[28] CYPE Ingenieros, Generador de Precios. España, (2019). http://www.generadordeprecios.info/.

[29] LCPC, Alize-LCPC Software. Version 1.3. User manual, 2011. http://www.alize-lcpc.com/documents/ALIZE-MU-V130-GB.pdf.

[30] University of Nevada, 3D-Move Analysis, (2013). http://www.arc.unr.edu/Software.html.

[31] D.X. Lu, M. Saleh, Laboratory evaluation of warm mix asphalt incorporating high RAP proportion by using evotherm and sylvaroad additives, Constr. Build. Mater. 114 (2016) 580–587. https://doi.org/10.1016/J.CONBUILDMAT.2016.03.200.

[32] A. Kusam, H. Malladi, A.A. Ayebali, N.P. Khosla, Laboratory Evaluation of Workability and Moisture Susceptibility of Warm-Mix Asphalt Mixtures Containing Recycled Asphalt Pavements, J. Mater. Civ. Eng. 29 (2017) 1–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001825.

2.4. Artículo Nº4: Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road

Autores: Esther Lizasoain-Arteaga
Irune Indacoechea-Vega
Borja Alonso
Daniel Castro-Fresno

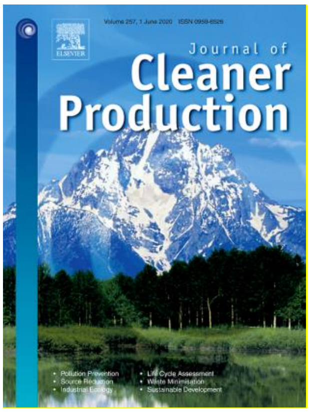
Año: 2020

Revista: Journal of Cleaner Production

Volumen: 253

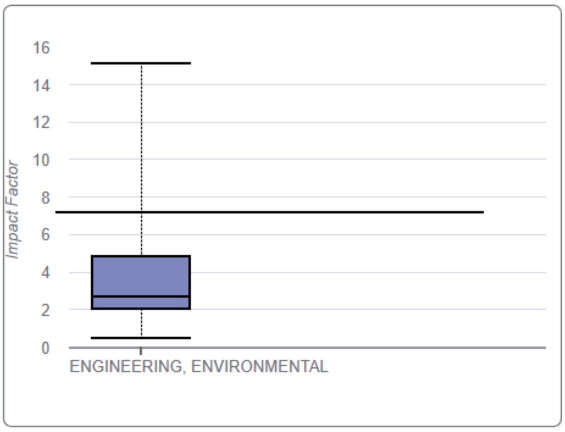
Páginas: 120500

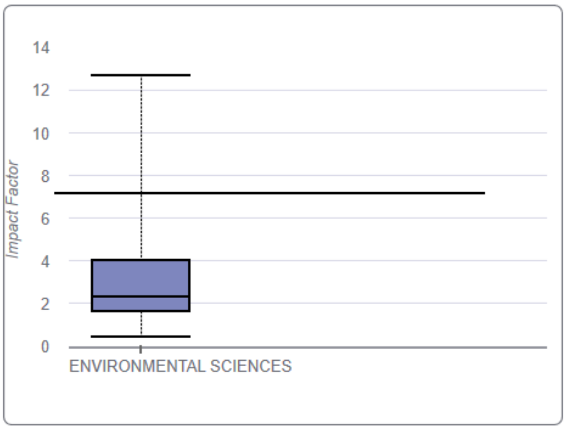
DOI: 10.1016/j.jclepro.2020.120050



Categoría	Año	Ranking	Cuartil	Percentil
Engineering, Environmental	2019	8/53	Q1	85.849
Environmental sciences	2019	19/265	Q1	93.019

Factor de Impacto JCR (2019): 7.246





Author's post-print: E. Lizasoain-Arteaga, I. Indacoechea-Vega, B. Alonso, D. Castro-Fresno. "Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road". J. Clean. Prod. 253 (2020), 120050. ISSN: 09596526. DOI: https://doi.org/10.1016/j.jclepro.2020.120050

Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road

E. Lizasoain-Arteaga[1]*, I. Indacoechea-Vega[1], B. Alonso[2], D. Castro-Fresno[1]

[1]GITECO Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain
[2]GIST Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain

Email addresses: lizasoaine@unican.es (E. Lizasoain-Arteaga); indacoecheai@unican.es (I. Indacoechea-Vega); alonsobo@unican.es (B. Alonso); castrod@unican.es (D. Castro-Fresno)

*Corresponding author. Tel +34942203943; Fax: +34942201703

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.

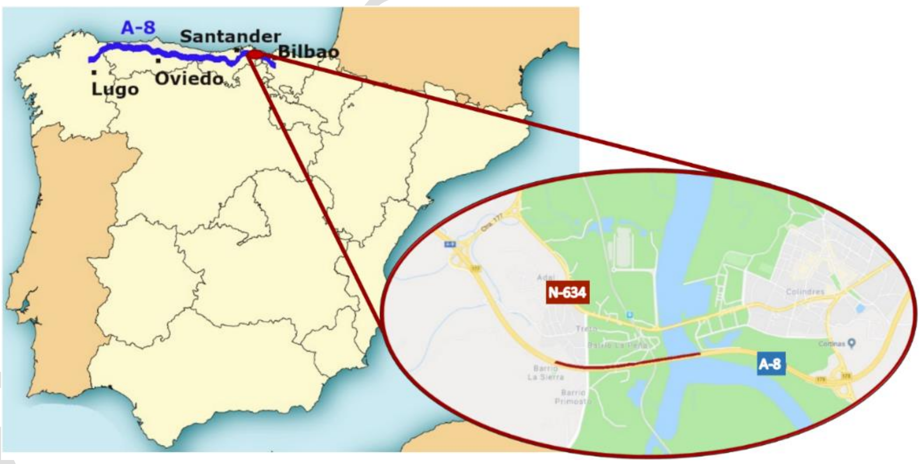


Figure 1. Studied section.

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.

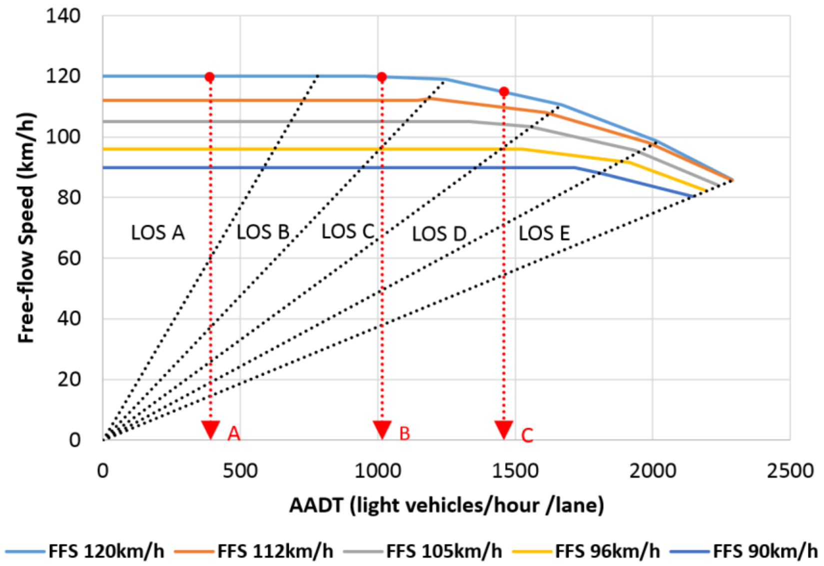


Figure 2. AADT LOS A-8. Real conditions.

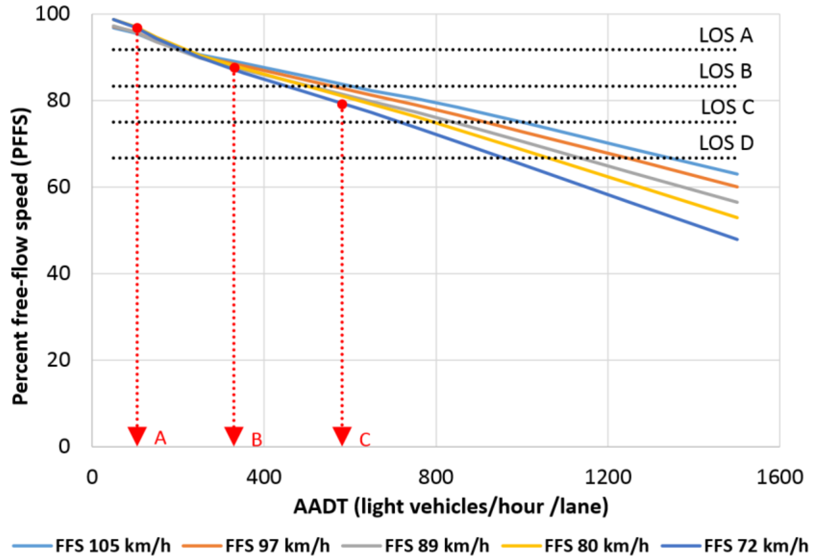


Figure 3. AADT LOS N-634. Real conditions.

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.

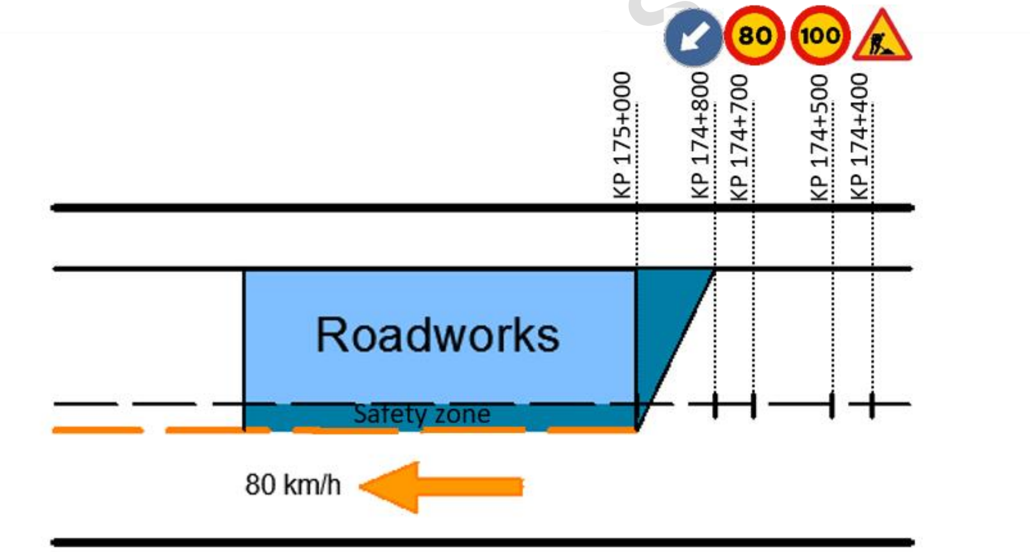


Figure 4. Maintenance strategy diagram.

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.

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

$$Emission\ (t) = max\ [E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)] \quad (2)$$

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 $a_n(t) \geq -0.5$ m/s2 and $a_n(t) < -0.5$ 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
	Car 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

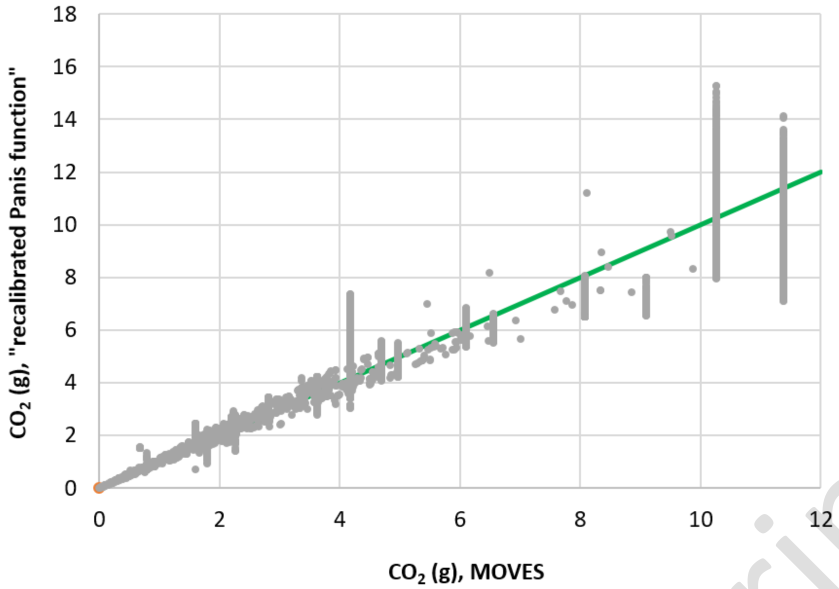


Figure 5. Correspondence between the CO_2 emissions calculated with MOVES' emission rates (horizontal axis) and the "Recalibrated" Panis Function (vertical axis).

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).

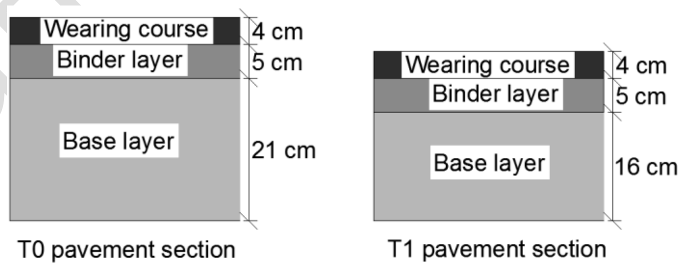


Figure 6. Pavement sections.

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.

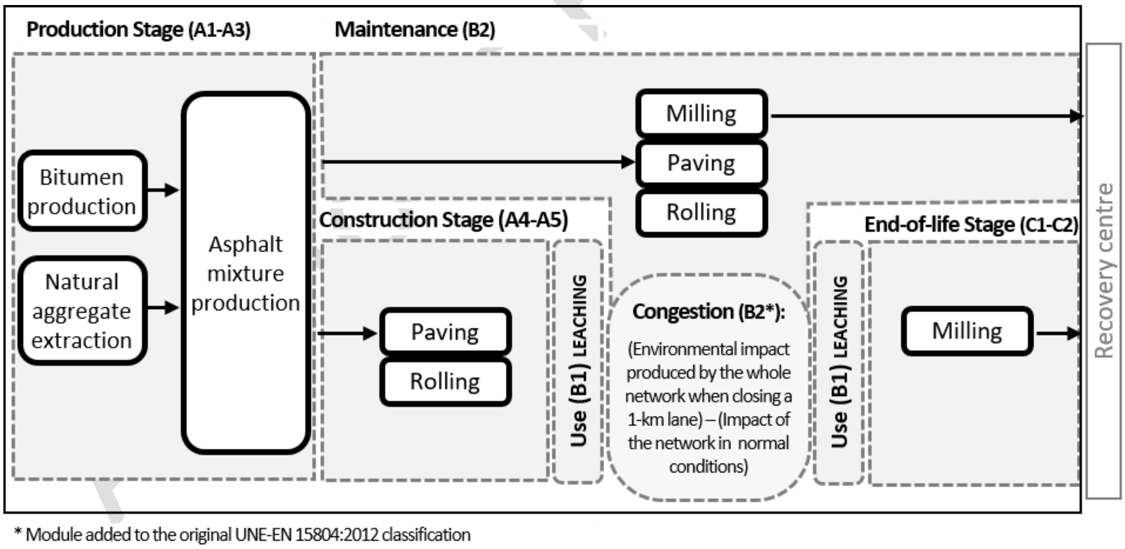


Figure 7. LCA boundaries.

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 (K.P. 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.

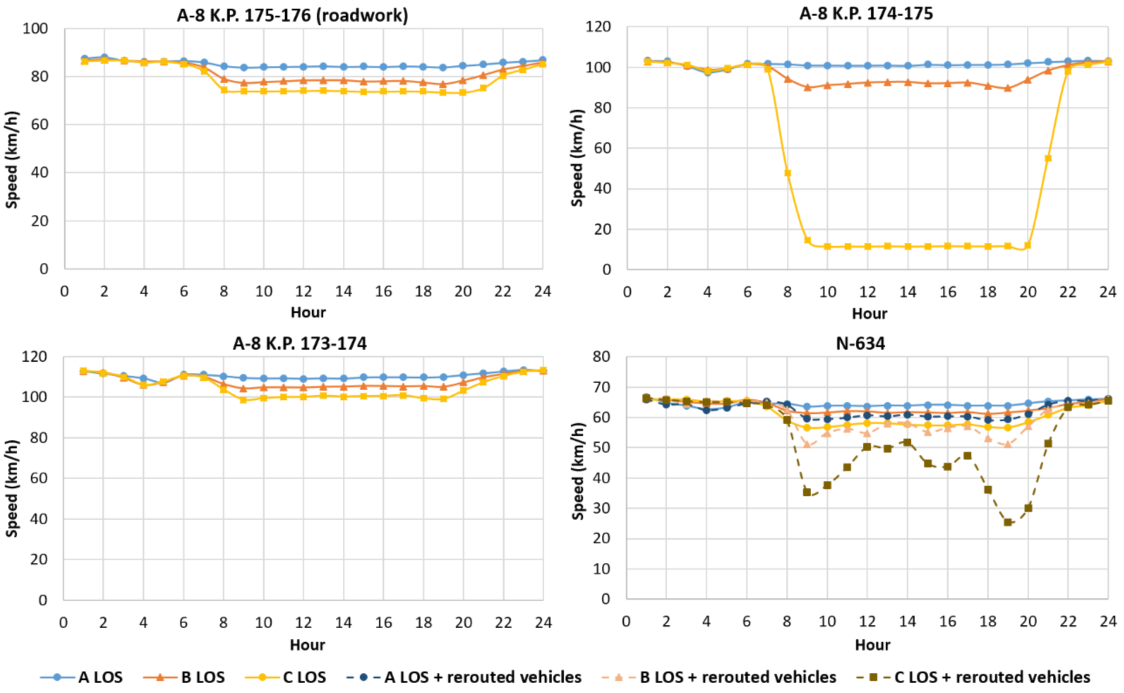


Figure 8. Aimsun average speed variation.

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.

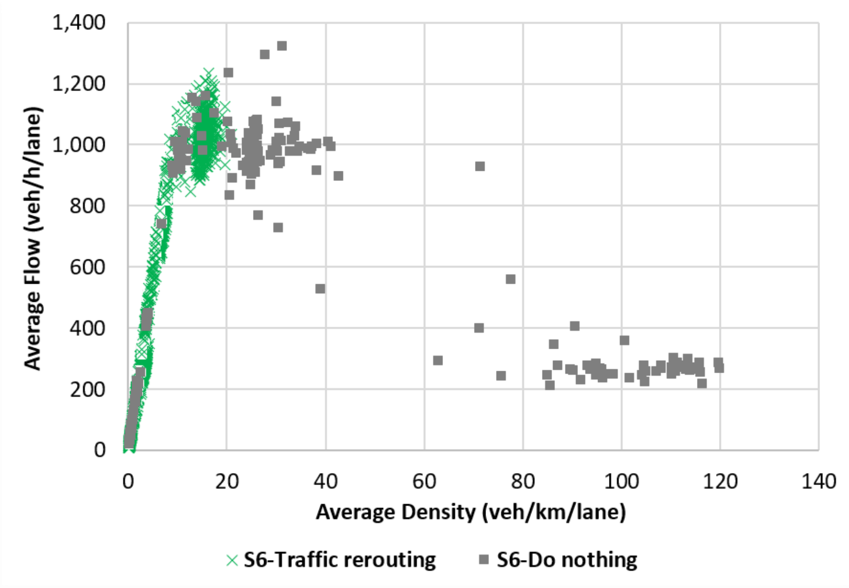


Figure 9. Network Fundamental Diagram comparing scenario 6 with traffic management strategy (30% rerouting) and "do nothing" case

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

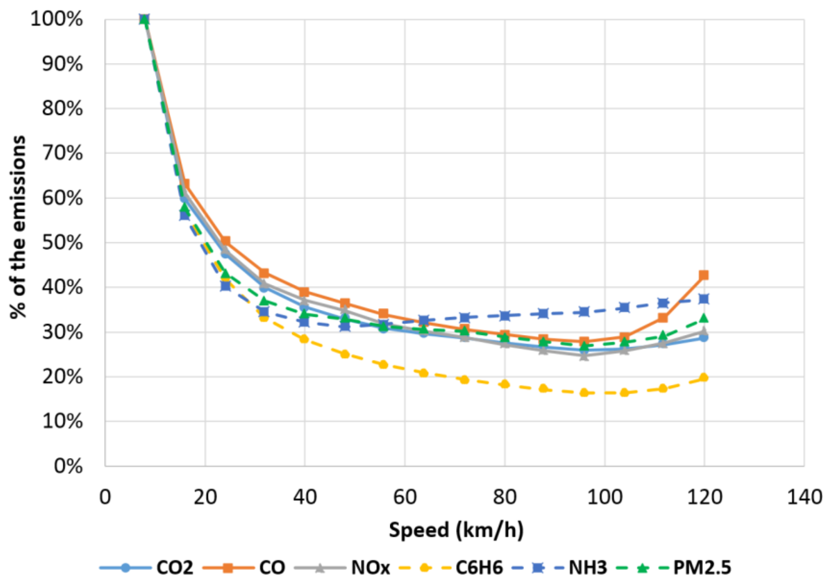


Figure 10. Relationship between vehicle emissions and speed ((Lizasoain-Arteaga et al., 2019)).

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

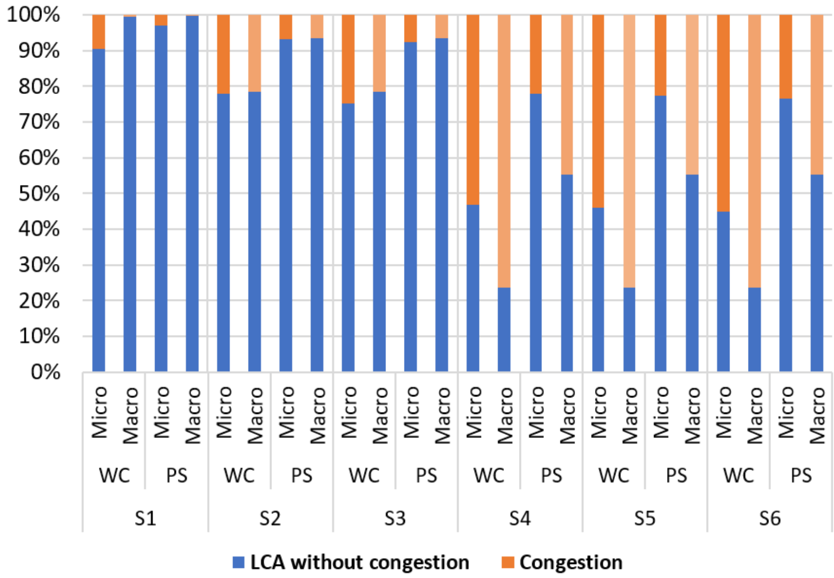


Figure 11. Congestion contribution to the "Damage to Human Health" impact.

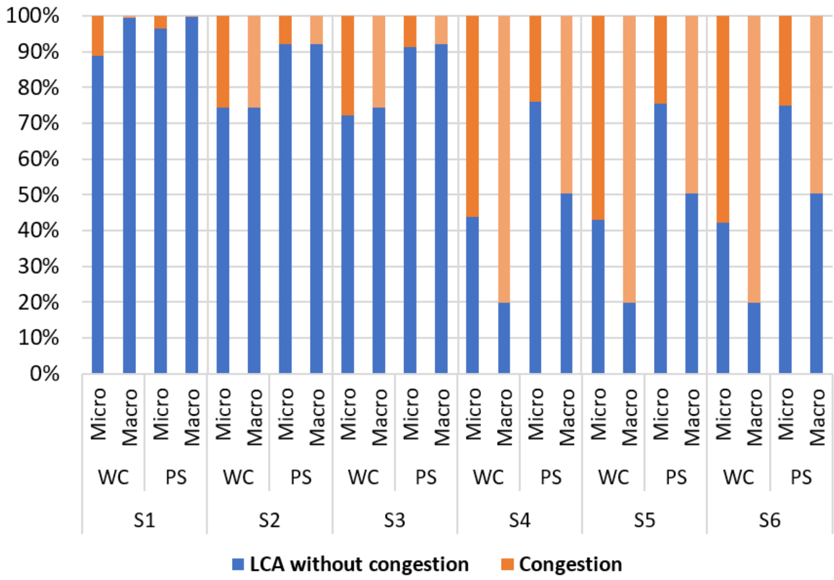


Figure 12. Congestion contribution to the "Damage to Ecosystem Diversity" impact.

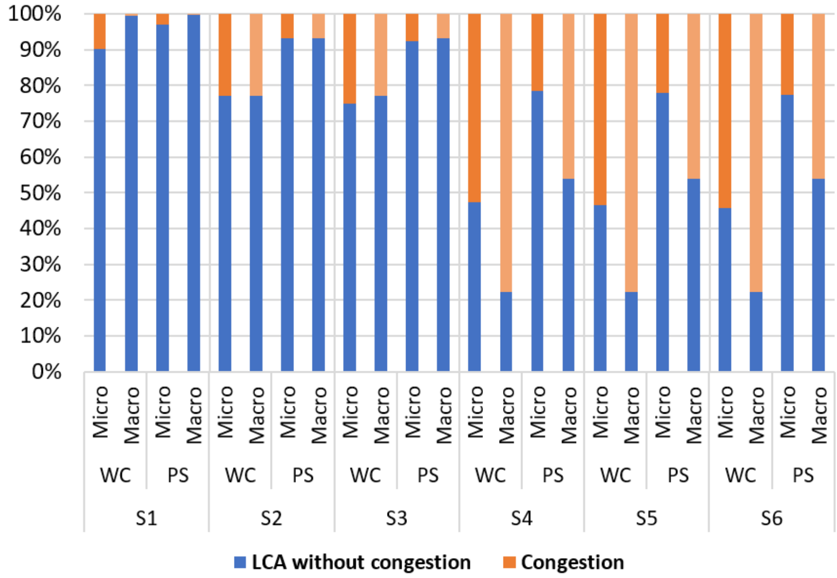


Figure 13. Congestion contribution to the "Damage to Resource Availability" impact.

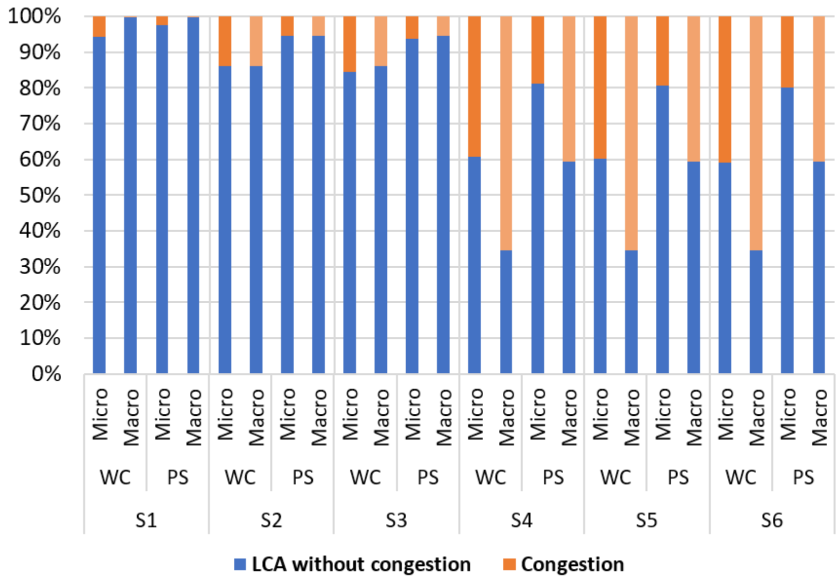


Figure 14. Contribution of congestion to the LCA results calculated with the CML 2001 Jan 16 Characterization Method.

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 $PM_{2.5}$.

Acknowledgements

This work was funded by the doctoral studentship program from the University of Cantabria, co-financed by the Government of Cantabria.

References

Alonso, B., Ibeas, A., Musolino, G., Rindone, C., Vitetta, A., 2019. Effects of traffic control regulation on Network Macroscopic Fundamental Diagram: a statistical analysis of real data. Transp. Res. Par A Policy Pract.

Anthonissen, J., Van den bergh, W.,

, J., 2016. Review and environmental impact assessment of green technologies for base courses in bituminous pavements. Environ. Impact Assess. Rev. 60, 139–147. https://doi.org/https://doi.org/10.1016/j.eiar.2016.04.005

Chiu, C.-T., Hsu, T.-H., Yang, W.-F., 2008. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. Resour. Conserv. Recycl. 52, 545–556. https://doi.org/https://doi.org/10.1016/j.resconrec.2007.07.001

Dirección General de Tráfico, 2017. Parque de vehículos. Anuario.

EAPA, 2007. Long-Life Asphalt Pavements. Technical version.

Erke, A., Sagberg, F., Hagman, R., 2007. Effects of route guidance variable message signs (VMS) on driver behaviour. Transp. Res. Part F Traffic Psychol. Behav. 10, 447–457. https://doi.org/https://doi.org/10.1016/j.trf.2007.03.003

Galatioto, F., Huang, Y., Parry, T., Bird, R., Bell, M., 2015. Traffic modelling in system boundary expansion of road pavement life cycle assessment. Transp. Res. Part D Transp. Environ. 36, 65–75. https://doi.org/https://doi.org/10.1016/j.trd.2015.02.007

Geroliminis, N., Daganzo, C.F., 2008. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. Transp. Res. Part B Methodol. 42, 759–770. https://doi.org/https://doi.org/10.1016/j.trb.2008.02.002

Häkkinen, T., Mäkelä, K., 1996. Environmental adaption of concrete. Environmental impact of concrete and asphalt pavements. VTT Tied. - Valt. Tek. Tutkimusk.

Horvath, A., Hendrickson, C., 1998. Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements. Transp. Res. Rec. J. Transp. Res. Board 1626, 105–113. https://doi.org/10.3141/1626-13

Int Panis, L., Broekx, S., Liu, R., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Sci. Total Environ. 371, 270–285. https://doi.org/https://doi.org/10.1016/j.scitotenv.2006.08.017

Inyim, P., Pereyra, J., Bienvenu, M., Mostafavi, A., 2016. Environmental assessment of pavement infrastructure: A systematic review. J. Environ. Manage. 176, 128–138. https://doi.org/https://doi.org/10.1016/j.jenvman.2016.03.042

ISO, 2006a. ISO 14040: Environmental Managemen - Life Cycle Assessment - Principles and Framework, 2 end. International Organization for Standarization.

ISO, 2006b. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standarization.

Jiménez-Palacios, J.L., 1999. Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. PhD dissertation. Massachusetts Institute of Technology, Cambridge, Mass.

Jullien, A., Monéron, P., Quaranta, G., Gaillard, D., 2006. Air emissions from pavement layers composed of varying rates of reclaimed asphalt. Resour. Conserv. Recycl. 47, 356–374. https://doi.org/https://doi.org/10.1016/j.resconrec.2005.09.004

Kim, C., Ostovar, M., Butt A, A., Harvey J, T., 2018. Fuel Consumption and Greenhouse Gas Emissions from On-Road Vehicles on Highway Construction Work Zones. Int. Conf. Transp. Dev. 2018, Proceedings. https://doi.org/doi:10.1061/9780784481561.028

Knoop, V., Hoogendoorn, S., van Zuylen, H., 2010. Rerouting behaviour of travellers under exceptional traffic conditions — an empirical analysis of route choice. Procedia Eng. 3, 113–128. https://doi.org/10.1016/j.proeng.2010.07.012

Koo, R., Yim, Y., 1998. Commuter Response to Traffic Information on an Incident. Transp. Res. Rec. 1621, 36–42. https://doi.org/10.3141/1621-05

Koupal, J., Cumberworth, M., Michaels, H., Beardsley, M., Brzezinski, D., 2003. Design and Implementation of MOVES: EPAís New Generation Mobile Source Emission Model.

Kucharski, R., Gentile, G., 2019. Simulation of rerouting phenomena in Dynamic Traffic Assignment with the Information Comply Model. Transp. Res. Part B Methodol. 126, 414–441. https://doi.org/https://doi.org/10.1016/j.trb.2018.12.001

Lizasoain-Arteaga, E., Indacoechea-Vega, I., Pascual-Muñoz, P., Castro-Fresno, D., 2019. Environmental impact assessment of induction-healed asphalt mixtures. J. Clean. Prod. 208, 1546–1556. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.223

Ministerio de Fomento., 2003. Norma 6.1-IC. Secciones de firme.

Ministerio de Fomento, 2017. Mapas de tráfico [WWW Document]. URL https://www.fomento.gob.es/carreteras/trafico-velocidades-y-accidentes-mapa-estimacion-y-evolucion/mapas-de-trafico/2017

Ministerio de Fomento, 1989. Norma de carreteras 8.3-IC. Señalización de obras.

Moral Quiza, A., 2016. La herramienta ambiental Análisis del Ciclo de Vida en el estudio de secciones de firme.

Mroueh, U.M., Eskola, P., Laine-Ylijoki, J., Wellman, K., Mäkelä, E., Juvankoski, M., 2000. Life cycle assessment of road construction. Finnra Reports 17/2000.

National Research Council (U.S.). Transportation Research Board., 2010. HCM 2010 : highway capacity manual.

Nicholls, J.., Carswell, I., Thomas, C., Sexton, B., 2010. Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring. 674 TRL Rep.

PE International, 2014. Best Practice LCA: Impact Assessment.

RIVM, 2016. ReCiPe 2016 V1.1.

Santero, N., Masanet, E., Horvath, A., 2010. Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research. https://doi.org/10.2172/985846

Santero, N.J., Masanet, E., Horvath, A., 2011. Life-cycle assessment of pavements. Part I: Critical review. Resour. Conserv. Recycl. 55, 801–809. https://doi.org/https://doi.org/10.1016/j.resconrec.2011.03.010

Sirmatel, I.I., Geroliminis, N., 2018. Economic Model Predictive Control of Large-Scale Urban Road Networks via Perimeter Control and Regional Route Guidance. IEEE Trans. Intell. Transp. Syst. 19, 1112–1121. https://doi.org/10.1109/TITS.2017.2716541

Trupia, L., 2018. System Boundary Expansion in Road Pavement Life Cycle Assessment. University of Nottingham.

Wu, X., Liu, H.X., Geroliminis, N., 2011. An empirical analysis on the arterial fundamental diagram. Transp. Res. Part B Methodol. 45, 255–266. https://doi.org/https://doi.org/10.1016/j.trb.2010.06.003

Yildirimoglu, M., Sırmatel, I.İ., Geroliminis, N., 2018. Hierarchical control of heterogeneous large-scale urban road networks via path assignment and regional route guidance, Transportation Research Part B Methodological. https://doi.org/10.1016/j.trb.2018.10.007

Yu, B., Lu, Q., 2012. Life cycle assessment of pavement: Methodology and case study. Transp. Res. Part D Transp. Environ. 17, 380–388. https://doi.org/https://doi.org/10.1016/j.trd.2012.03.004

3. METODOLOGÍA

La aplicación de la metodología de ACV se rige por dos normas ISO, la 14040:2006 [58] y la 14044:2006 [59], las cuales especifican los requisitos y directrices que se deben seguir para realizar un análisis adecuado. Según estas normas, el ACV se compone de 4 etapas interrelacionadas (Figura 1):

- La primera de estas etapas es la definición del objetivo y del alcance del análisis. En ella se debe de establecer claramente el objetivo del ACV, los límites del sistema, las hipótesis de partida y la unidad funcional que actúa como unidad de referencia a la hora de hacer comparaciones.
- La segunda etapa es el análisis del inventario del ciclo de vida y consiste en la creación de una base de datos consistente que recoja y cuantifique todos los recursos consumidos y emisiones producidas por cada proceso que interviene en el ciclo de vida de la carretera.
- La etapa de evaluación del impacto del ciclo de vida es la tercera. Aquí las emisiones previamente detectadas se transforman en impactos ambientales mediante la aplicación de modelos de caracterización.
- Finalmente, en la interpretación del ciclo de vida se resumen y se discuten los resultados, proponiendo conclusiones y recomendaciones.

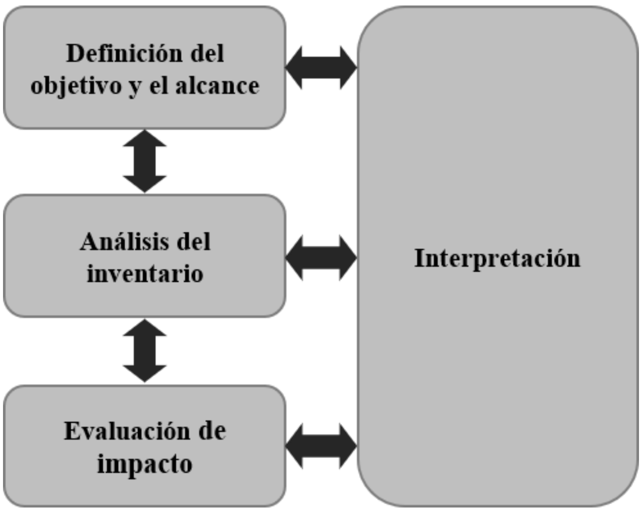


Figura 1. Etapas de un ACV [59].

Teniendo en cuenta que cada artículo que conforma la presente tesis doctoral adaptó su objetivo y alcance para poder evaluar cada una de las lagunas del conocimiento detectadas y obtuvo resultados y conclusiones diferentes, este capítulo se centra únicamente en 2 etapas de la metodología del ACV: el análisis del inventario y la evaluación del impacto.

3.1. Análisis del inventario del ciclo de vida

Como ya se ha comentado, esta etapa consiste en la creación de una base de datos consistente de los recursos consumidos y emisiones producidas por los distintos procesos que intervienen a lo largo del ciclo de vida de la carretera. Su creación requirió tanto la recopilación de datos de distintas fuentes bibliográficas y bases de datos como la realización de ensayos de laboratorio y aplicación de modelos teóricos. A continuación, se describen las hipótesis y fuentes de datos utilizadas para crear el inventario de cada fase de la vida de la carretera. Las fases se definieron siguiendo la clasificación propuesta por la norma UNE-EN 15804:2012 relativa a las normas de Declaración Ambiental de Productos (DAP) de materiales de construcción [60]. En lo que respecta a los procesos de generación de electricidad, producción de combustibles fósiles y transporte de materiales (procesos compartidos por todas las etapas del ACV), se utilizaron los definidos en la base de datos Gabi v9.1 para el promedio europeo y en la base de datos del Laboratorio Nacional de Energías Renovables (NREL) [61].

3.1.1. Etapa de producto

Esta etapa incluye la extracción y el procesamiento de las materias primas, su transporte a la planta de asfalto y la fabricación de la mezcla asfáltica.

3.1.1.1. Extracción y procesamiento de materias primas

A lo largo de la presente tesis doctoral, además de los materiales usualmente empleados en carreteras (áridos, betún y filler) se han utilizado otros más novedosos bien para dotar a las mezclas de características especiales (como una mayor durabilidad) o bien para tratar de reducir su impacto ambiental. Algunos de los procesos de extracción y procesamiento de esos materiales (especialmente los relacionados con los más convencionales) han sido estudiados en detalle por otros autores. Sin embargo, los materiales más novedosos requirieron un estudio más exhaustivo. En la Tabla 1 se muestra una simplificación del inventario creado y las fuentes de las que se obtuvo la información. No obstante, cabe señalar que:

- El betún nanomodificado (desarrollado por ACCIONA Infraestructura) se calculó combinando el inventario de los 2 materiales que lo componen: betún modificado con polímeros (PMB) y Carbon Black (CB) [34].
- Evotherm, un aditivo que permite reducir la temperatura de fabricación de la mezcla, fue excluido del análisis por la falta de datos tanto de su producción como de su composición y porque la cantidad empleada en las mezclas es muy reducida (0,018 %) [60].
- El inventario de las EAFS se explica en detalle en la sección 3.1.1.2, debido a su complejidad.

Tabla 1. Recursos energéticos consumidos en la extracción y procesamiento de materias primas.

Material	Combustibles fósiles (MJ/t)	Electricidad (MJ/t)	Fuente
Áridos naturales gruesos y finos	22,06	19,08	[12,14,69,61–68]
Filler	29,21	85,75	GaBi V9.1
Asfalto reciclado (RAP)	27,65	0,67	[70]
Acero	4.745,03	1.648,25	GaBi V9.1
Betún convencional	2.370,55	18,4	[4]
Betún PMB	4.259,40	89,76	[4]
Betún CB	7.711,20	199,82	[4] GaBi V9.1

3.1.1.2. Asignación de impacto a las EAFS

Para calcular el inventario de la escoria, se adoptó el proceso descrito por Arenal [20], según el cual, la producción de acero da como resultado la generación de otros dos materiales, la escoria negra y la escoria blanca, produciéndose unos 130 kg y 25 kg respectivamente, por cada tonelada de acero fabricada. La escoria negra, una vez extraída del horno, se enfría bruscamente mediante un cañón de agua a alta presión, siendo luego sumergida en un estanque para continuar su enfriamiento. Después del proceso de enfriamiento, se emplea un separador magnético para extraer el acero restante que podría quedar entre la escoria (alrededor del 2 %). Finalmente, las escorias se trituran (cuando es necesario) y se criban para conseguir un tamaño adecuado. Sin embargo, para asignarle el impacto ambiental que le corresponde es muy importante determinar si las escorias deben de ser consideradas como residuo o subproducto, y todavía no se ha llegado a un consenso al respecto.

Según algunos autores [26,71,72], las escorias deberían considerarse como residuos ya que no cumplen completamente los requisitos para ser considerados subproductos establecidos en la Directiva marco sobre residuos 200/98/CE [73] al no estar asegurado su uso ni estar suficientemente estudiados los problemas ambientales. En consecuencia, no se asignaría ninguna carga ambiental a las escorias. En cambio, otros autores afirman que, desde su punto de vista, las escorias son subproductos, ya que se cumplen esos requisitos [74] y por lo tanto, parte del impacto generado durante la producción de acero debería de ser asignado a las escorias. Sin embargo, la asignación de los impactos es una cuestión muy controvertida dentro del campo de los ACV [75], por lo que incluso la norma ISO 14044 [59] recomienda evitarla siempre que sea posible dividiendo el proceso unitario en subprocesos o ampliando los límites del sistema para incluir otros usos que el subproducto pudiera tener. No obstante, como la expansión del sistema parece estar dedicada a la evaluación de los productos principales y puede presentar incoherencias al analizar los subproductos, también surgen diferentes enfoques a este respecto [76].

PE International [77] y Saade et al. [78] entienden que cuando un subproducto se utiliza para sustituir a otro material, el subproducto asume el impacto ambiental de su propio tratamiento pero también recibe un crédito por el impacto evitado. Por otro lado, Weidema [79] afirma que la carga ambiental del tratamiento del subproducto debe ser asumida por el producto principal (en este caso el acero), que también recibe el crédito por los impactos evitados. Por lo tanto, para respetar la conservación de la masa, el subproducto asume el impacto de producir el material evitado que previamente se sustrajo del producto principal. Sin embargo, esto no sería atractivo para las empresas que quieren utilizar el subproducto, ya que todas las ventajas ambientales van a parar al producto principal, dejando los procesos posteriores del subproducto intactos. Además, en el caso de la sustitución de áridos naturales por EAFS, restar el impacto de la producción de áridos al del acero dejaría su impacto ambiental prácticamente igual, mientras que se perjudicaría enormemente el uso de las escorias. Por esta razón, Martin et al [80] desarrollaron el método 50/50, un enfoque intermedio que divide el impacto de tratar el subproducto y el crédito recibido por el impacto evitado entre el producto principal y el subproducto. Sin embargo, como propone Weidema [79], el subproducto seguiría asumiendo el impacto de extraer el producto evitado con el fin de conservar la masa.

Teniendo en cuenta la gran variedad de opiniones existentes al respecto, se seleccionaron 4 de ellas para evaluar su afección a los resultados del ACV (véase Figura 2).

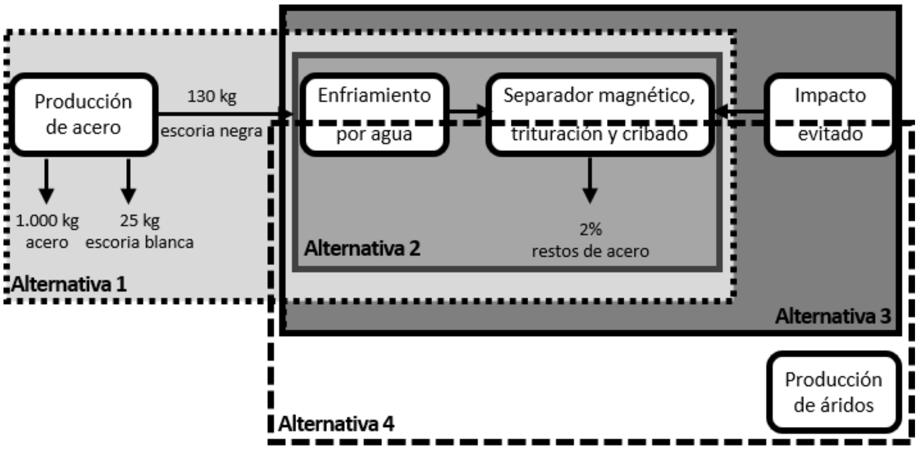


Figura 2. Alternativas de asignación de impacto a EAFS.

La alternativa 1 consiste en asignar a las escorias una parte de los impactos de la producción del acero, además de los impactos generados durante su procesamiento (enfriamiento, separación magnética, trituración y cribado). Para ello se aplicó una asignación basada en el beneficio económico del proceso, combinando la masa y el coste de los materiales. Comúnmente, los ACV se realizan utilizando un aspecto u otro por separado. No obstante, si uno de los materiales se produjera en una cantidad muy pequeña, pero tuviera un valor muy alto no quedaría reflejado en el proceso de asignación.

Según el proveedor de las escorias, su precio varía mucho según la oferta y la demanda: cuando se dispone de mucha escoria, ésta es prácticamente regalada mientras que, para cubrir los gastos, su precio debería ser similar al de la piedra caliza. De forma conservadora se asumió un coste de 10 €/t para la escoria negra. De esta manera, si la asignación se realizara por masa la escoria recibiría el 11 % del impacto de la producción de acero mientras que por coste recibiría el 1.39 %. Como puede verse en la Tabla 2, con el método de asignación elegido (basado en el beneficio económico) a la escoria se le atribuye el 0.23 % del impacto del acero. Por lo tanto, incluso asumiendo un precio alto, la asignación de impactos utilizada es menor que en las otras dos opciones.

Tabla 2. Coeficientes de asignación de impactos.

Material	Fuente del precio	Precio (€/t)	Masa (t)	Asignación
Acero	[81]	550,00	1,000	99,70%
Escoria negra	Proveedor	10,00	0,127	0,23%
Escoria blanca	Proveedor	0,00	0,025	0,00%
Chatarra	[82]	150,00	0,003	0,07%

En la Alternativa 2, solo se incluyeron aquellos procesos que se realizan exclusivamente a las escorias. De esta manera, las escorias representan un residuo de la industria siderúrgica que se seguirá produciendo mientras siga existiendo demanda de acero.

La alternativa 3 amplía los límites del sistema de la alternativa 2 para incluir el impacto que se evita al no tener que extraer áridos naturales. Así, el beneficio del reciclaje solo lo reciben las escorias, lo que fomenta su uso. De lo contrario, el acero tendría que asumir el impacto de enviar las escorias a vertedero.

Por último, la alternativa 4 aplica el método 50/50 propuesto por Martin et al. [80] que distribuye los beneficios entre el acero y las escorias, pero sin olvidarse de la conservación de la masa.

Una simplificación del inventario usado en cada alternativa puede verse en la Tabla 3.

Tabla 3. Inventario simplificado de las EAFS.

Inventario	Alternativa 1	Alternativa 2	Alternativa 3	Alternativa 4
Combustibles fósiles (MJ/t)	108,91	22,64	0,58	22,35
Electricidad (MJ/t)	30,22	0,25	-18,83	9,67

3.1.1.3. Distancias de transporte hasta la planta asfáltica

Las distancias de transporte empleadas en esta tesis doctoral se muestran en la Tabla 4. Cabe mencionar que a la caliza y a la escoria se les asume siempre un uso local mientras que la distancia de transporte de la ofita puede variar de un artículo a otro según el objetivo del análisis.

Tabla 4. Distancias de transporte.

Material	Distancia de transporte (km)
Ofita	Variable
Caliza	30
Escoria	30
RAP	30
Betún	100

3.1.1.4. Fabricación de la mezcla asfáltica

La energía de fabricación de las mezclas asfálticas está principalmente condicionada por dos aspectos: el calor específico de los áridos y su humedad. Es por lo que ambas propiedades se estudiaron en 3 tipos de árido grueso: una ofita y 2 EAFS con propiedades muy diferentes (véase Tabla 5).

Tabla 5. Propiedades de los áridos gruesos.

Test	Normativa	Ofita	Escoria 1	Escoria 2
Peso específico (t/m3)	EN 1097-6	2,937	3,735	3,920
Coeficiente de Los Ángeles	EN 1097-2	16	18	17
Índice de lajas	EN 933-3	8	2	5
Absorción de agua (fracción 8/11.2)	EN 1097-6	0,60%	0,95%	1,72%
Absorción de agua (fracción 2/4)	EN 1097-6	0,20%	0,81%	3,09%
Expansividad	EN 1744-1	0%	0,6%	<3,5%

El calor específico de los áridos se evaluó mediante la técnica de la calorimetría diferencial de barrido, la cual se aplicó a diferentes fracciones de material (2/4, 4/8, 8/11.2 y 11.2/16) para determinar si el tamaño del árido influía en el calor específico debido, por ejemplo, a la presencia de diferentes compuestos en función del tamaño de partícula. Sin embargo, esta premisa se descartó en base a los resultados mostrados en la Figura 3, según los cuales, el tamaño más grande y más pequeño de árido necesitan casi la misma energía para aumentar la temperatura 1ºC.

La media y la desviación estándar del calor específico de cada material se puede ver en la Figura 4. La ofita es el material que más energía requiere para ser calentado, seguido de la escoria 1 y la escoria 2. No obstante, la ofita es también el material con la mayor desviación estándar. De hecho, el calor específico más bajo de la ofita es menor que el calor específico más alto de la escoria 1. Por lo tanto, se consideraron 3 valores de calor específico para cada material a fin de evaluar estas circunstancias (véase la Tabla 6).

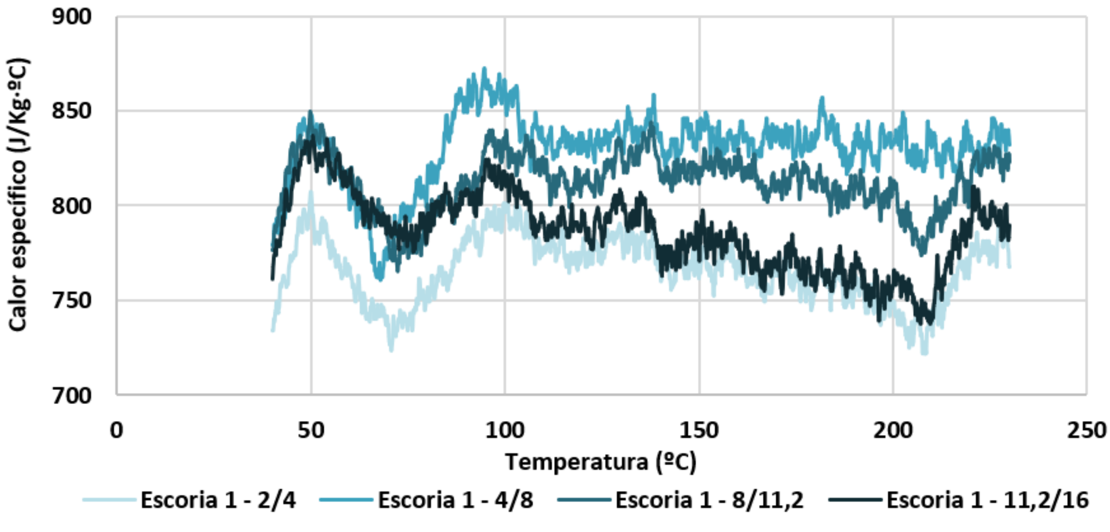


Figura 3. Calor específico de la escoria 1 según el tamaño de partículas.

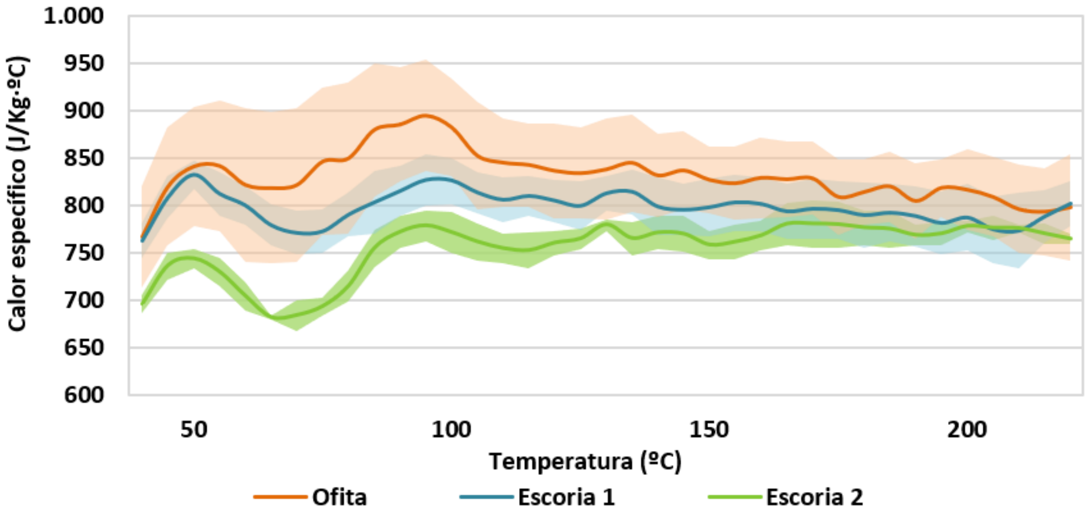


Figura 4. Calor específico de los áridos gruesos.

Tabla 6. Calor específico de los áridos gruesos.

Material	C Media (kJ/kg·°C)	C Min (kJ/kg·°C)	C Max (kJ/kg·°C)
Ofita	0,831	0,772	0,889
Escoria 1	0,798	0,768	0,829
Escoria 2	0,757	0,726	0,788

El contenido de agua de los áridos es el otro aspecto que afecta a la energía necesaria para producir la mezcla asfáltica, ya que parte de la energía se empleará en el secado de los áridos. Este contenido de agua depende de la humedad ambiental, de si el árido está protegido de la lluvia y de su porosidad. Además, las diferentes geometrías de los poros también podrían afectar al proceso de secado, ya que cuanto mayor es la superficie específica, mayor es la transferencia de calor. Estos aspectos se analizaron en el laboratorio mediante el desarrollo de un ensayo que evaluó el proceso de secado de una muestra saturada de árido. Para ello, se saturó una muestra sumergiéndola en agua durante 24 horas y posteriormente se colocó en un tamiz para drenar el exceso de agua, pero sin secar la superficie, simulando así el peor escenario. El árido se introdujo entonces en un horno calentado a 60 ºC y se midió el contenido de agua cada 5 minutos. La evolución de la humedad a lo largo del tiempo puede verse en la Figura 5.

Estos resultados concuerdan con la absorción de los áridos mostrados en la Tabla 5: la escoria 2, al tener un valor de absorción más alto, requiere más tiempo de secado que la escoria 1 y la ofita (que tienen una absorción muy similar). Sin embargo, como la velocidad de secado es similar para todos los áridos (0,07 %/min, 0,08 %/min y 0,10 %/min para la ofita, la escoria 1 y la escoria 2, respectivamente) se puede afirmar que, al menos en este caso, el tiempo de secado solo depende de la cantidad de agua retenida en el árido. Por esta razón, se han tenido en cuenta tres contenidos de humedad para evaluar su influencia en el consumo de energía de la planta asfáltica: el máximo calculado en el ensayo, el 50 % de la humedad máxima calculada y un 1 % en todos los materiales.

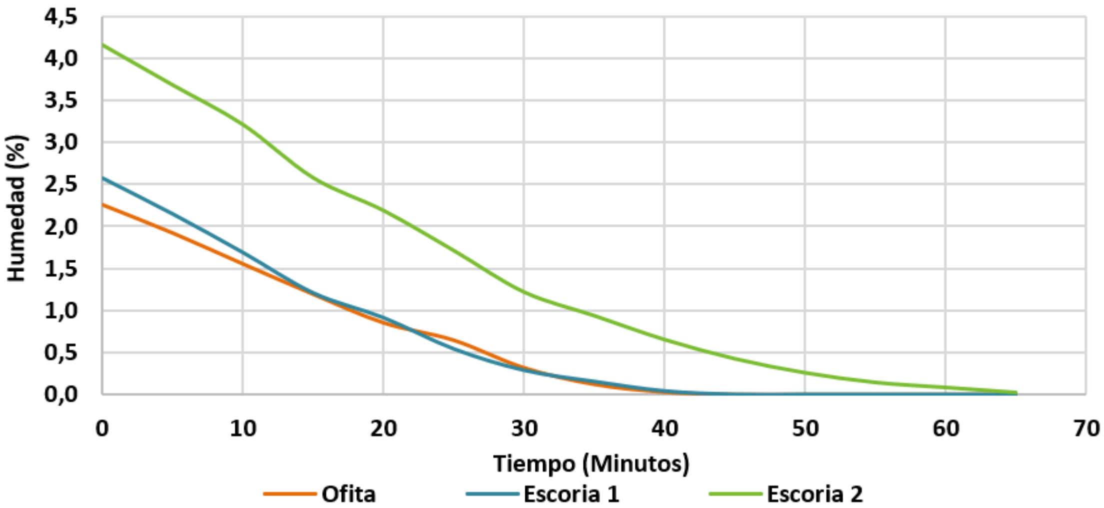


Figura 5. Pérdida de humedad de los áridos con el tiempo.

La energía consumida en la planta asfáltica se calculó en base al estudio termodinámico de un tambor secador desarrollado por Peinado et al. [83]. Sin embargo, el modelo fue adaptado para poder evaluar distintos tipos de áridos y para simular una planta alimentada con gas natural en vez del fuelóleo pesado utilizado en el modelo original. Además de esta energía consumida en el tambor secador (que según Stotko representa el 85 % del consumo total de la planta [84]), se añadieron al modelo otras fuentes de consumo energético como los calentadores de betún o el motor del tambor secador, entre otros, que implican el consumo de un 12 % de electricidad y un 3 % de diésel. Los parámetros necesarios para alimentar el modelo pueden verse en la Tabla 7 y los resultados en la Tabla 8. Como la humedad del árido afecta a los resultados al menos 3 veces más que la variación del calor específico y la evaluación de todas las opciones daría lugar a un gran número de alternativas, las fases posteriores del análisis se realizaron considerando solo el calor específico medio de cada árido, pero varios porcentajes de humedad.

Tabla 7. Parámetros del estudio termodinámico de la planta asfáltica.

Parámetro	Valor
Fracción de filler en los sólidos de entrada (%)	8
Filler retenido con los sólidos (%)	1
Temperatura ambiente (ºC)	15
Temperatura del sólido a la salida (ºC)	170
Temperatura del filler en los gases de escape (ºC)	Temperatura del aire a la salida
Temperatura del aire a la salida (ºC)	0,8 *Temperatura del sólido a la salida [85]
Temperatura de referencia (ºC)	25
Humedad del sólido a la entrada (%)	Varias
Humedad del sólido a la salida (%)	0,5
Relación estequiométrica	2,25
Humedad relativa	0,0038
Pérdidas térmicas (%)	20 [86]

Tabla 8. Consumo energético de la planta asfáltica por tonelada de mezcla.

Energía	Mezcla de referencia			Mezcla con escoria 1			Mezcla con escoria 2		
	Media	**Min**	**Max**	**Media**	**Min**	**Max**	**Media**	**Min**	**Max**
Humedad máxima									
Gas natural (MJ/t)	239,55	231,92	247,05	246,36	242,05	250,81	277,57	273,2	281,95
Electricidad (MJ/t)	33,82	32,74	34,88	34,78	34,17	35,41	39,19	38,57	39,81
Diésel (MJ/t)	8,45	8,19	8,72	8,69	8,54	8,85	9,80	9,64	9,95
50 % de la humedad máxima									
Gas natural (MJ/t)	198,09	190,46	205,59	200,64	196,34	205,28	212,20	207,83	216,58
Electricidad (MJ/t)	27,97	26,89	29,03	28,33	27,72	28,95	29,96	29,34	30,58
Diésel (MJ/t)	6,99	6,72	7,26	7,08	6,93	7,24	7,49	7,34	7,64
1 % de humedad									
Gas natural (MJ/t)	193,32	185,69	200,83	191,71	187,40	196,16	183,37	178,99	187,74
Electricidad (MJ/t)	27,29	26,21	28,35	27,06	26,46	27,69	25,89	25,27	26,50
Diésel (MJ/t)	6,82	6,55	7,09	6,77	6,61	6,92	6,47	6,32	6,63

3.1.2. Etapa de construcción

Esta etapa incluye el transporte de la mezcla asfáltica desde la planta hasta la obra (la cual se asume que está situada a 30 km de distancia), así como la construcción de la carretera.

De acuerdo con la información recibida de un socio industrial, la pavimentación y compactación de 1 t de mezcla asfáltica convencional implica el consumo de 1,56 litros de diésel. Sin embargo, como la energía de compactación puede verse afectada por la incorporación de materiales alternativos, se realizaron ensayos de compactación en el laboratorio con la máquina giratoria a distintas mezclas asfáltica. Dado que la energía obtenida en este ensayo es un valor de carácter meramente comparativo que no se corresponde con la energía de compactación requerida en obra, el consumo de diésel de cada mezcla se calculó aplicando al dato de consumo disponible (los 1,56 litros) la misma relación detectada entre las energías de compactación (véase Figura 6 y Tabla 9). No obstante, cabe mencionar que al realizar el cálculo de esta manera se asumió también una variación del consumo energético en la pavimentación de la carretera y no solo de la compactación. Además, en las mezclas WMA (tanto con betún PMB como con CB), al no encontrarse diferencias con respecto a la HMA se le asumió un consumo de 1,56 l/t.

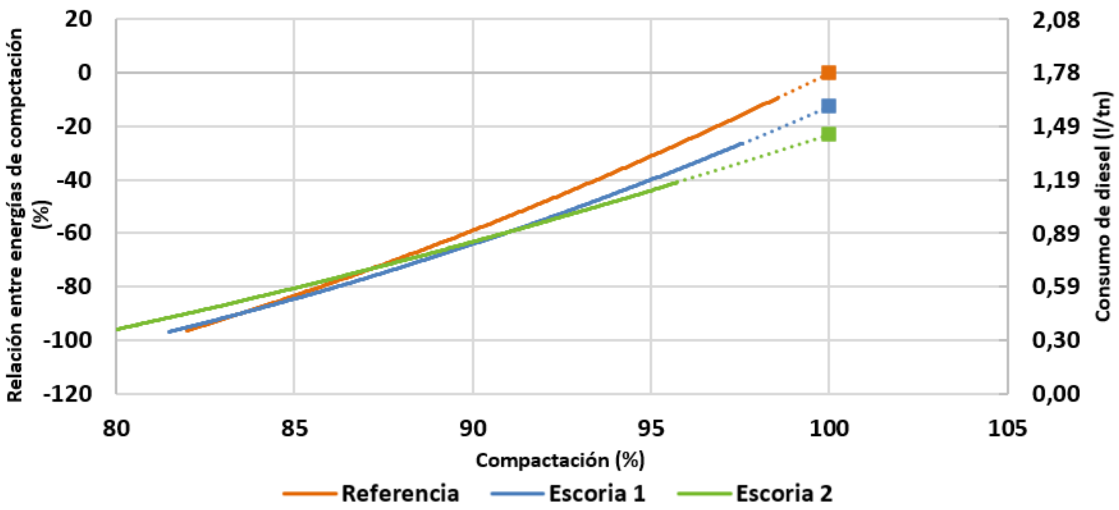


Figura 6. Energía de compactación y consumo de diésel durante la construcción.

Tabla 9. Consumo de diésel durante el extendido y compactación de 1 t de mezcla asfáltica.

Resultados	Referencia	Escoria 1	Escoria 2
Δ E. de compactación (test) (%)	0,0	-12,41	-23,00
Consumo de diésel en obra (l/t)	1,56	1,37	1,20

3.1.3. Etapa de uso

En el análisis solo se han considerado los módulos de lixiviación, mantenimiento y congestión debido a la falta de datos útiles para comparar aspectos como la regularidad superficial de la carretera y también a la variabilidad de los resultados de los modelos de resistencia a la rodadura existentes [46].

3.1.3.1. **Lixiviación**

Uno de los posibles peligros que pueden surgir de la sustitución de áridos naturales por escorias es el aumento de los elementos o compuestos químicos liberados al medio ambiente debido al contacto con el agua de lluvia. Sin embargo, cuando las escorias se utilizan como áridos dentro de mezclas asfálticas, este contacto se ve disminuido gracias al recubrimiento que proporciona el betún. Para tener en cuenta este efecto, se aplicó el ensayo definido en la norma EN 12457-4:2002 [87], empleada habitualmente para analizar el comportamiento ambiental de residuos granulares, no solo a las escorias sino también a las mezclas asfálticas sin compactar con el fin de analizar los lixiviados de este material de una manera más realista.

La Figura 7 muestra la relación entre el lixiviado generado por la escoria 1 cuando se analiza como material granular y cuando está embebida dentro de la mezcla asfáltica. En general, la cantidad de elementos químicos liberados en el medio ambiente disminuye debido al betún y solo los que están por debajo del límite de detección permanecen constantes. Sin embargo, 3 de las 18 sustancias analizadas aumentan: el carbono orgánico disuelto (COD), los nitratos (NO_3^-) y el cobre (Cu). Este aumento podría ser causado tanto por el árido calizo como por el betún presentes en la mezcla asfáltica. De hecho, los lixiviados de estos compuestos son mayores en la mezcla de referencia que en las que contienen EAFS (véase la Tabla 10).

Los valores de lixiviación utilizados en el ACV de cada una de las mezclas se muestran en la Tabla 10. Cabe señalar que el berilio (Be), cobalto (Co), cadmio (Cd) y mercurio (Hg) se consideraron nulos, ya que estaban por debajo del límite de detección en todas las muestras analizadas, a pesar de la gran precisión del equipo empleado para realizar los ensayos.

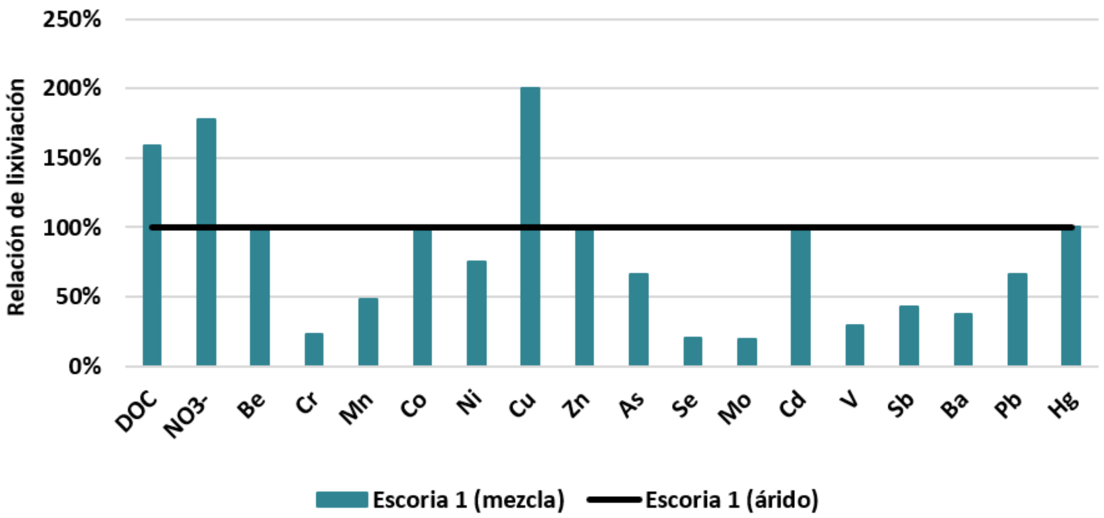


Figura 7. Efecto del betún en la lixiviación de mezclas asfálticas.

Tabla 10. Lixiviados por kg de mezcla asfáltica suelta.

Mezcla	COD	NO_3-	Cr	Mn	Ni	Cu	Zn	As	Se	Mo	V	Sb	Ba	Pb
Referencia	31,6	1,3	0,009	0,001	0,003	0,005	0,066	0,001	0,006	0,022	0,033	0,002	0,025	0,001
Escoria 1	25,1	0,6	0,01	0,002	0,002	0,002	0,001	0,001	0,002	0,018	1,246	0,001	0,218	0,001
Escoria 2	19,2	0,25	0,016	0,002	0,001	0,001	0,001	0,001	0,004	0,048	1,006	0,005	0,312	0,001

3.1.3.2. **Mantenimiento**

El mantenimiento de una carretera implica el fresado de la capa deteriorada (lo que según el socio industrial consume 0,41 l/t), el transporte del RAP al centro de recuperación (situado a 30 km de distancia) y la producción y construcción de una nueva capa asfáltica. Sin embargo, el programa de mantenimiento dependerá de las mezclas que conforman el firme.

En el caso de firmes convencionales, la experiencia indica que la durabilidad de la capa de rodadura puede variar entre los 10 y 15 años dependiendo de si se trata de una mezcla porosa o una densa [88–90]. Además, en el año 30 suele ser necesaria realizar una rehabilitación completa del firme en la que se retiran y se reponen las 3 capas asfálticas que lo componen (rodadura, intermedia y base). Sin embargo, para predecir el comportamiento de mezclas y firmes más novedosos es necesario hacer uso de programas de cálculo.

Para esta investigación se seleccionaron dos paquetes de software: Alize y 3D-Move. Alize es un software desarrollado por las organizaciones francesas LCPC y SETRA, que calcula la respuesta de un firme frente a las cargas de los camiones considerando un comportamiento isotrópico elástico lineal [29]. En cambio, 3D-Move utiliza un enfoque de capas finitas que tiene en cuenta un comportamiento viscoelástico de las mezclas [30]. En ambos casos, se seleccionó el mismo eje simple de doble rueda para cargar el firme: 900 kPa de presión, 32 KN de carga, 0,106 m de radio y 0,3192 m de distancia entre los centros de las ruedas.

3.1.3.3. **Congestión**

Formular recomendaciones implica el análisis de una amplia variedad de situaciones a partir de las cuales extraer conclusiones. Por ello, para evaluar la relevancia del impacto ambiental producido por la congestión se deberían considerar aspectos como la Intensidad Media Diaria (IMD), la existencia de rutas alternativas, la geometría de la carretera o las características del tráfico (porcentaje de vehículos pesados y distribución horaria). Sin embargo, como analizar el efecto de todas estas variables daría lugar a un número inmanejable de casos de estudio, en esta investigación se introdujo el concepto de Nivel de Servicio (NS) en su lugar, que es un parámetro que determina la calidad del flujo de tráfico en función de los aspectos mencionados. Según el Manual de Capacidad de Carreteras [91], existen 6 NS designados con letras de la A a la F, donde la A representa la circulación a flujo libre (sin que los usuarios estén afectados por la presencia de otros vehículos) y la F representa una carretera totalmente congestionada.

Para el análisis se seleccionó un tramo situado entre los Puntos Kilométricos (PK) 175 y 176 de la autopista A-8, que con una IMD de 41.026 vehículos conecta las principales ciudades de la costa norte de España (véase Figura 8). Este tramo cuenta con una ruta alternativa, la carretera nacional N-634, que tiene una IMD de 12.151 vehículos. De esta manera, cuando se crea congestión en la autopista debido al cierre de un carril, un cierto porcentaje de vehículos puede desviarse hacia la carretera nacional. En consecuencia, la congestión y el consiguiente impacto ambiental producido no solo dependerán de la calidad del flujo de la carretera que se está reparando (A-8), sino también del NS de la ruta alternativa (N-634). Por esta razón, se definieron 6 escenarios combinando los NS de ambas carreteras (Tabla 11). Además, para poder captar el efecto del cierre de 1km de carril en el conjunto de la red se simularon más de 15 km de cada una de las carreteras.

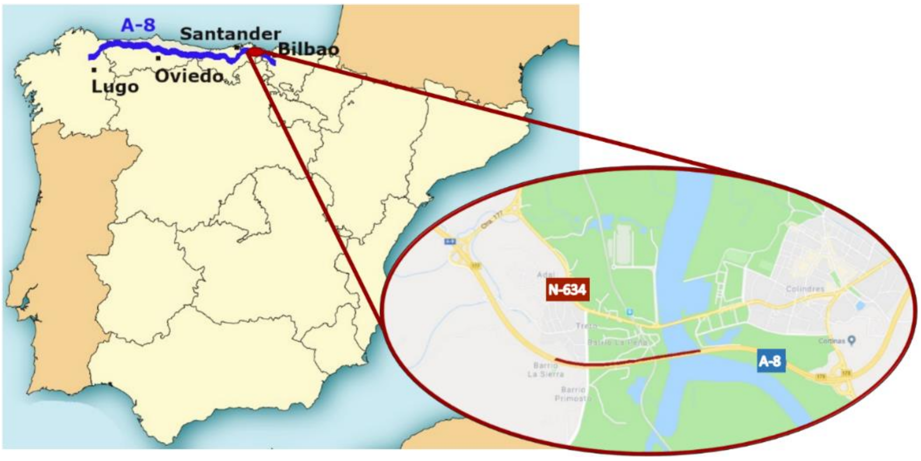


Figura 8. Sección de estudio para el análisis de la congestión.

Tabla 11. Escenarios de tráfico analizados.

Escenario	A-8 NS	N-634 NS	A-8 IMD (vehículos/día)	N-634 IMD (vehículos/día)
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

Para calcular la IMD de cada carretera para cada escenario definido en la Tabla 11 se siguió el procedimiento establecido en el Manual de Capacidad de Carreteras [91]. Este manual establece la intensidad de servicio en condiciones ideales de distintos tipos de carretera. Es decir, define el máximo número de vehículos que pueden atravesar una sección por unidad de tiempo sin sobrepasar un NS dado cuando el ancho de carril es 3,6 m, solo circulan vehículos ligeros, el terreno es llano y los conductores son habituales. Sin embargo, como las carreteras seleccionadas no cumplen con estas circunstancias, se adaptó la intensidad de servicio para reflejar la realidad del caso de estudio utilizando las características de las carreteras proporcionadas por el Ministerio de Fomento [92] (véase Tabla 12, Figura 9 y Figura 10). Cabe destacar que se asumieron los valores de factor de hora punta, tipo de terreno, factor de ajuste por tipo de conductor y la distribución direccional. Como se ve en la Figura 9, la IMD de una autopista para un NS determinado depende de la densidad de la carretera y de su velocidad libre (VL). Por su parte, en la carretera N-634 (una carretera rural tipo 3 que discurre a través de pequeños pueblos turísticos), la IMD depende del porcentaje de velocidad libre. Al no existir un único valor de IMD que dé lugar a cada NS, sino que es posible elegir dentro de un rango, se tomó como IMD representativa el valor medio de cada rango.

Tabla 12. Características de las carreteras.

Características	A-8	N-634
Velocidad libre (km/h)	120	72
Velocidad media (km/h)	104	63
Vehículos pesados (%)	9,75	2,66
Vehículos de recreo (%)	0	0
Factor de hora punta	0,95	0,88
Tipo de terreno	Llano	Llano
Factor de ajuste por tipo de conductor	1	1
Porcentaje de vehículos en la hora punta (k)	7,02	7,02
Distribución direccional (R)	0,5	0,5

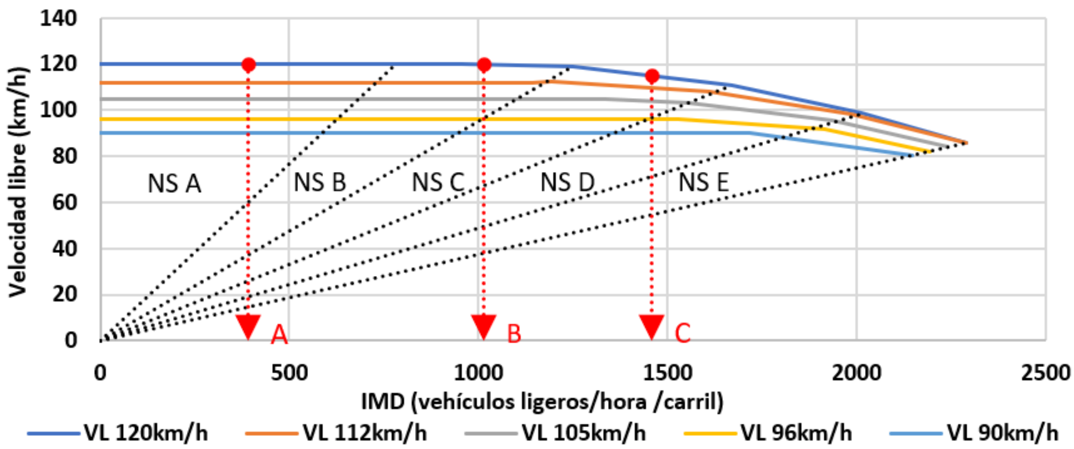


Figura 9.IMD de los NS de la carretera A-8 en condiciones reales.

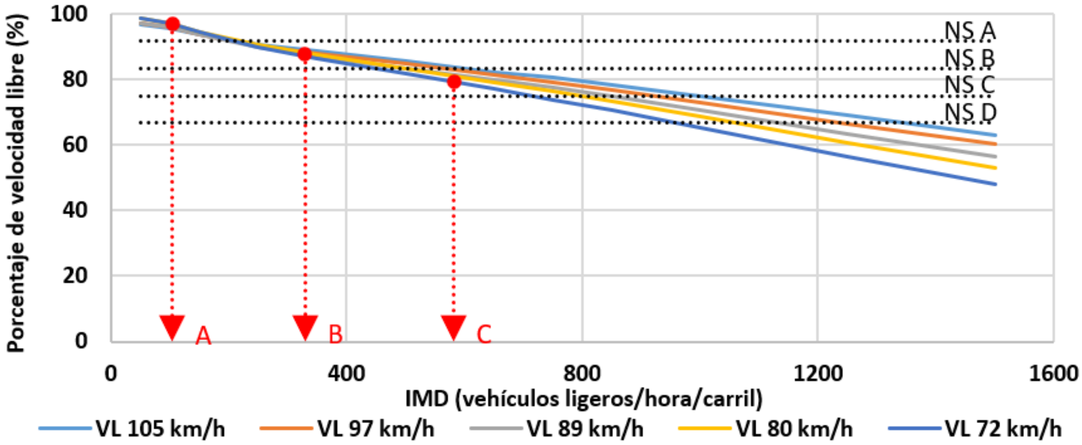


Figura 10. IMD de los NS de la carretera N-634 en condiciones reales.

Modelización del tráfico

Para calcular la congestión ocasionada durante las acciones de mantenimiento se utilizaron 2 programas de simulación de tráfico que aplican 2 enfoques diferentes: macro y micro simulación.

Para la macro simulación se seleccionó el "Kentucky Highway User Cost Program v1.0" (KyUCP). Este software, programado en Excel siguiendo el Manual de Capacidad de Carreteras, permite calcular la longitud de la cola de una obra lineal basándose en la IMD de la carretera, los límites de velocidad en condiciones normales y durante las obras y el número de carriles cerrados por mantenimiento. Sin embargo, el programa fue modificado ya que no contemplaba la posibilidad de tener una ruta alternativa que pudiera absorber parte de la demanda cuando se crearan colas. En concreto, se consideró que un 30 % de la demanda se desviaría a la ruta alternativa cuando se detectasen colas de más de 1 km [93–96].

Por otro lado, Aimsun Next v8.3.0 fue empleado para la micro simulación. En este caso, fue preciso crear y calibrar la red de carreteras utilizando las relaciones de velocidad-ocupación y velocidad-flujo de la sección estudiada para reflejar el comportamiento real del usuario en cuanto a las decisiones de seguimiento de los vehículos, uso de carriles y cambio de carril. Para ello, se utilizaron los datos de las estaciones de aforo del Ministerio de Fomento y del Grupo de Investigación de Sistemas de Transporte de la Universidad de Cantabria. A continuación, se modificó la matriz origen-destino para ajustar la IMD de las carreteras a la previamente definida para cada escenario. Sin embargo, este cambio en el número de vehículos podría cambiar el tiempo de viaje asociado a las diferentes rutas disponibles, afectando con ello al camino seleccionado por cada vehículo y, en consecuencia, a los resultados. Para evitar esto, se forzó a que los vehículos siguieran siempre las trayectorias originales sin importar el escenario analizado y nuevamente, durante la etapa de mantenimiento y para colas superiores a 1 km, se desvió el 30 % de los vehículos a la carretera nacional.

El plan de corte empleado durante los trabajos de mantenimiento se definió siguiendo la Norma Española 8.3-IC de señalización de obras viales [97]. Como se muestra en la Figura 11, al cerrar un carril de la carretera el ancho del carril adyacente se reduce 0,30 m para crear una zona de seguridad, reduciendo la velocidad de 120 km/h a 80 km/h de forma gradual.

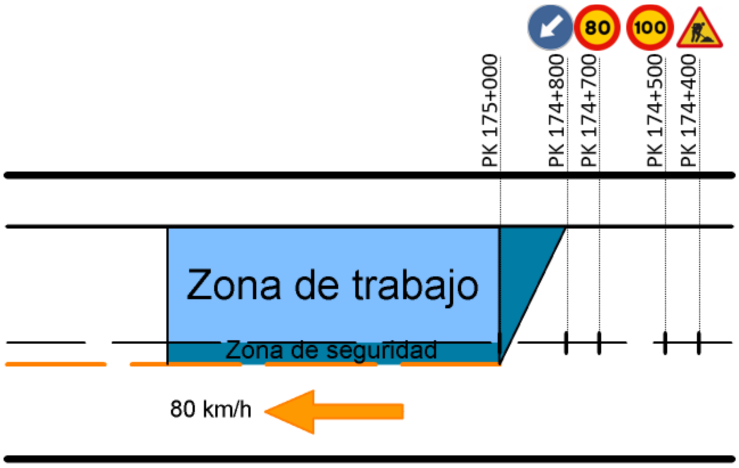


Figura 11. Plan de corte durante las actividades de mantenimiento.

Cálculo de emisiones

Para la evaluación del impacto ambiental, dado que KyUCP no incluye un modelo de emisiones, se utilizó el programa “Motor Vehicle Emission Simulator” (MOVES). Este modelo, desarrollado por la EPA, tiene un gran número de contaminantes disponible y una amplia aceptación por parte de la comunidad científica. En el caso de Aimsun, el programa ya incorpora el modelo de emisiones desarrollado por Panis et al. [98] que permite calcular de forma automática las emisiones producidas por el tráfico simulado. En concreto, el modelo proporciona las emisiones de 4 contaminantes (Dióxido de Carbono, CO_2; Óxidos de Nitrógeno, NOx; Compuestos Orgánicos Volátiles, VOC; Partículas en suspensión, PM) basándose en la velocidad y aceleración instantánea de cada vehículo y distinguiendo entre diferentes tipos de vehículos y combustibles. Sin embargo, debido al número limitado de contaminantes que aborda el modelo de Panis, se propuso la utilización de MOVES en ambos casos.

Para definir los contaminantes más relevantes a incluir en el análisis, se calcularon con el programa MOVES las emisiones producidas por 100 vehículos que circulan a la velocidad que produce las máximas emisiones (8 km/h) por un carril de 1 km, considerando la edad y el tipo combustible consumido por el parque de vehículos actual de la región. A continuación, se realizó un ACV básico con las emisiones obtenidas anteriormente, lo que permitió detectar la importancia de cada una de ellas en cada categoría de impacto contemplada en la metodología ReCiPe. Las emisiones evaluadas fueron CO_2, CO, NOx, CH_4, C_6H_6, NH_3, VOC y $PM_{2,5}$ y los resultados mostraron que las emisiones de VOC y CH_4 podrían ser omitidas del ACV sin perder por ello la precisión del análisis (véase Tabla 13).

Tabla 13. Contribución de los contaminantes a las distintas categorías de impacto del ACV.

Impacto / Contaminante	CO_2	CO	NOx	CH_4	C_6H_6	NH_3	VOC	$PM_{2,5}$
Cambio climático	100%	-	-	-	-	-	-	-
Ecotoxicidad del agua dulce	-	-	-	-	100%	-	-	-
Toxicidad humana	-	-	-	-	100%	-	-	-
Toxicidad marina	-	-	-	-	100%	-	-	-
Eutrofización marina	-	-	38%	-	-	5%	-	-
Formación de partículas	-	-	76%	-	-	6%	-	12%
Formación de oxidantes fotoquímicos	-	33%	61%	-	-	-	-	-
Acidificación terrestre	-	-	76%	-	-	18%	-	-
Ecotoxicidad terrestre	-	-	-	-	100%	-	-	-

En lo que respecta a MOVES, entre las opciones de cálculo que ofrece está la de utilizar las trayectorias individuales de los vehículos obtenidas de programas de micro simulación. Por lo tanto, realizar la simulación con Aimsun e introducir los registros de las trayectorias en MOVES para poder comparar los resultados de la micro y la macro simulación era una opción. Sin embargo, debido al elevado número de datos registrados en los escenarios evaluados (más de 15 millones) y la dificultad de manejarlos, esta opción fue descartada y se optó por integrar el modelo de emisiones MOVES en Aimsun. Para ello, se recalibró el modelo de Panis [98] (integrado en Aimsun) para que se ajustara al modelo de emisiones de MOVES. Cabe señalar que las tasas de emisiones de MOVES están vinculadas a 23 modos de operación para vehículos en funcionamiento, que se calculan combinando la velocidad de los vehículos y la potencia específica vehicular (VSP), pero además incluye otros modos de operación para el ralentí, el frenado y el calentamiento, entre otros. La VSP, que puede calcularse con la eq. 1 de Jiménez-Palacios [99], da una indicación de la cantidad de energía demandada por el motor durante su funcionamiento y combina múltiples factores físicos que influyen en el consumo y las emisiones del vehículo, tales como la velocidad $v_n(t)$, la aceleración $a_n(t)$ o los parámetros de carga [100].

Teniendo esto en cuenta, se realizaron nuevas simulaciones de tráfico en Aimsun (100 vehículos en un carril de 1 km) introduciendo varios ciclos semafóricos, lo que dio lugar a diferentes patrones de aceleración y desaceleración de los vehículos. En total, se registraron más de 30.000 trayectorias en la base de datos de Aimsun. Con las velocidades y aceleraciones instantáneas de las 30.000 trayectorias y con su VSP (determinada a través de la eq. 1), fue posible distribuir cada trayectoria en los modos de operación propuestos por MOVES y por lo tanto calcular las emisiones relacionadas con cada una de ellas.

A continuación, se calibró la función de Panis (eq. 2) con los datos de las velocidades de las trayectorias $v_n(t)$, las aceleraciones $a_n(t)$ y las emisiones mediante un modelo de regresión múltiple llevado a cabo con el programa de estadística Minitab 17, con el que se extrajo las constantes E0 y f1 a f6. Esta metodología se aplicó a dos tipos de vehículos (vehículos de pasajeros y camiones tráiler) y a los seis contaminantes mencionados anteriormente. Los resultados se presentan en la Tabla 14.

$$\text{VSP} = v_n \times [1{,}1 a_n + 9{,}81 pendiente\ (\%) + 0{,}132] + 0{,}000302 {v_n}^3 \quad (1)$$

$$Emisión\ (t) = max\ [E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)] \quad (2)$$

Para obtener una mejor correlación, la función de emisiones de ciertos contaminantes se ajustó dos veces, para las trayectorias de aceleración ($a_n(t) \geq -0{,}5$ m/s^2) y para las trayectorias de desaceleración ($a_n(t) < -0{,}5$ m/s2), lo que dio como resultado diferentes valores para E0 y f1 a f6 (véase la Tabla 14). Como la necesidad de dividir el modelo en dos funciones ya fue observada en Int Panis et al. [98], el modelo de emisión disponible en Aimsun ya contempla la posibilidad de insertar diferentes factores para $a_n(t) \geq -0{,}5$ m/s^2 y $a_n(t) < -0{,}5$ m/s^2. En la Figura 12 se muestra la correspondencia entre las emisiones de CO_2 calculadas distribuyendo las trayectorias en modos de operación (MOVES) y mediante el uso de la Función Panis "recalibrada".

Tabla 14. Factores recalibrados de la función de Panis.

Contam,	Tipo de vehículo	E_0	f_1	f_2	f_3	f_4	f_5	f_6
CO_2	Coche	8,70E-01	8,44E-01	8,82E-02	2,72E-03	2,23E+00	-8,13E-01	2,29E-01
	Camión	2,53E+00	2,24E+00	9,61E-01	6,93E-03	1,04E+00	-2,58E+00	2,99E+00
CO	Coche a $\geq -0{,}5\ m/s^2$	0,00E+00	1,39E-02	3,56E-04	1,50E-05	-5,66E-02	-2,44E-03	1,74E-02
	Coches 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
	Camión	-2,58E-02	1,51E-02	6,46E-03	-9,01E-05	-1,58E-02	-6,03E-03	1,45E-02
NOx	Coche a $\geq -0{,}5\ m/s^2$	9,00E-04	-6,87E-04	2,15E-04	5,00E-06	4,78E-03	-1,72E-03	6,56E-04
	Coche 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
	Camión a $\geq -0{,}5\ m/s^2$	0,00E+00	4,21E-02	1,85E-03	3,05E-04	1,79E-02	-4,03E-02	2,29E-02
	Camión 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	Coche	1,78E-05	1,58E-05	1,88E-07	2,50E-08	2,29E-06	-6,93E-06	5,60E-06
	Camión a $\geq -0{,}5\ m/s^2$	0,00E+00	1,88E-05	1,79E-05	-5,50E-07	1,08E-04	5,57E-05	4,90E-06
	Camión 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	Coche a $\geq -0{,}5\ m/s^2$	0,00E+00	6,16E-05	-3,70E-06	4,75E-07	4,39E-05	-3,49E-05	1,07E-05
	Coche 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
	Camión a $\geq -0{,}5\ m/s^2$	0,00E+00	1,14E-04	-1,68E-06	4,80E-07	1,06E-05	4,66E-06	-3,90E-07
	Camión 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
$PM_{2,5}$	Coche a $\geq -0{,}5\ m/s^2$	3,65E-05	3,23E-05	2,79E-06	7,51E-08	-1,48E-03	3,71E-04	1,74E-04
	Coche 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
	Camión a $\geq -0{,}5\ m/s^2$	0,00E+00	1,28E-03	3,25E-04	-1,53E-06	-6,95E-04	2,04E-04	1,05E-03
	Camión 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

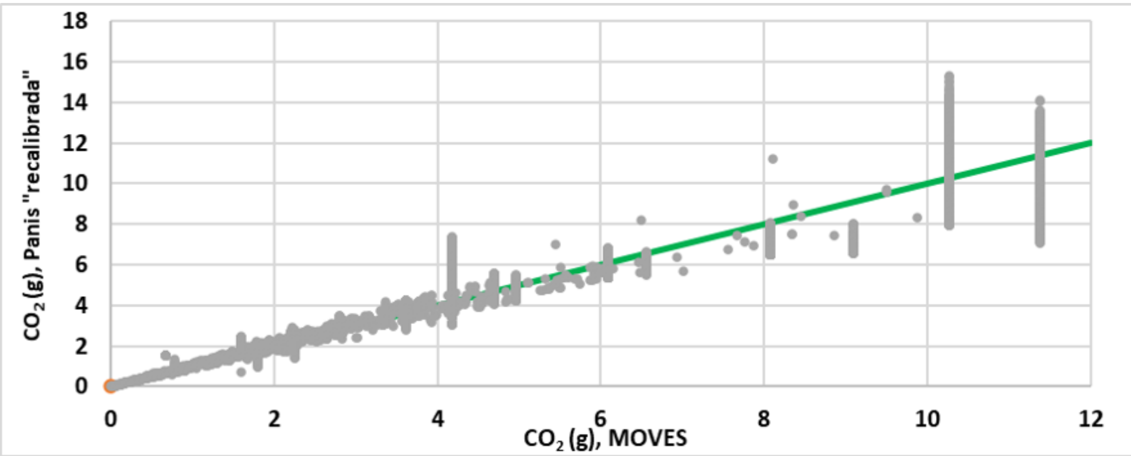


Figura 12. Correspondencia entre las emisiones de CO_2 calculadas con las tasas de emisión de MOVES (eje horizontal) y la Función de Panis "recalibrada" (eje vertical).

3.1.4. Etapa de fin de vida

Esta etapa incluye el fresado del asfalto y el transporte del RAP al centro de recuperación. Sin embargo, el procesamiento del RAP no ha sido contemplado aquí, ya que la National Asphalt Pavement Association [101] recomienda incluir el impacto de la trituración y cribado del RAP en la etapa de suministro de material. Por lo tanto, este análisis termina con la llegada del RAP al centro de recuperación.

3.2. Evaluación del impacto del ciclo de vida

Una vez completado el inventario, los recursos consumidos y las emisiones detectadas fueron transformadas en impactos mediante la aplicación del modelo de caracterización ReCiPe (H), el cual calcula los impactos a dos niveles: punto medio y punto final (véase Tabla 15). La diferencia entre los dos niveles es que mientras que los indicadores de punto medio se centran en problemas ambientales específicos, los de punto final evalúan el impacto ambiental en las áreas de protección (salud humana, calidad del ecosistema y escasez de recursos). Sin embargo, los 2 enfoques son complementarios ya que los factores de punto medio están más relacionados con los flujos elementales (lo que implica una menor incertidumbre) y los de punto final proporcionan una mayor información sobre la relevancia ambiental de los flujos (con mayor incertidumbre) [102].

Tabla 15. Categorías de impacto del modelo de caracterización ReCiPe 2016.

Categorías de impacto		Indicador	UNIDADES
		ReCiPe 2016 Punto medio (H)	
LOP	Uso del suelo	Ocupación y transformación en el tiempo	m^2×yr eq.
GWP	Cambio climático	Aumento de la radiación infrarroja	kg CO_2 eq.
FD	Agotamiento de recursos fósiles	Poder calorífico	kg oil eq.
FETP	Ecotoxicidad de agua dulce	Efecto de sustancias tóxicas en agua dulce	kg 1,4 DCB eq.
FEP	Eutrofización de agua dulce	Aumento del fósforo en agua dulce	kg P eq.
HT_C	Toxicidad humana: cancerígena	Aumento del riesgo de padecer cáncer	kg 1,4-DCB eq.
HTn_C	Toxicidad humana: no cancerígena	Aumento del riesgo de padecer enfermedades	kg 1,4-DCB eq.
IRP	Radiación ionizante	Aumento de la cantidad absorbida	kBq Co-60
METP	Ecotoxicidad marina	Efecto de sustancias tóxicas en agua marina	kg 1,4-DCB eq.
ME	Eutrofización marina	Aumento del nitrógeno disuelto	kg N eq.
ODP	Agotamiento de la capa de ozono	Disminución del ozono estratosférico	kg CFC-11 eq.
FMFP	Formación de partículas finas	Aumento de la aspiración de PM 2,5	kg $PM_{2,5}$ eq.
EOFP	Formación de oxidantes fotoquímicos: ecosistema	Aumento del ozono troposférico (AOT40)	kg NOx eq.
HOFP	Formación de oxidantes fotoquímicos: salud humana	Aumento de la aspiración de ozono troposférico (M6M)	kg NOx eq.
TAP	Acidificación terrestre	Aumento de protones en suelos naturales	kg SO_2 eq.
TETP	Ecotoxicidad terrestre	Efecto de sustancias tóxicas en suelos	kg 1,4-DCB eq.
WCP	Consumo de agua	Aumento del consumo de agua	m^3
SOP	Escasez de recursos minerales	Disminución de minerales disponibles	kg Cu eq.
		ReCiPe 2016 Punto final (H)	
HH	Daño a la salud humana	Años de vida perdidos por enfermedad	DALY
ED	Daño a la diversidad de los ecosistemas	Pérdida de especies en 1 año	Especies*año
RA	Daño a la disponibilidad de recursos	Aumento de costes por la extracción de recursos	$

Sin embargo, cuando se realiza un ACV los resultados pueden variar dependiendo del modelo de caracterización utilizado. Por eso, en esta tesis doctoral se ha comprobado la consistencia de los resultados realizando un análisis de sensibilidad en el que se ha aplicado otro modelo de caracterización, en concreto el modelo CML 2001 en su actualización de enero de 2016 (véase Tabla 16). Ambos modelos (ReCiPe y CML) fueron desarrollados por la Universidad de Leiden, pero calculan los factores de caracterización aplicando hipótesis diferentes. Un ejemplo de ello son las unidades con las que ambos modelos miden cada categoría de impacto o que mientras que ReCiPe asume para los cálculos el promedio meteorológico europeo, CML considera que siempre brilla el sol [103].

Tabla 16. Categorías de impacto del modelo de caracterización CML 2001.

	Categorías de impacto	**UNIDADES**
ADP elements	Agotamiento de Recursos abióticos (elementos)	kg Sb eq.
ADP fossil	Agotamiento de Recursos abióticos (energía)	MJ
AP	Potencial de acidificación	kg SO_2 eq.
EP	Potencial de eutrofización	kg Phosphate eq.
FAETP	Potencial de ecotoxicidad de agua dulce	kg DCB eq.
GWP	Potencial de calentamiento global	kg CO_2 eq.
HTP	Potencial de toxicidad humana	kg DCB eq.
MAETP	Potencial de ecotoxicidad de agua marina	kg DCB eq.
ODP	Potencial de agotamiento de la capa de ozono	kg R11 eq.
POCP	Potencial de creación de ozono fotoquímico	kg Ethene eq.
TETP	Potencial de Ecotoxicidad terrestre	kg DCB eq.

Cuando se aplica el modelo CML, la única forma de reducir el número de impactos para facilitar la interpretación de los resultados y la toma de decisiones es la aplicación de 2 pasos adicionales (normalización y ponderación), los cuales no tienen una base científica y son desaconsejados por la ISO 14044 [59] en aseveraciones comparativas destinadas a ser divulgadas al público. La normalización permite transformar todas las categorías de impacto a una unidad común dividiendo los resultados calculados por los valores de una situación de referencia como, por ejemplo, los impacto producidos por los 28 estados miembros de la Unión Europea en el año 2000. La ponderación, por su parte, permite considerar la relevancia de cada impacto, ya que no todos los países se enfrentan a los mismos problemas ambientales y no todos los impactos producen el mismo efecto en los seres vivos. En este caso, como el método CML 2001 no propone ningún factor de ponderación, se calculó un promedio de los diferentes valores propuestos por la EPA, BEES, NOGEPA y BREE [104,105] (véase Tabla 17).

Tabla 17. Factores de ponderación de impactos.

Categorías de impacto	Factores de ponderación
Agotamiento de Recursos abióticos (elementos)	8,0
Agotamiento de Recursos abióticos (energía)	7,7
Potencial de acidificación	6,3
Potencial de eutrofización	8,7
Potencial de ecotoxicidad de agua dulce	4,2
Potencial de calentamiento global	27,8
Potencial de toxicidad humana	14,5
Potencial de ecotoxicidad de agua marina	4,8
Potencial de agotamiento de la capa de ozono	7,4
Potencial de creación de ozono fotoquímico	6,6
Potencial de Ecotoxicidad terrestre	4,0

4. RESULTADOS Y DISCUSIÓN

4.1. Análisis exhaustivo del impacto ambiental producido por el uso de escorias procedente de hornos de arco eléctrico en mezclas asfálticas

El objetivo de esta parte de la investigación es evaluar el impacto ambiental producido por la sustitución de ofita (una diabasa cuyo piroxeno ha sido alterado que se emplea comúnmente en el norte de España como árido grueso de alta calidad) por EAFS. Como el proceso de producción y el postratamiento influyen directamente en las propiedades finales de las EAFS, se seleccionaron 2 con propiedades muy diferentes (véase Tabla 5). Además, se empleó un árido convencional (caliza) en la fracción filler de las mezclas.

En primer lugar, se diseñaron 3 mezclas asfálticas densas (ref, escoria 1 y escoria 2) de acuerdo al método de diseño Marshal, utilizando un betún convencional con penetración 50/70. La granulometría de las 3 mezclas se determinó siguiendo los límites establecidos por la normativa española de diseño de firmes [106]. Sin embargo, debido al mayor peso específico de las escorias, la granulometría se definió en volumen en vez de en peso. Como se ve en la Figura 13, el elevado peso específico de las escorias dio lugar a mezclas asfálticas con una mayor densidad. Además, la incorporación de escorias mejoró la estabilidad de la mezcla de referencia alcanzando valores de deformación similares o incluso inferiores. A partir de estos resultados y para el análisis posterior, se seleccionaron mezclas con 5,8 % de huecos, asegurando de esta forma la comparación de mezclas con una estructura interna similar.

El porcentaje de betún utilizado en las mezclas está muy influenciado por el peso específico de las escorias y por su absorción. En el caso de la escoria 1, con una absorción similar a la de la ofita, el porcentaje de betún en peso es menor que el de la mezcla de referencia debido a su elevado peso específico. Sin embargo, la escoria 2, que también tiene un peso específico elevado, necesita un porcentaje de betún más cercano al de la mezcla de referencia debido a su mayor absorción. Para eliminar el efecto del peso específico del material, la dosificación también se muestra en volumen (véase la Tabla 18). Comparando los porcentajes de betún en volumen, la mezcla con escoria 1 necesita prácticamente la misma cantidad de betún que la mezcla de referencia para el mismo volumen de mezcla asfáltica, mientras que la escoria 2 requiere un 32 % más para conseguir una envoltura homogénea de todos los áridos.

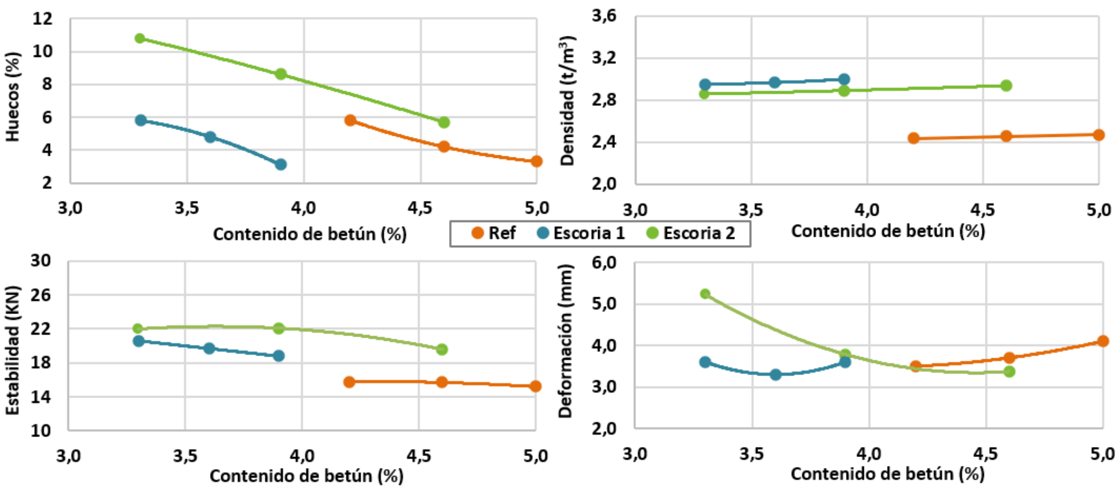


Figura 13. Diseño de las mezclas asfálticas empleadas en el estudio del impacto ambiental de las EAFS.

Tabla 18. Características de las mezclas asfálticas empleadas en el estudio del impacto ambiental de las EAFS.

Detalles	%w/w			%v/v		
	Ref	**Escoria 1**	**Escoria 2**	**Ref**	**Escoria 1**	**Escoria 2**
Ofita	61,60	-	-	56,38	-	-
Caliza	34,20	29,40	29,19	33,69	33,87	33,89
Escoria	-	67,30	66,21	-	56,68	53,00
Betún	4,20	3,30	4,60	9,93	9,45	13,11
Densidad (t/m3)	2,43	2,95	2,94	2,43	2,95	2,94
Huecos (%)	-	-	-	5,80	5,80	5,70

El ACV de las 3 mezclas se realizó teniendo en cuenta 4 procedimientos de asignación (véase Figura 2) y considerando distintas distancias de transporte para la ofita. Además, se consideró que los áridos tenían el máximo contenido de humedad posible (2,26 %, 2,57 % y 4,16 % la ofita, escoria 1 y escoria 2, respectivamente) (véase Figura 5).

Como unidad funcional se seleccionó la capa de rodadura de un carril de 1 km de longitud, 3,75 m de anchura y 0,04 de espesor, considerando un periodo de análisis de 30 años y una durabilidad de 15 años para todas las mezclas [89,107]. En cuanto a los límites del sistema, se tuvieron en cuenta las etapas de producción, construcción, uso (mantenimiento y lixiviación) y fin de vida del material. Sin embargo, dado que se trata de una carretera simulada y que todas las mezclas se someterían a las mismas actividades de mantenimiento, no se evaluó la congestión a pesar de ser una etapa muy importante del ciclo de vida de una carretera.

Los resultados de comparar los impactos de punto final de las mezclas con escoria con los de la mezcla de referencia calculados con el modelo de caracterización ReCiPe (H) se muestran en la Figura 14. El eje “x” representa la distancia de transporte de la ofita, mientras que el eje “y” representa el aumento o la disminución del impacto ambiental de las mezclas con escoria respecto a la mezcla de referencia.

Los resultados muestran que las alternativas 2 y 4 producen valores muy similares de los impactos HH y ED. De hecho, para la misma distancia de transporte de la ofita, la alternativa 2 produce solo un 1,3 % más de impacto ambiental que la alternativa 4. La alternativa 1, al asumir parte de las cargas ambientales asociadas al proceso de fabricación del acero, produce un 13,0 % más de impacto ambiental que la alternativa 2. Sin embargo, como la alternativa 3 se beneficia del crédito recibido por el impacto evitado sin tener en cuenta la conservación de la masa, logra un 7,8 % menos de impacto. No obstante, estas relaciones no se mantienen en el impacto de RA, el cual se ve claramente afectado por la consideración o no del impacto evitado y de la conservación de la masa. Esto hace que la alternativa 4 sea el procedimiento de asignación más perjudicado y la alternativa 3 el más beneficiado, dejando las alternativas 1 y 2 con resultados muy similares. Por lo tanto, parece que la alternativa 2 siempre se mantiene en una posición intermedia entre los otros métodos. Además, esta alternativa tiene la ventaja de cumplir directamente con la conservación de la masa y de no requerir un debate sobre los posibles futuros usos de los subproductos o sobre qué producto debería recibir el crédito. Por consiguiente, se seleccionó la alternativa 2 para el resto del estudio.

Cuando se comparan las dos escorias se observa el mejor comportamiento de la escoria 1 debido a la mayor absorción de la escoria 2, lo cual aumenta la cantidad de betún de la mezcla, así como el contenido de agua de los áridos. De hecho, mientras que la escoria 1 podría sustituir ofita situada a 177 km de distancia consiguiendo mejoras en los impactos HH y ED, la escoria 2 podría sustituir áridos situados a más de 296 km de distancia. En cuanto al impacto RA, los resultados no varían demasiado al modificar la distancia de transporte de la ofita. De hecho, la escoria 1 siempre resulta ser una buena alternativa a la ofita mientras que la escoria 2 siempre produce un mayor impacto.

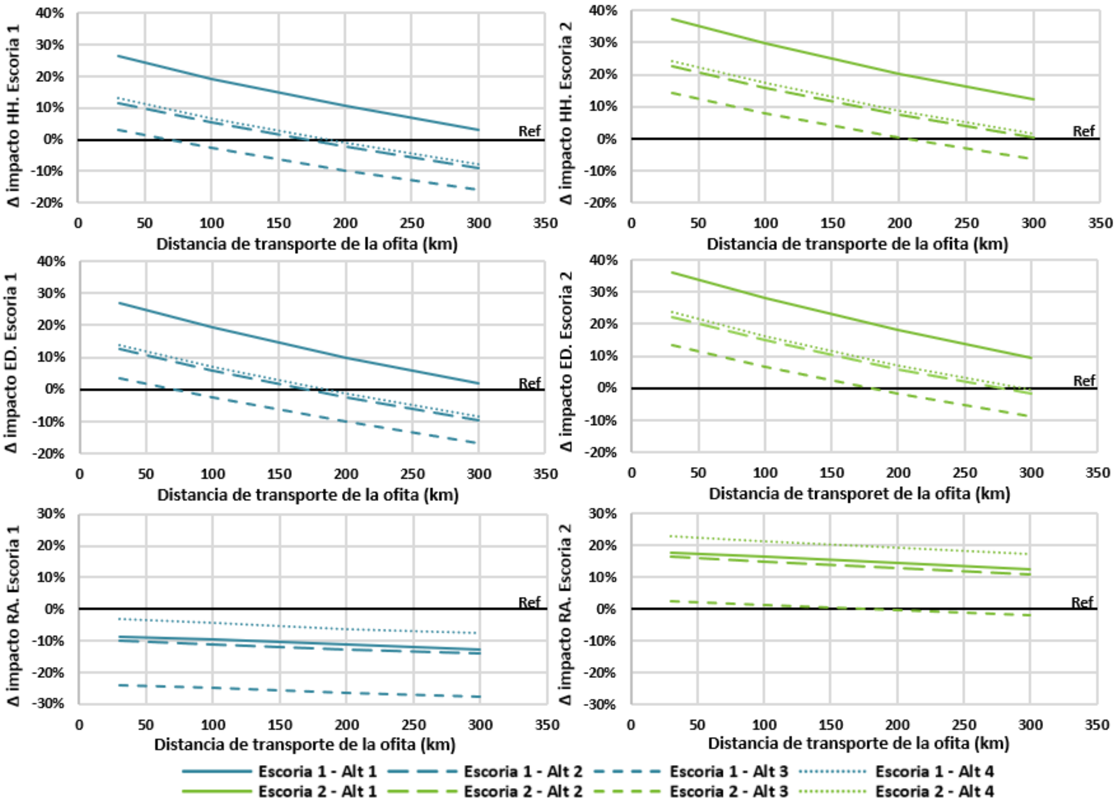


Figura 14. ACV considerando 4 procedimientos de asignación de impactos y el máximo contenido de humedad de los áridos.

Para comprender mejor estos resultados, se evaluó la contribución de cada proceso en los resultados del ACV centrando el análisis en un caso concreto en el que se supuso una distancia de transporte de la ofita de 200 km (véase Figura 15).

Como era de esperar, la producción de mezcla asfáltica es el proceso que más contribuye a los impactos de HH y ED, siendo su relevancia mayor en la escoria 2 debido a la mayor humedad del árido. A este proceso le sigue la producción de betún en la mezcla con escoria 2 y las actividades de construcción en la mezcla con escoria 1. Hay que recordar que la mezcla con escoria 2 necesita un mayor porcentaje de betún que las otras dos mezclas. Además, la selección de 200 km como distancia de transporte de la ofita aumenta la relevancia del transporte en la mezcla de referencia siendo este proceso responsable del 24 % del impacto total.

En cuanto al impacto RA, el transporte de los materiales apenas afectan a los resultados. De hecho, en la mezcla de referencia este proceso solo representa el 6 % del impacto total. Por el contrario, la producción de betún es el proceso más importante, siendo responsable del 67 %, 73 % y 79 % del impacto total de las mezclas de referencia, escoria 1 y escoria 2, respectivamente. Esto explica los resultados observados en la Figura 14: la escoria 1, al necesitar menos betún, siempre produce menos impacto RA que la ofita mientras que la escoria 2, necesitando más betún, siempre produce más impacto RA.

Por último, la lixiviación es despreciable en las tres categorías de impacto analizadas representando menos del 0,2 % en todos los casos.

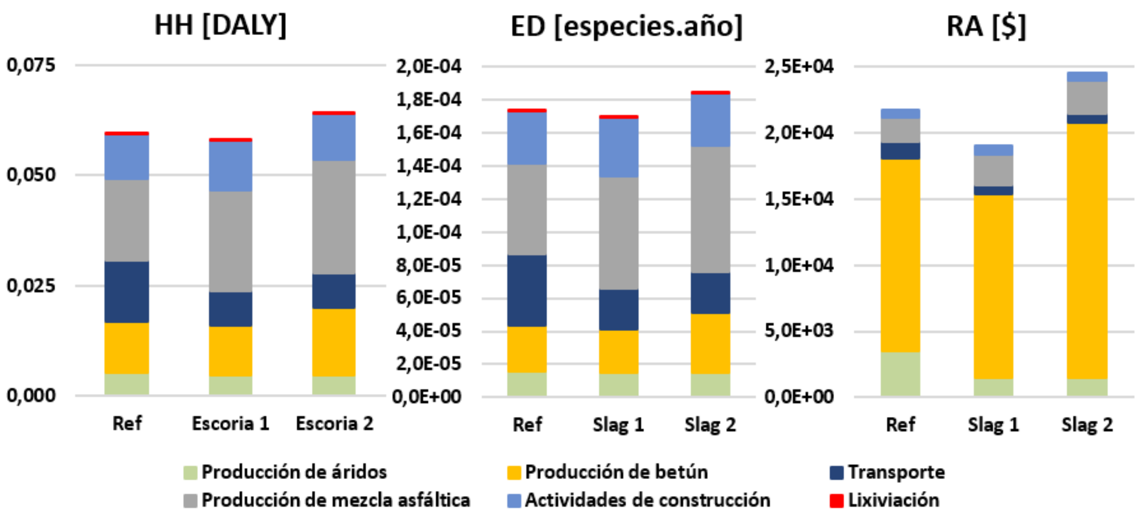


Figura 15. Contribución de cada proceso al ACV. Procedimiento de asignación: alternativa 2. Distancia de transporte: 200 km.

Teniendo en cuenta la gran importancia que tiene la producción de mezcla asfáltica en los impactos HH y ED y que es posible reducir la humedad de los áridos, por ejemplo, al almacenarlos bajo techo o al protegerlos de la lluvia de alguna otra forma, se reevaluó la distancia a partir de la cual el uso de la escoria resulta beneficioso utilizando el 50 % de la humedad empleada anteriormente (1,13 %, 1,29 % y 2,08 %). Al realizar el análisis bajo estas hipótesis, los resultados muestran que la escoria 1 y la escoria 2 podrían sustituir a los áridos naturales situados a más de 149 km y 235 km de distancia, respectivamente, lo que implica una reducción de unos 30 km y 60 km con respecto a la distancia calculada anteriormente cuando se utilizó la humedad máxima. Sin embargo, a pesar de esta disminución del 50 % en el porcentaje de humedad, la escoria 2 todavía contendría más agua que la escoria 1 y la ofita. De hecho, incluso considerando el mismo porcentaje de humedad en todos los áridos, las escorias seguirían teniendo más agua que la ofita debido a su mayor peso específico. Por eso, para evaluar el impacto ambiental de los tres áridos en condiciones similares, se repitió el análisis asumiendo un 1% de humedad en todos ellos. Este porcentaje, que es similar a la tasa de absorción de la escoria 1, es solo ligeramente inferior al que ya se ha considerado para la ofita y la escoria 1, por lo que los resultados no se ven prácticamente afectados. Sin embargo, supone un gran cambio para la escoria 2, que podría incluso sustituir a ofita extraída a 190 km de distancia. No obstante, la escoria 2 seguiría produciendo entre un 9 % y un 14 % más de impacto RA que la mezcla de referencia debido a su mayor contenido de betún (véase la Figura 16).

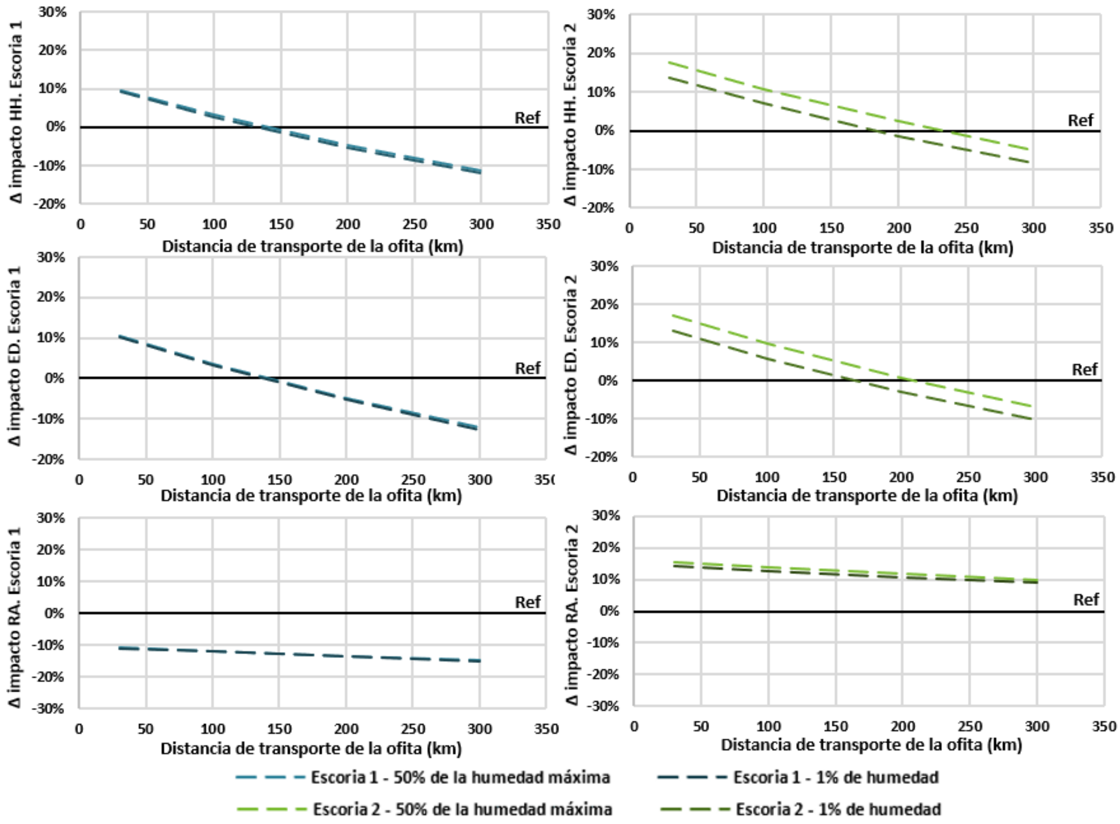


Figura 16. ACV aplicando la alternativa 2 como procedimiento de asignación y 2 contenidos de humedad de los áridos.

Por último, se estudió la sensibilidad del análisis aplicando el modelo de caracterización CML 2001 (actualización de enero de 2016) al caso específico descrito anteriormente en el que se empleó la humedad máxima de los áridos y una distancia de transporte de la ofita de 200 km.

La Tabla 19 muestra la relación entre los impactos producidos por las mezclas con escoria y la mezcla de referencia cuando se aplican ambos modelos de caracterización. ReCiPe evalúa más categorías de impacto que CML, pero en todos los impactos comunes se observa que en ambos casos la variación del impacto con respecto a la referencia tiene el mismo signo y un orden de magnitud similar. ReCiPe proporciona una mayor diferencia en el impacto de escasez de recursos minerales mientras que CML calcula una mayor ecotoxicidad del agua dulce, toxicidad humana y potencial de formación de oxidantes fotoquímicos. Sin embargo, las mayores diferencias se producen cuando se comparan los impactos finales de ReCiPe con los impactos normalizados y ponderados de CML: mientras que ReCiPe calcula impactos similares para las mezclas con escoria y de referencia, CML predice impactos un 145 % y un 137 % más altos para las mezclas con escoria 1 y 2, respectivamente.

Tabla 19. Relación entre el impacto de las mezclas con escoria y de referencia utilizando los modelos de caracterización ReCiPe y CML.

Categoría de impacto	ReCiPe		CML	
	Escoria 1	**Escoria 2**	**Escoria 1**	**Escoria 2**
	Impactos de punto medio			
Cambio climático	-1%	10%	-1%	10%
Formación de partículas finas	-6%	3%		
Agotamiento de recursos fósiles	-3%	26%	-3%	26%
Consumo de agua	89%	94%		
Ecotoxicidad de agua dulce	936%	745%	2,715%	2,178%
Eutrofización de agua dulce	-7%	24%		
Toxicidad humana: cancerígena	-7%	-7%	110%	100%
Toxicidad humana: no cancerígena	2%	-5%		
Radiación ionizante	-6%	3%		
Uso del suelo	-17%	-17%		
Ecotoxicidad marina	787%	626%	815%	670%
Eutrofización marina	-18%	-18%	-5%	-3%
Escasez de recursos minerales	-63%	-63%	-6%	0%
Formación de oxidantes fotoquímicos: ED	-5%	-3%	-245%	-294%
Formación de oxidantes fotoquímicos: HH	-5%	-3%		
Agotamiento de la capa de ozono	-8%	-4%	-6%	3%
Acidificación terrestre	-5%	4%	-5%	4%
Ecotoxicidad terrestre	-8%	-2%	-16%	-16%
Categoría de impacto	**Impacto de punto final**		**Normalizado y ponderado**	
Daño a la salud humana	-2%	7%		
Daño a la diversidad de los ecosistemas	-2%	6%	145%	137%
Daño a la disponibilidad de recursos	-13%	13%		

Cuando se analiza la contribución de cada proceso al impacto total del ACV se puede ver la diferencia entre los dos modelos de caracterización (Figura 17). La lixiviación, que era despreciable según el método ReCiPe, representa ahora el 61 % y el 53 % del impacto total en las mezclas con escoria 1 y 2. Más del 90 % de este impacto es causado por el vanadio, un elemento químico que solo está incluido en las normativas relativas al límite de lixiviación de los áridos procedentes de desechos en 4 de los 10 países estudiados en Saveyn et al. [108]. De hecho, todas las mezclas asfálticas aquí estudiadas cumplen esas 4 legislaciones. Por lo tanto, teniendo en cuenta que al comparar los impactos de punto medio con ambos métodos los resultados no son tan diferentes, la variación de los resultados finales puede deberse a la forma en que se suman estos impactos, es decir, a la normalización y ponderación.

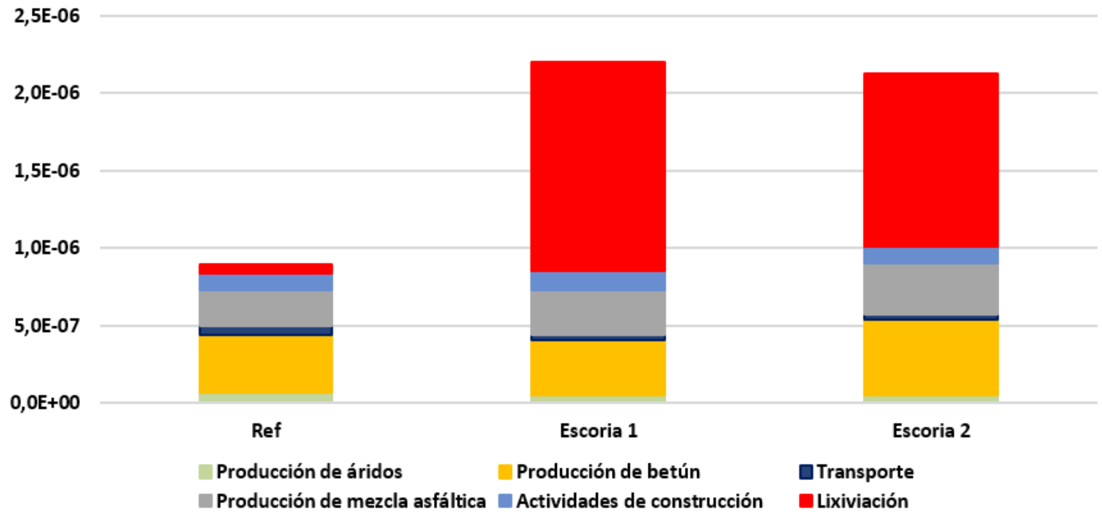


Figura 17. Contribución de cada proceso al ACV. Distancia de transporte: 200 km. Modelo de caracterización CML Impacto total (normalizado y ponderado).

4.2. Análisis de la influencia de la durabilidad de los firmes asfálticos en los resultados del ACV

Para evaluar la influencia de la durabilidad de los firmes asfálticos en los resultados del ACV se diseñaron 3 mezclas porosas (PA) que combinaban 3 tecnologías: sustitución de materiales vírgenes, mezclas asfálticas templadas (WMA) y betún nanomodificado. Este tipo de mezclas porosas tiene ciertas ventajas sobre las mezclas densas (AC) a pesar de su menor durabilidad ya que su alto contenido de huecos (más de un 20 %) mejora el drenaje de la carretera, el efecto isla de calor y la contaminación acústica [33]. Sin embargo, su impacto podría ser aún menor tras la aplicación de las tecnologías mencionadas. Teniendo esto en cuenta, las mezclas se diseñaron introduciendo cambios de forma secuencial: en primer lugar, se diseñó una mezcla caliente (HMA) que contenía EAFS y RAP y que utilizaba un betún PMB 45/80-65; después, se fabricó una mezcla WMA que incorporaba Evotherm a la mezcla anterior para reducir la temperatura de fabricación; y finalmente, se utilizó un betún nanomodificado (NB) desarrollado por ACCIONA Infraestructuras con negro de carbono (CB) y estireno-butadieno-estireno (SBS) [34] para producir otra WMA.

Las características de las mezclas pueden comprobarse en la Tabla 20. Cabe señalar que los porcentajes de EAFS, RAP y el contenido de betún se mantuvieron constantes a lo largo de las diferentes etapas del diseño de la mezcla. Además, las mezclas solo emplearon áridos convencionales (caliza) en la fracción filler, ya que el filler del RAP no era suficiente para cumplir los requisitos de este tipo de mezclas.

Respecto a las temperaturas de fabricación, las probetas de HMA, se mezclaron a unos 165°C y se compactaron a 155°C siguiendo las indicaciones del productor de betún. Sin embargo, las mezclas WMA se fabricaron variando la temperatura de fabricación hasta alcanzar el mismo porcentaje de huecos que la mezcla HMA, lo que supuso una reducción del 12 % en la temperatura de fabricación en la mezcla WMA-PMB y un 6 % en la WMA-NB (véase la Tabla 21). Sin embargo, debido al contenido de humedad de los áridos, la energía de fabricación de la mezcla no se redujo en la misma medida que la temperatura, sino que disminuyó un 8,8 % y un 4,4 % según el modelo de Peinado et al. [83].

Tabla 20. Características de las mezclas asfálticas empleadas en el estudio de influencia de la durabilidad en el ACV.

Detalles	HMA - PMB	WMA - PMB	WMA- NB
Áridos (%)	0,0	0,0	0,0
Filler calizo (%)	2,0	2,0	2,0
Betún virgen (%)	3,6	3,6	3,6
Escoria (%)	80,4	80,4	80,4
RAP (%)	14,0	14,0	14,0
Evotherm	0,000	0,018	0,018
Densidad (t/m3)	2,554	2,555	2,539
Huecos (%)	20,8	20,7	21,1

Tabla 21. Temperatura de fabricación de las mezclas asfálticas (ºC).

Mezcla	Tª mezclado	Tª compactación	Tª áridos	Tª betún	Tª RAP
HMA – PMB	165	155	195	165	110
WMA – PMB	145	135	175	145	110
WMA – NB	155	145	185	155	110

Una vez definida la composición de las mezclas asfálticas, se evaluó el rendimiento mecánico de las mismas mediante las pruebas mecánicas exigidas por las normas europeas: Densidad máxima (EN 12697-5 procedimiento C), densidad aparente (EN 12697-6 procedimiento D), contenido de huecos de aire (EN 12697-8), ensayo de pérdida de partículas (EN 12697-17), ensayo de sensibilidad al agua (EN 12697-12), ensayo de tracción indirecta (EN 12697-23), ensayo de rigidez (EN 12697-26) y ensayo de resistencia a la fatiga (EN 12697-24).

Los resultados demostraron la viabilidad técnica de producir estas mezclas porosas altamente sostenibles. De hecho, se detectó que Evotherm mejoraba la pérdida de partículas de la mezcla, aumentando los valores de resistencia a la tracción indirecta y la rigidez. El nanobetún, por su parte, mejoró la susceptibilidad al agua de las mezclas a costa de incrementar (de una forma no significativa desde el punto de vista estadístico) la pérdida de partículas. Además, las mezclas WMA-NB también mostraron un peor comportamiento a fatiga que las mezclas con PMB. Sin embargo, esta diferencia en su comportamiento se vería reducida en condiciones reales, tanto por el mayor módulo dinámico de la mezcla WMA-NB como por la menor importancia del daño a fatiga en las capas de rodadura.

El ACV se realizó considerando como unidad funcional un carril de 1 km de longitud con una anchura de 3,5 m y un espesor 25 cm (5 cm de capa de rodadura, 10 cm de intermedia y 10 cm de base). Además, se incluyeron en el análisis las etapas de producción, construcción, uso (mantenimiento y lixiviación) y fin de vida del material. El análisis se realizó asumiendo distintas durabilidades para cada uno de los firmes. Sin embargo, se consideró que antes de que fallase el firme serían necesarias 2 acciones de mantenimiento en la capa de rodadura debido a la menor durabilidad de las mezclas PA. Además, para poder comparar los resultados de las mezclas en igualdad de condiciones los impactos calculados se anualizaron dividiéndolos entre su vida de servicio.

En esta parte de la investigación también se realizó un ACCV de las tecnologías para tener en cuenta el enfoque económico además del ambiental. Normalmente, la metodología del ACCV cuantifica los costos de la agencia (los que asume el propietario de la carretera) y del usuario. Sin embargo, en este análisis solo se consideraron los de la agencia debido a los límites del sistema definidos anteriormente. Además, como el valor del dinero no permanece constante a lo largo del tiempo, se aplicó un 4 % de tasa de descuento para calcular el valor actual de los costos futuros [109]. Los datos de los costes empleados en el análisis, así como sus fuentes, se muestran en la Tabla 22.

Tabla 22. Base de datos de costos.

Materiales/procesos	Unidades	Costos	Fuente
Betún convencional	€/t	440	[110]
Betún PMB	€/t	540,00	[110]
Betún NB	€/t	704,00	Calculado
Áridos naturales	€/t	7,50	Proveedor
Filler	€/t	41,36	[111]
RAP	€/t	4,65	PaLaTe v2.0
Escorias	€/t	10,00	Proveedor
Evotherm	€/t	6,200,00	ACCIONA Infraestructura
Planta asfáltica HMA	€/t	8,16	[111]
Planta asfáltica WMA-PMB	€/t	7,56	Calculado
Planta asfáltica WMA-NB	€/t	7,86	Calculado
Construcción	€/t	4,74	[111]
Fresado	€/t	29,30	[111]
Transporte	€/(t*km)	0,10	[111]

Por último, como los resultados sobre la sostenibilidad dependen en gran medida de la vida útil de la carretera, se llevó a cabo una simulación del comportamiento del firme a lo largo de dicha vida útil. En el caso de las capas intermedias y base, el principal mecanismo de fallo es la fatiga mientras que, en las mezclas porosas empleadas en la capa de rodadura, el tipo de fallo más común es la pérdida de partículas. El ensayo Cántabro puede arrojar luz sobre este aspecto, sin embargo, no existe una correlación directa entre los resultados de los ensayos realizados en el laboratorio y la durabilidad real de la mezcla. Por lo tanto, se supuso que el conjunto del firme fallaría por fatiga y su comportamiento se simuló utilizando dos paquetes de software: Alize y 3D-Move. Los resultados de los ensayos que se utilizaron para alimentar los programas de cálculo se pueden ver en la Tabla 23. Respecto a los datos relativos a la dosificación y comportamiento mecánico de las capa base e intermedia, se utilizaron valores usuales de este tipo de mezclas asfálticas [112,113].

Tabla 23. Módulo dinámico y ley de fatiga de las mezclas asfálticas empleadas en el estudio de influencia de la durabilidad en el ACV.

Temperatura (ºC)	Módulo dinámico (kPa)				Ley fatiga	
	0.1 Hz	0.5 Hz	10 Hz	20 Hz	k1	k2
			HMA-PMB			
4	2,68E+06	3,77E+06	6,31E+06	6,95E+06		
20	5,67E+05	9,11E+05	1,92E+06	2,36E+06	4,71E-15	5,55E+00
40	2,15E+05	3,27E+05	9,42E+05	1,26E+06		
			WMA-PMB			
20	4,84E+05	9,10E+05	2,49E+06	3,07E+06	2,69E-15	5,51E+00
			WMA-NB			
4	4,84E+06	6,29E+06	9,22E+06	9,79E+06		
20	1,16E+06	1,89E+06	3,92E+06	4,05E+06	2,83E-05	2,71E+00
40	1,75E+05	3,77E+05	8,02E+05	1,23E+06		
			Intermedia y base			
4	6000000	8322000	15264000	17578000		
20	938000	1797000	5000000	6624000	1,18E-08	3,67E+00
40	443000	569000	1319000	1815000		

Los resultados de comparar los impactos en función de la durabilidad de las dos mezclas WMA con respecto a la HMA se muestran en la Figura 18. Como es obvio, cuanto mayor sea la vida útil de la carretera menores serán los impactos económicos y ambientales.

Cuando el análisis se realiza considerando solo la capa de rodadura, las diferencias entre las mezclas son más obvias. La reducción de 20ºC en la temperatura de fabricación de la mezcla WMA-PMB conlleva una disminución del 1,0 %, 2,9 % y 3,3 % en los impactos RA, HH y ED, respectivamente, cuando no se produce una extensión de la vida útil. Sin embargo, la incorporación de Evotherm aumenta el coste de la mezcla un 0,6 %, lo que hace que la mezcla WMA-PMB necesite aumentar su vida al menos un 0,5 % para igualar el coste de la mezcla HMA.

En cuanto a la mezcla WMA-NB, la incorporación de nanotecnología incrementa el impacto ambiental y económico de la mezcla si no se produce una extensión de la vida útil. De nuevo, el impacto económico es el más restrictivo de los impactos costando la mezcla WMA-NB un 8,8 % más que la mezcla HMA. Este impacto es seguido por el HH, que es un 4,6 % más alto que el producido por la mezcla HMA y el impacto RA es el que sufre una menor variación con un 0,5 % de incremento.

Al incluir toda la sección del firme dentro de los límites del sistema del ACV y ACCV el efecto de las tecnologías (aplicadas sólo en la capa de rodadura) se mitiga. El aspecto económico sigue siendo el impacto más restrictivo, pero en este caso los firmes WMA-PMB y WMA-NB necesitan un incremento de la vida útil del 0,2 % y 3,0 % para poder ser considerados rentables. Por otra parte, algunas ventajas ambientales de la tecnología WMA-PMB comienzan a apreciarse incluso cuando el firme dura un 1,4 % menos, obteniéndose mejoras en los 3 impactos ambientales aun si la vida del firme se reduce en un 0,3%. Respecto a la tecnología WMA-NB, ésta comienza a mostrar beneficios cuando se logra un aumento de la vida útil del 0,2 % y requiere un aumento del 2,3 % para poder ser considerada totalmente respetuosa con el medio ambiente (con respecto a la referencia) debido al impacto HH que se genera durante la producción del CB.

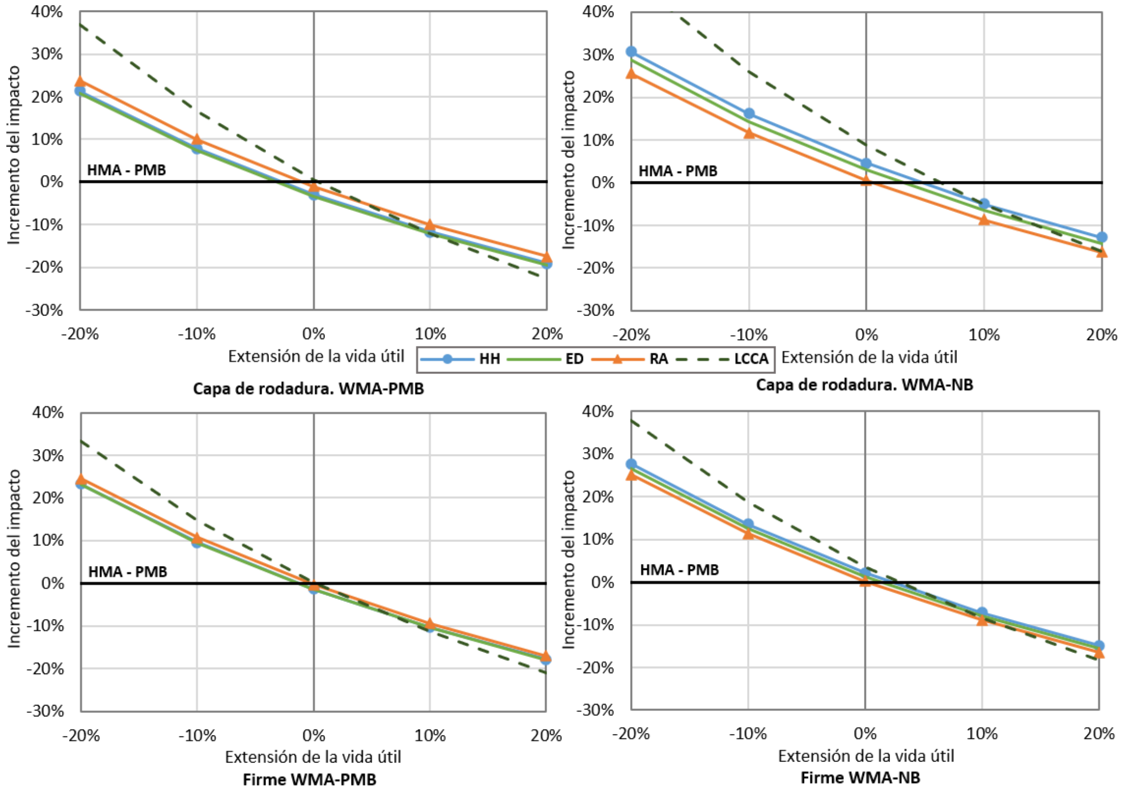


Figura 18. Comparación de los resultados del ACV y ACCV considerando la capa de rodadura y el firme completo.

Como el cálculo de la durabilidad de las mezclas PA no es posible con las herramientas que se disponen actualmente (al menos a nivel de laboratorio), se calculó la durabilidad de todo el paquete de firme asumiendo que el fallo se producirá por fatiga con los programas Alize y 3D-Move. Los resultados en valor absoluto (en años), así como su relación (en porcentaje), puede verse en la Tabla 24. Cuando se aplica un enfoque estático, Alize proporciona resultados más conservadores que 3D-Move debido a las variables intrínsecas del programa (como la adherencia entre las capas). Sin embargo, la relación entre la durabilidad de los firmes es muy similar sin importar el software que se utilice para calcularlo. En este sentido, los firmes WMA-PMB y WMA-NB aumentan la durabilidad del firme HMA alrededor de un 5 % y un 17 %, respectivamente. Por otra parte, cuando se realiza el análisis dinámico se puede observar claramente el efecto de la velocidad del vehículo en el deterioro del firme: cuanto menor sea la velocidad, mayor será el daño. Sin embargo, como la relación entre la durabilidad de los firmes apenas se ve afectada por la velocidad elegida, puede afirmarse que los firmes WMA-PMB y WMA-NB aumentan la vida útil en un 4 % y 11 %. En consecuencia, se obtienen incrementos de la vida útil menores cuando se aplica un enfoque dinámico.

Tabla 24. Durabilidad de los firmes.

Mezcla	Alize Estático	3D-MOVE					Estático (media)	Dinámico (media)
		Estático	10 km/h	20 km/h	60 km/h	100 km/h		
Valor absoluto (años)								
HMA-PMB	11,8	15,3	10,0	14,2	23,8	29,2	-	-
WMA-PMB	12,5	16,1	10,3	14,8	24,9	30,5	-	-
WMA-NB	13,9	17,8	11,1	15,9	26,4	32,2	-	-
Incremento de la durabilidad en comparación con el firme HMA-PMB (%)								
HMA-PMB	0%	0%	0%	0%	0%	0%	0%	0%
WMA-PMB	6%	5%	3%	4%	5%	5%	5%	4%
WMA-NB	17%	16%	12%	12%	11%	11%	17%	11%

Al considerarse la extensión de la vida útil calculada con los softwares se observan mejoras significativas en ambas tecnologías (véase Figura 19). El firme WMA-PMB, al lograr un incremento menor de la vida útil, permite reducir entre un 5,2 % y un 6,3 % el impacto ambiental cuando se realiza un análisis estático y entre el 4,1 % y 5,2 % con el análisis dinámico. Sin embargo, el uso del betún nanomodificado permite reducir un 8,2 %, 8,9 % y 10,0 % los impactos HH, ED y RA al realizar un análisis dinámico y un 12,3 %, 13,0 % y 14,0 % al realizar un análisis estático. Además, aunque se obtienen ventajas económicas con ambas tecnologías, el firme WMA-NB es el más rentable. De hecho, cuando se es optimista en el aumento de la vida útil, el firme WMA-NB logra una reducción del 15,0 % de los costes mientras que el WMA-PMB solo alcanza el 5,9 %. Sin embargo, aplicando el escenario más conservador, el firme WMA-NB puede reducir un 9,8 % los costes de agencia, mientras que el WMA-PMB solo los reduce en un 4,5 %.

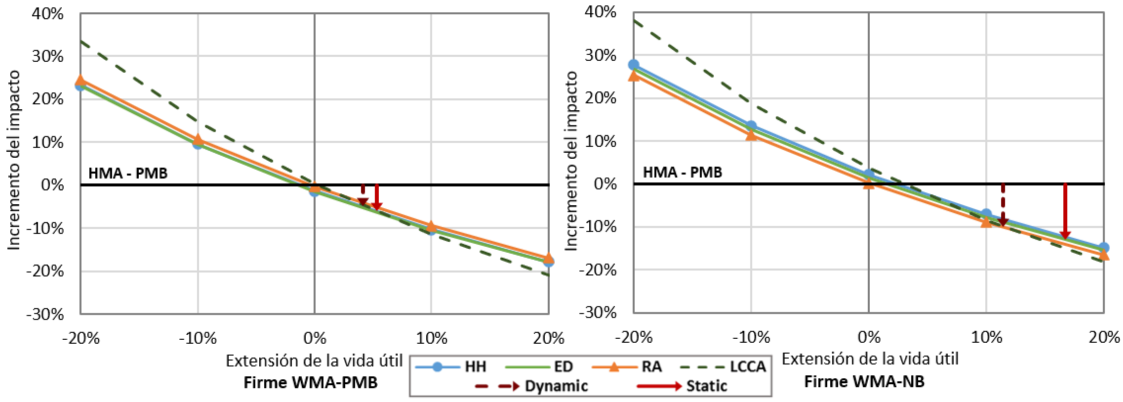


Figura 19. Comparación de los resultados del ACV y ACCV incluyendo las durabilidades calculadas.

4.3. Análisis de la importancia de la congestión producida por las labores de mantenimiento en el ACV de una carretera

La importancia de la congestión producida durante las labores de mantenimiento fue evaluada considerando como unidad funcional un carril de 1 km de la autopista A-8 y un periodo de análisis de 30 años. Este tramo cuenta con una ruta alternativa, la carretera nacional N-634, a la cual pueden desviarse los vehículos cuando se crea más de 1km de congestión debido al cierre del carril. Por ello, como el impacto ambiental dependerá de la calidad del flujo de la A-8 y la N-634, se definieron 6 escenarios combinando distintos NS de ambas carreteras (véase la Tabla 11). En cuanto al espesor del firme, éste depende de la categoría de tráfico pesado de la carretera, categoría que es establecida por la Norma española 6.1-IC en función de la intensidad media diaria de vehículos pesados (IMDp) [114]. En base a esta normativa y los 6 escenarios definidos, 2 secciones de firme fueron analizadas en esta parte del trabajo: la sección de la categoría de tráfico T1 (800 ≤ IMDp <2,000) que le corresponde al NS A de la autopista y la sección de la categoría T0 (2,000 ≤ IMDp <4,000) que le corresponde a los NS B y C (véase Figura 20).

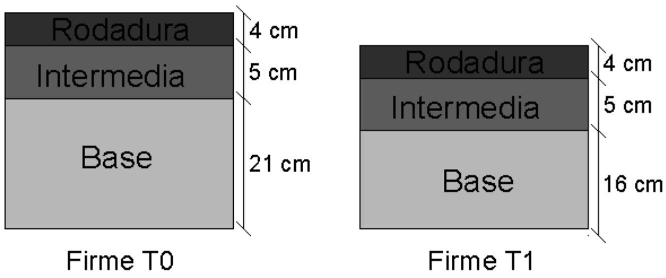


Figura 20. Secciones de firme empleadas en el análisis de la importancia de la congestión.

Normalmente, cuando se comparan dos carreteras en las que la única diferencia es la capa de rodadura, el modelo se simplifica analizando solo los aspectos diferenciadores [15,115]. Sin embargo, en aquellos casos en los que las diferencias están presentes en toda la estructura o se necesita un análisis más detallado, se recomienda el estudio del firme completo. Por ello, en este estudio se incluyeron ambos enfoques en el análisis. Las características de las mezclas asfálticas consideradas para cada capa del firme pueden verse en la Tabla 25 [112].

Tabla 25. Características de las mezclas asfálticas empleadas en el análisis de la importancia de la congestión.

Detalles	Rodadura	Intermedia	Base
Tipo de mezcla	AC 16	AC 16	AC 22
Áridos gruesos y finos (% peso)	90,4	89,4	92,2
Betún (% peso)	4,6	4,6	3,8
Filler (% peso)	5	6	4
Densidad (t/m^3)	2,459	2,357	2,371

El ACV se realizó teniendo en cuenta la producción de materiales, construcción, mantenimiento, congestión, lixiviación y fin de vida. Al considerarse una capa de rodadura densa, que según la EAPA y Nicholls et al. tiene una vida útil media de 15 años [89,107], se propuso el programa de mantenimiento que se muestra en la Tabla 26 y se asumió que las actividades de fresado y reposición de la capa de rodadura implicaban cerrar el carril durante 24 horas [116]. Además, en lo que respecta a los lixiviados, se consideró que solo la capa de rodadura entraría en contacto con el agua al tratarse de una capa densa y, por lo tanto, impermeable.

Tabla 26. Programa de mantenimiento empleado en el análisis de la importancia de la congestión.

Año	**0**	**15**	**30**
Actividad	Construcción del firme	Fresado y reposición de la capa de rodadura	Fresado final de la sección

Como se comentó en el apartado 3.1.3.3, se llevaron a cabo simulaciones del comportamiento del tráfico para los 6 escenarios antes definidos con 2 programas distintos (micro con AINSUM y macro con KyUCP) tras el cierre de un carril durante 24 horas en una red de más de 15 km. Las colas detectadas se muestran en la Tabla 27.

Tabla 27. Longitud de las colas de tráfico (km).

Hora	E1		E2 & E3		E4 & E5 & E6	
	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

Cuando el cierre de carril se realiza en una carretera en la que la hora punta corresponde a un NS A, no se crea congestión con ninguno de los programas empleados para realizar las simulaciones (KyUCP y Aimsun). En este escenario (E1), alrededor de 740 vehículos llegan al tramo estudiado en la hora de mayor tráfico y la capacidad de un solo carril (1587 vehículos ligeros por hora [91]) es suficiente para absorber la demanda de tráfico. Además, la única variación de velocidad que se produce a lo largo del día en los distintos tramos de carretera es la necesaria para adaptarse a los límites fijados para la zona de obras (Figura 21).

En los escenarios 2 y 3, en los que la Autopista A-8 presenta un NS B, se observa una ligera reducción de la velocidad de los vehículos durante las horas de mayor tráfico (8 a.m. - 8 p.m.) en el modelo de micro simulación (Figura 21). Esta disminución es más relevante en el tramo anterior a la obra (PK 174-175) ya que los vehículos que circulan por el carril derecho tienen que encontrar un hueco para cambiar de carril. Esta maniobra de tráfico crea un pequeño cuello de botella que no es lo suficientemente grande como para hacer que los conductores cambien de trayectoria y, por lo tanto, la Carretera Nacional (N-634) no se ve afectada por la congestión. Por el contrario, el software KyUCP no considera velocidades intermedias entre 104 km/h (velocidad media de la A-8) y 8 km/h (velocidad de congestión) y, en consecuencia, se calculan colas más grandes. De hecho, bajo este enfoque 2.498 vehículos cambian su ruta para evitar la congestión de la autopista.

Estas colas creadas cuando la autopista presenta un NS B se incrementan a medida que la IMD aumenta. En este sentido, en los escenarios 4, 5 y 6 (NS C) el modelo de macro simulación calcula colas de alrededor de 9 km de longitud a pesar de la desviación del 30 % de la demanda. Sin embargo, en la micro simulación se calculan colas de alrededor de 1km al reducirse mucho la velocidad de los vehículos en el tramo anterior a la obra.

La Figura 21 también muestra que los vehículos desviados son fácilmente absorbidos por la carretera nacional reduciéndose solo un 7 % la velocidad cuando la carretera tiene originalmente un NS A. Sin embargo, esta afección empeora cuando la calidad del flujo disminuye, produciendo casi un 60 % de reducción de la velocidad en las horas de más tráfico cuando se analiza el escenario 6 (NS C).

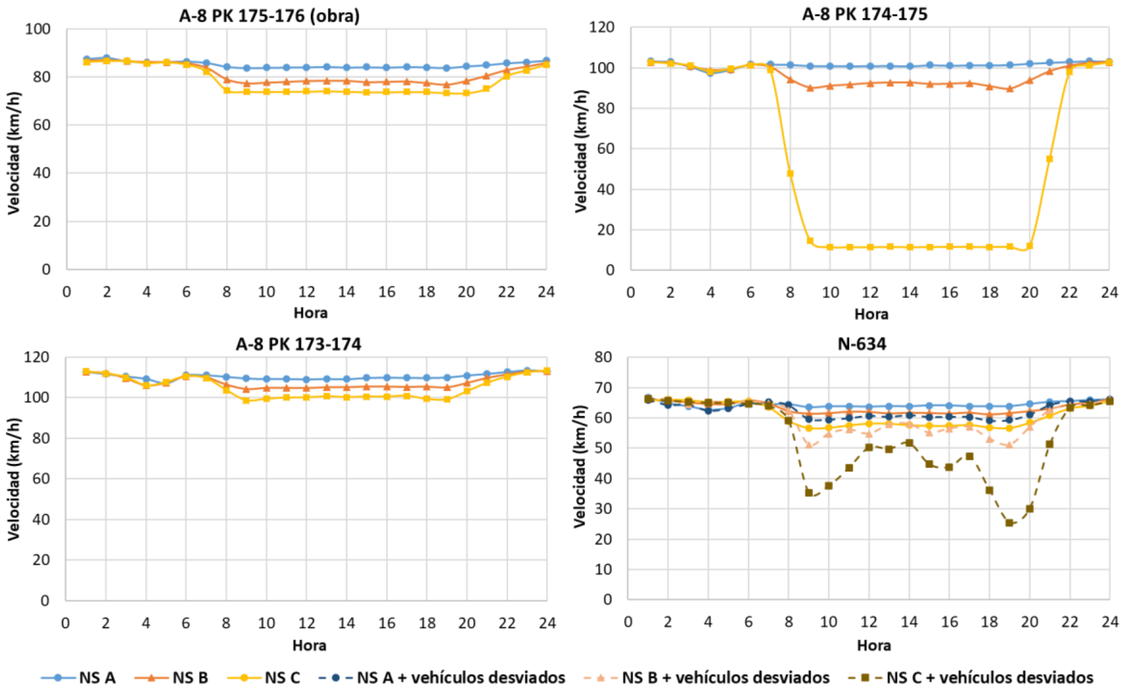


Figura 21. Variación de la velocidad media calculada con Aimsun.

En vista de esta reducción de la velocidad en la ruta alternativa, podría pensarse que desviar los coches de la autopista A-8 a la carretera N-634 cuando esta última presenta una IMD elevada podría implicar una transferencia del problema de una carretera a la otra, quedando la red en su conjunto igualmente congestionada. Por ello, su comportamiento se evaluó utilizando el Diagrama Macroscópico Fundamental de la red (NMFD) [117], el cual ha sido ampliamente utilizado en varios estudios como una herramienta útil para medir y evaluar el estado general de una red de tráfico [118–121]. Así pues, en la Figura 22 se muestra el diagrama fundamental de la red para el escenario 6, comparando su comportamiento tanto cuando se aplica la estrategia de desviar el 30 % del tráfico como cuando no se aplica ninguna estrategia. Como era de esperar, las condiciones del tráfico empeoran a medida que aumenta la demanda. Sin embargo, mientras que la red sigue siendo estable cuando se sigue la estrategia de gestión del tráfico, ésta llega a la región inestable en el caso de "no hacer nada".

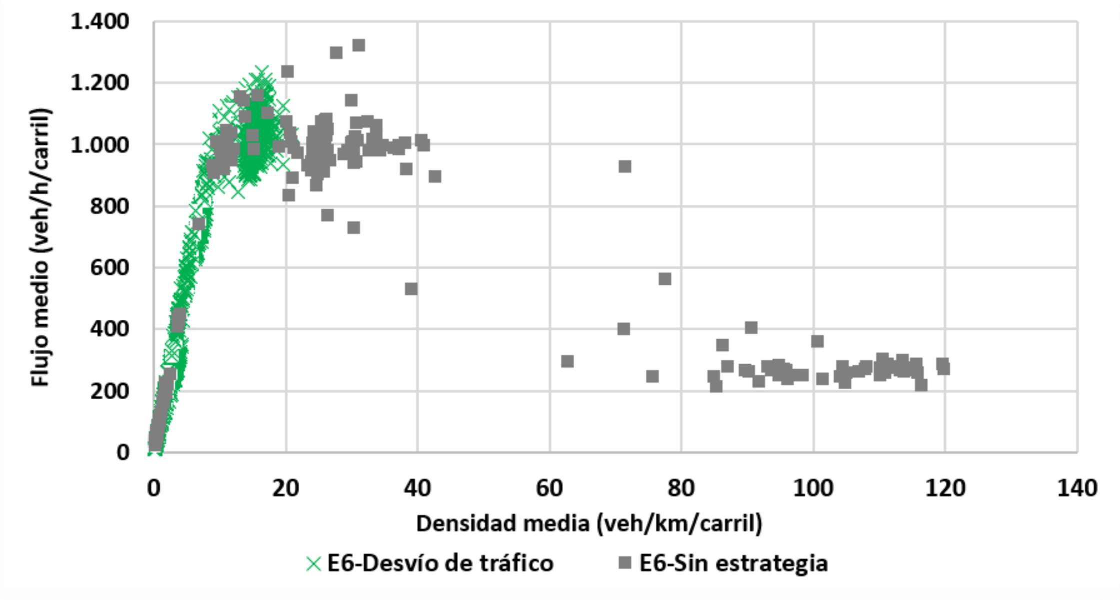


Figura 22.Diagrama Fundamental de la red del escenario 6 al aplicar una estrategia de gestión de tráfico (desvío del 30 % de los vehículos) y sin aplicar estrategia.

La variación de la velocidad y la creación de colas afectan a las emisiones generadas por los vehículos. Las emisiones producidas por el tráfico durante las actividades de mantenimiento se pueden ver en la Tabla 28 y la Tabla 29 para la macro simulación y la micro simulación, respectivamente. Estas cantidades se han calculado restando la contaminación generada en condiciones normales a las emisiones producidas durante las obras. Por eso, los resultados de la macro simulación son los mismos para el escenario 2 y 3 y también para el 4, 5 y 6. Como la única diferencia entre ellos es el número de vehículos que originalmente circulan por la carretera N-634 y no se considera ninguna variación en la velocidad debido al incremento del número de vehículos, las diferencias desaparecen al realizar la resta.

La Figura 23 muestra la relación entre las emisiones de los vehículos y la velocidad. Para una misma distancia recorrida, las emisiones máximas se obtienen cuando los vehículos circulan a 8 km/h (velocidad de congestión). Esta cantidad se reduce a medida que la velocidad aumenta hasta alcanzar los 100 km/h, momento en el que se produce el factor de emisión mínimo. Sin embargo, esta tendencia no se sigue en el caso del NH_3, ya que la emisión mínima se genera a 50 km/h. Esto explica los resultados de la Tabla 28. La reducción de la velocidad de 104 km/h a 80 km/h en el escenario 1 implica un aumento de casi todas las emisiones analizadas excepto del NH_3. Además, cuando se predicen colas similares (escenarios 1, 2 y 3), las emisiones son mayores en la micro simulación, ya que el programa permite un cierto nivel de adaptabilidad de la velocidad de los vehículos a las condiciones de tráfico. Sin embargo, esta situación cambia en los demás escenarios debido a las colas mucho más largas calculadas con el modelo de macro simulación (cuanto mayor es la longitud de la cola, más emisiones se generan).

Tabla 28. Emisiones ambientales de la macro simulación.

Escenario	CO_2 (Kg)	CO (Kg)	NOx (Kg)	C_6H_6 (Kg)	NH_3 (Kg)	$PM_{2,5}$ (Kg)	Energía (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

Tabla 29. Emisiones ambientales de la micro simulación.

Escenario	CO_2 (Kg)	CO (Kg)	NOx (Kg)	C_6H_6 (Kg)	NH_3 (Kg)	$PM_{2,5}$ (Kg)	Energía (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

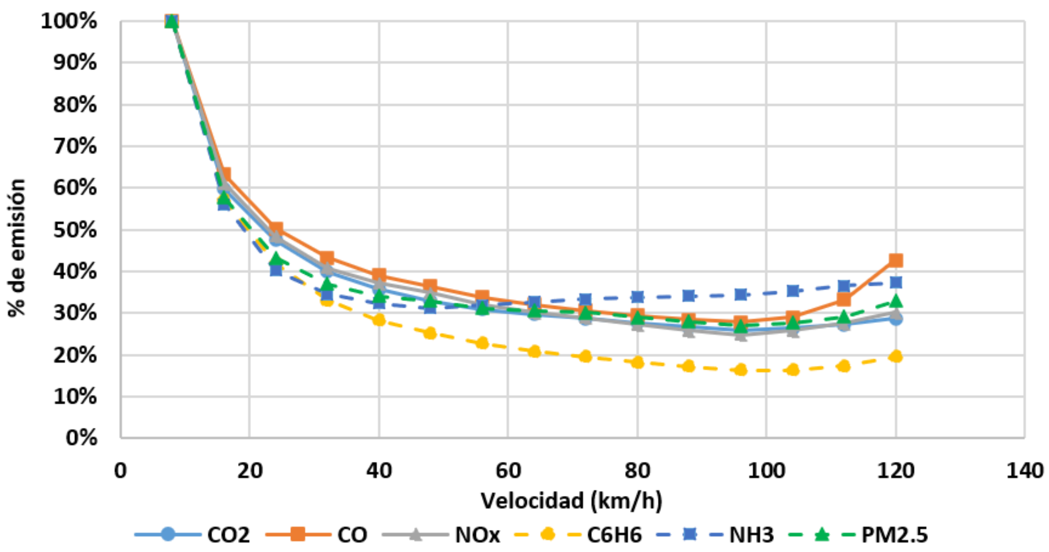


Figura 23. Relación entre las emisiones producidas por los vehículos y la velocidad.

El impacto ambiental producido a lo largo de toda la vida de la unidad funcional (1 km de carril de autopista) para los 6 escenarios y los 2 métodos de simulación seleccionados (micro y macro) al considerar solamente la capa de rodadura (R) o toda la sección de firme (F) se muestran en la Tabla 30 y en la Figura 24. En ellas, los impactos producidos por la congestión y por el resto de las etapas del ciclo de vida se muestran por separado para poder apreciar la contribución de la congestión al ACV total calculado con el modelo de caracterización ReCiPe.

Los resultados muestran que la afección al tráfico durante las actividades de mantenimiento es significativa en casi todas las situaciones analizadas y su importancia aumenta exponencialmente con el número de vehículos. Cuando solo se analiza la capa de rodadura, la congestión representa entre el 0,4 % y el 11 % del impacto en el escenario 1 (NS A), alrededor del 22 % en los escenarios 2 y 3 (NS B) y más del 52 % en los escenarios 4, 5 y 6 (con NS C). De hecho, esta etapa es relevante incluso si se tiene en cuenta la sección completa del firme, suponiendo más del 0,1 %, 6 % y 21 % del impacto total en los tres NS analizados. De hecho, la congestión solo es despreciable (<1 %) en el escenario 1 cuando se utiliza el software KyUCP. Además, los resultados son muy similares cuando se comparan los tres impactos de punto final, aunque se detectó una afección ligeramente mayor a los ecosistemas que a la salud humana o a la disponibilidad de recursos.

Además, se detectó que el NS de la autopista influye más en los resultados del ACV que el NS de la carretera nacional. De hecho, cuando la IMD de la N-634 pasa de un NS A a un NS C, la contribución de la congestión al impacto total se incrementa en torno al 2 %. Sin embargo, aplicando este mismo planteamiento a la autopista A-8 se obtiene un incremento de más del 43 % y 76 % en todos los impactos cuando se utiliza la micro y macro simulación respectivamente en el ACV de la capa de rodadura, y del 18 % y 44 % cuando se analiza el firme completo.

Las diferencias entre los resultados obtenidos con los dos modelos de simulación empleados (micro y macro) dependen de la IMD de la autopista, obteniéndose los resultados más similares cuando la A-8 tiene un NS B. De hecho, en el escenario 1 la micro simulación proporciona resultados un 9 % mayores que los obtenidos con la macro simulación, reduciéndose esta diferencia hasta un 2% en los escenarios 2 y 3. Sin embargo, esta tendencia cambia al analizar los escenarios 4, 5 y 6 ya que la macro simulación proporciona resultados un 22 % mayores que la micro simulación.

Para comprobar la consistencia de estos resultados, el ACV fue recalculado usando la actualización de enero de 2016 del modelo de caracterización CML 2001, obteniendo resultados muy similares a los de ReCiPe (véase Figura 24). De hecho, la única variación entre los dos modelos es que con CML, la contribución de la congestión al ACV de la capa de rodadura es alrededor de un 10 % menor que la calculada con ReCiPe.

Finalmente, mencionar que los resultados obtenidos en este trabajo concuerdan con las principales conclusiones alcanzadas por otros autores [18,47,52] en lo que respecta a la importancia de la congestión y a la relación exponencial existente entre las emisiones y el número de vehículos. Sin embargo, las diferencias en la unidad de referencia, el alcance, los límites del sistema o incluso el objetivo de los trabajos no permiten una comparación directa de los resultados.

Tabla 30. Resultados de los impactos ambientales para los 6 escenarios, 2 enfoques y 2 modelos de simulación utilizados.

			Daño a la salud humana [DALY]		Daño a la diversidad de los ecosistemas [Especies.año]		Daño a la disponibilidad de recursos [$]	
			ACV sin congestión	Congestión	ACV sin congestión	Congestión	ACV sin congestión	Congestión
E1	R	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
	F	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
E2	R	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
	F	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
E3	R	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
	F	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
E4	R	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
	F	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
E5	R	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
	F	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
E6	R	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
	F	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

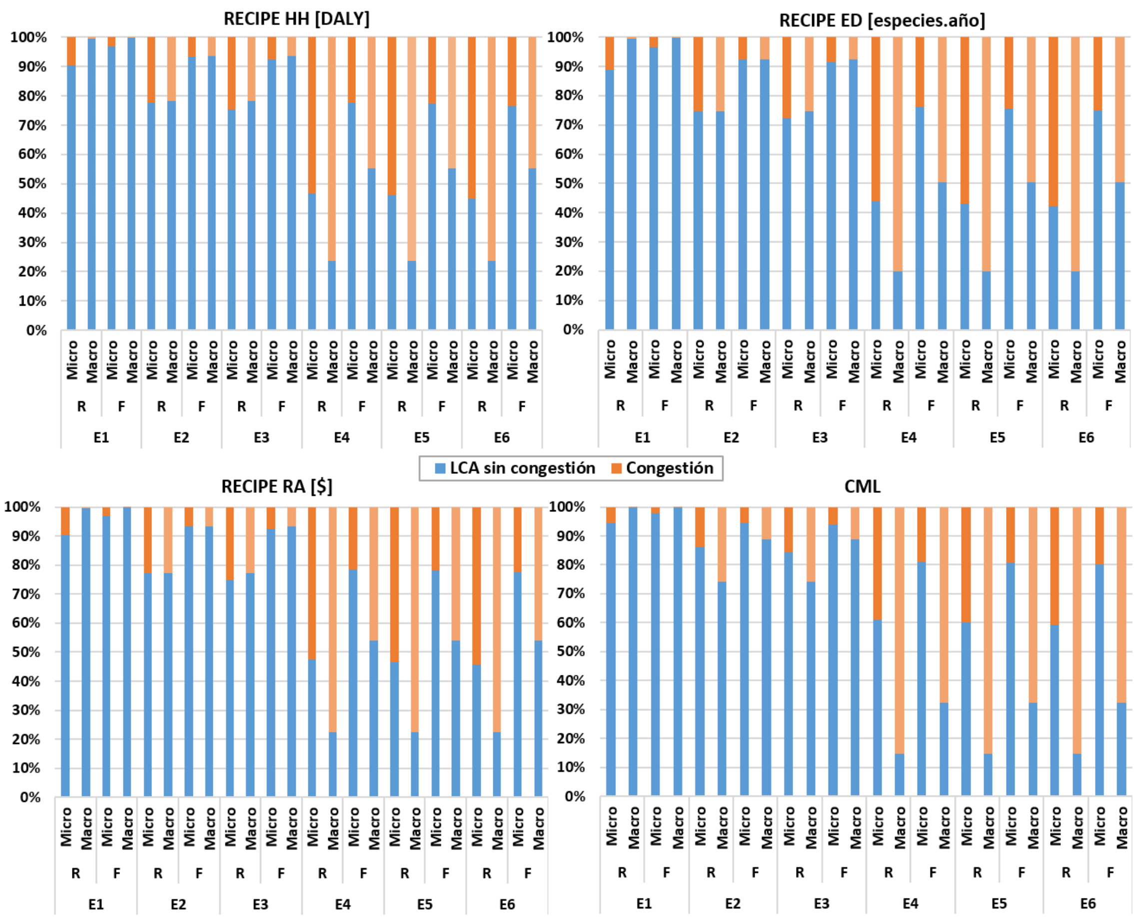


Figura 24. Contribución de la congestión al ACV de una carretera.

5. CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

5.1. Conclusiones generales

La infraestructura vial es vital para el desarrollo económico y social de las naciones al permitir el transporte de recursos e impulsar el comercio entre las regiones. Sin embargo, también genera problemas ambientales que empeoran a medida que crece la red de transporte y se acrecientan los efectos del cambio climático. Para paliar este efecto, se están desarrollando nuevas tecnologías más duraderas, rentables y respetuosas con el medio ambiente que tratan de reducir el consumo de recursos naturales, reducir la temperatura de fabricación de mezclas asfálticas o incrementar la durabilidad de los materiales. No obstante, hace falta que esos avances vayan de la mano de análisis eficientes, fiables y completos de su sostenibilidad.

El análisis de ciclo de vida es un método normalizado que se ha utilizado durante décadas con este fin, pero que todavía se encuentra en desarrollo en lo que respecta a su aplicación a carreteras. La existencia de lagunas en el conocimiento relativas a ciertas fases de su vida útil y la falta de directrices y metodologías que faciliten su inclusión en el análisis están dando lugar a ACVs simplificados en los que no se tienen en cuenta aspectos que pueden ser determinantes en la selección de una tecnología. Por eso, la presente tesis doctoral trata de paliar estas carencias analizando en mayor profundidad diversos aspectos de la metodología que están generando incertidumbre en su aplicación a firmes asfálticos.

La aplicación de la metodología del ACV a mezclas susceptibles de ser sanadas por inducción permitió identificar los aspectos que requerían un estudio más pormenorizado, así como crear una base de datos relativa a los procesos que intervienen a lo largo de la vida de un firme asfáltico. Los ensayos y modelos aplicados a la producción de escoria de acería permitieron completar la base de datos inicial, así como dar recomendaciones tanto sobre su uso como sobre la manera de realizar ACVs de este tipo de material. La aplicación de programas de simulación del comportamiento de firme hizo evidente la pérdida de precisión que se obtiene al hacer suposiciones sobre la vida de las tecnologías. Finalmente, el estudio de la importancia de la congestión creada durante las labores de mantenimiento de la carretera reveló tanto la importancia de esta fase dentro de los resultados totales como la importancia de reproducir fielmente la geometría de la carretera y el comportamiento de los vehículos.

Por ende, a partir de la bibliografía revisada y de los estudios llevados a cabo tanto previamente a esta tesis doctoral como durante el desarrollo de la misma, se confirma la importancia de ciertos aspectos de la vida de la carretera que no suelen ser tenidos en cuenta al aplicar la metodología del ACV y se cumple el objetivo principal de la tesis al proponer recomendaciones que facilitan su correcta realización.

5.2. Conclusiones específicas

A continuación, se resumen las conclusiones específicas para cada aspecto de la metodología de ACV analizado en la presente tesis doctoral.

5.2.1. Análisis exhaustivo del impacto ambiental producido por el uso de escorias procedente de hornos de arco eléctrico en mezclas asfálticas

- El procedimiento de asignación de impactos que solo tiene en cuenta los procesos que se realizan exclusivamente a las escorias es la alternativa más razonable. La asignación de parte del impacto del proceso de fabricación del acero a las escorias las convierte en un material poco atractivo mientras que la concesión de un crédito por el impacto evitado genera problemas en cuanto a la conservación de la masa y al material que debe recibir el crédito.
- La absorción de las escorias afecta en gran medida a los resultados del ACV, aumentando el contenido de betún de las mezclas, así como la humedad del árido. Sin embargo, dependiendo del proceso de producción, es posible encontrar escorias con una porosidad similar a la de los áridos naturales.
- La humedad de los áridos es crucial en el ACV de una carretera. Las escorias con una absorción baja pueden sustituir áridos de alta calidad situados a más de 144 km de distancia cuando están protegidos de la intemperie, aumentando esta distancia a 177 km cuando su humedad es alta. Del mismo modo, las escorias con una absorción alta pueden sustituir áridos situados entre 190 km y 296 km de distancia en función de su contenido de humedad. Sin embargo, su mayor contenido de betún puede impedir que las escorias consigan mejorar el impacto RA.
- El revestimiento que proporciona el betún reduce la mayoría de los elementos químicos lixiviados por la mezcla asfáltica, lo que hace que la lixiviación sea despreciable cuando se emplea el modelo de caracterización ReCiPe.
- Aunque se observan tendencias similares en los impactos de punto medio calculados con ReCiPe y CML, los resultados difieren enormemente cuando se normalizan y ponderan los impactos CML y cuando se calculan los impactos de punto final de ReCiPe. Teniendo en cuenta la gran subjetividad y variabilidad de los procesos de normalización y ponderación, se recomienda utilizar los impactos de punto final de ReCiPe cuando sea necesario reducir el número de impactos para hacer aseveraciones comparativas.

5.2.2. Análisis de la influencia de la durabilidad de los firmes asfálticos en los resultados del ACV

- El efecto de la durabilidad es clave a la hora de obtener resultados fiables del ACV pudiéndose obtener conclusiones erróneas sobre la mejora (o no) ambiental de un producto si la estimación de su vida útil es muy imprecisa.

- En general, las simulaciones estáticas del comportamiento del firme proporcionan resultados más conservadores que los análisis dinámicos cuando los resultados se expresan en términos absolutos. Sin embargo, al comparar la durabilidad de los firmes en términos porcentuales, las simulaciones estáticas calculan mayores aumentos de la vida útil.
- Alize y 3D-Move pueden utilizarse indistintamente para calcular la relación entre la durabilidad de los firmes de forma estática. Sin embargo, el valor absoluto es diferente debido a las características intrínsecas de cada software. Esto también se observa en el análisis dinámico cuando se simulan varias velocidades de tráfico; aunque los valores absolutos de la durabilidad difieren, se puede seleccionar cualquier velocidad siempre que el análisis se realice con fines comparativos.
- La consideración de todo el firme dentro de los límites del sistema cuando la tecnología solo se aplica en la capa de rodadura atenúa los resultados del ACV y ACCV.

5.2.3. Análisis de la importancia de la congestión producida por las labores de mantenimiento en el ACV de una carretera

- Se recomienda considerar al menos los siguientes 6 contaminantes en los cálculos de la congestión para lograr una buena precisión en los resultados del ACV: CO_2, CO, NOx, C_6H_6, NH_3, y $PM_{2,5}$.
- Los programas de macro simulación de tráfico solo deben ser empleados para realizar cálculos aproximados o análisis preliminares ya que subestiman las emisiones producidas cuando la autopista presenta un NS A y sobreestima la longitud de las colas cuando se analiza un NS C, incluso cuando se considera una desviación del 30% de la demanda. Los resultados calculados por la micro y macro simulación solo son similares cuando se estudian carreteras con NS B.
- La etapa de congestión siempre debería incluirse en el ACV de una carretera cuando el programa de mantenimiento implique el cierre del carril durante más de 24 horas, salvo en el caso de análisis preliminares en los que se observe un NS A durante su hora punta. De hecho, se ha demostrado que la demora del tráfico producida durante el cierre de un carril es relevante incluso cuando se tiene en cuenta toda la sección de firme asfáltico. Sin embargo, como es obvio, su contribución es menor que cuando solo se considera la capa de rodadura. En cuanto a los cierres de menos de 24 horas, la relevancia de la congestión dependerá de la hora del día a la que se produzca el cierre, así como de su duración. Por lo tanto, y debido a que este estudio no ha sido incluido en la presente tesis doctoral, sería recomendable la realización de una evaluación preliminar que indique si es necesario llevar a cabo un estudio más detallado.
- Las rutas alternativas deben incluirse en el análisis del tráfico. Aunque su IMD no afecta significativamente a los resultados de la ACV (entorno al 2%) su exclusión daría lugar a una sobreestimación de la congestión y el comportamiento real de los conductores no estaría representado en el modelo.

5.3. Futuras líneas de investigación

En base a los resultados obtenidos en la presente tesis doctoral y a las observaciones realizadas durante el desarrollo de la misma, se plantean las siguientes futuras líneas de investigación:

- Ampliar los límites del sistema en el estudio de EAFS para incluir otros posibles usos y determinar con cuál se obtienen mayores mejoras ambientales.
- Determinar la variación de los resultados del ACV al utilizar programas más avanzados de simulación del comportamiento de firmes, incluyendo aspectos como la variación de la temperatura del firme o la posibilidad de desarrollar grietas top-down.
- Correlacionar la durabilidad de los firmes calculada con programas informáticos con datos de durabilidad obtenidos a mayor escala, como el ensayo acelerado de pavimento o con datos reales de carreteras.
- Determinar la importancia de la congestión producida durante las labores de mantenimiento en carreteras convencionales.
- Estudiar la mejor forma de incorporar el ruido producido por el tráfico en su circulación por distintos tipos de firmes en el ACV de una carretera.

6. EXTENDED ABSTRACT

Title

Recommendations for the application of the life cycle assessment methodology to asphalt pavements

6.1. Introduction

6.1.1. Framework

On September 2015, the United Nations General Assembly adopted the 17 Sustainable Development Goals (SDG), which address “satisfying the needs of the present without compromising the ability of future generations to meet their own needs” [1]. These goals are focused on solving three worldwide problems by 2030: extreme poverty, inequality and injustice and environmental deterioration.

The road industry can contribute significantly to the accomplishment of some of these goals by reducing the economic, environmental and social impacts produced when trying to maintain a reliable performance of roads. However, not only is it necessary to foster the implementation of more durable, cost-effective and environmentally friendly practices, but it is also necessary to guarantee their sustainability by conducting analyses that take into account the particular circumstances of their implementation.

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 in many different fields since late 60s: beverage containers, cars, nitric acid plants or wine production. Regarding the quantification of the impact generated by roads, Häkkinen and Mäkelä [12] and Horvath and Hendrickson [13], among others, performed this kind of analysis to compare the impact generated by concrete and asphalt mixtures. Years later, Mroueh et al. [14] used this methodology to determine the benefits of adding industrial by-products (such as coal ash or blast furnace slags) to the pavement structure. Kucukvar et al [16] developed a model to compare different types of warm asphalt mixes with hot asphalt mixes. However, despite this background, applying LCA to pavements is still at an immature stage [18] 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. More specifically, there are 4 major gaps related to:

- the use of recycled materials in asphalt mixtures;
- the durability of the pavement;
- the rolling resistance;
- the importance of traffic jams generated during maintenance activities.

6.1.2. Thesis motivation and aims

The main goal of this research is to analyze in more detail several aspects of the LCA methodology that are generating uncertainty in its application to asphalt pavements, in order to promote more efficient, reliable and complete LCAs.

To achieve this main goal, it is highly necessary the fulfillment of the following specific aims:

- Identification of the phases, processes and procedures that raise questions about the application of the LCA methodology in asphalt pavements.
- Establishment of a methodology to perform LCAs on pavements which replace natural aggregates with electric arc furnace slags (EAFS).
- Analysis of the influence of durability in the LCA results when both the complete pavement section and only the wearing course are analysed.
- Comparison of asphalt pavements durability estimated with software packages which uses different calculation methodologies.
- Evaluation of the importance of maintenance-related traffic delay in the total environmental impact produced by roads when considering different starting hypotheses and calculation software.

6.2. Methodology

The application of the LCA methodology is governed by two ISO standards, 14040:2006 [58] and 14044:2006 [59], which specify the requirements and guidelines that a proper analysis should follow. According to these standards, the LCA is composed of 4 interrelated stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation.

Each article of this doctoral thesis adapted its goal and scope to evaluate each of the knowledge gaps detected, obtaining different results and conclusions. Therefore, this section focuses only on 2 stages of the LCA methodology: the analysis of the inventory and the evaluation of the impact.

6.2.1. Life cycle inventory analysis

This stage consists of creating a consistent database containing all the resources consumed and the emissions produced throughout the road's lifecycle. Its creation required both the collection of data from different bibliographic sources and databases and the performance of laboratory tests and application of theoretical models.

The road's life phases were defined following the classification proposed by the UNE-EN 15804:2012 standard regarding the Environmental Product Declaration (EPD) core rules for construction materials [60]. Regarding the electricity generation, fossil fuel production and transportation of materials processes (shared by all stages of the LCA), those defined in the Gabi v9.1 database for the European average and in the National Renewable Energy Laboratory database (NREL)[61] were used.

6.2.1.1. **Product stage**

This stage includes the extraction and processing of the raw materials, their transportation to the asphalt plant and the manufacturing of the asphalt mixture.

Extraction and processing of raw materials

In this research, in addition to the materials commonly used in roads, other more innovative materials have been employed. Some of the processes related to the extraction and processing of these materials (especially those related to conventional materials) have been studied in detail by other authors. However, the newest materials required further study. Table 1 shows a simplification of the inventory created and the sources checked. However, EAFS inventory is explained separately, due to its complexity.

Table 1. Energy resources consumed during the extraction and processing of raw materials.

Materials	Fossil fuels (MJ/t)	Electricity (MJ/t)	Source
Natural coarse and fine aggregates	22.06	19.08	[12,14,69,61–68]
Filler	29.21	85.75	GaBi V9.1
Reclaimed asphalt (RAP)	27.65	0.67	[70]
Steel	4,745.03	1,648.25	GaBi V9.1
Conventional bitumen	2,370.55	18.4	[4]
PMB bitumen	4,259.40	89.76	[4]
CB bitumen	7,711.20	199.82	[4] GaBi V9.1

EAF slag allocation

To calculate the slag's inventory, the process described in Arenal [20] was adopted. The steel production process results in the generation of two other materials, black and white slag. Black slag, once extracted from the furnace, is cooled abruptly with water. After this, the remaining steel that might be left in the slag fraction (around 2%) is separated with an overband magnetic separator. Finally, slags are crushed (when needed) and sieved to achieve an adequate size. However, to assign EAFS their corresponding environmental impact, it is essential to determine whether slag should be considered as a waste or by-product and no consensus has yet been reached on this issue. Therefore, to analyse the influence of different allocation alternatives, four were taken into account in this work:

- Alternative 1 consists of assigning part of the steel production impact to slags, in addition to that generated during their processing (cooling, scrap separation, crushing and sieving). To this end, an allocation based on the process's economic profit, combining the mass and economic values of the materials, was applied.
- In Alternative 2, only those processes that are exclusively performed on slags have been included. In this way, slag would be considered as a waste of the steel making industry that will continue to be produced as long as the need for steel remains.
- Alternative 3 expands the system boundaries to include the impact that is being avoided by not extracting natural aggregates. The benefit of recycling would only be received by slags to encourage their use. Otherwise steel would be attributed the impact of landfill.
- Alternative 4 applies the 50/50 method proposed by Martin et al. [80] to distribute the by-product treatment and the credit received between steel and slag. However, to take into account the mass balance, slags will also assume the impact of producing the displaced product.

A simplification of the inventory used in each of the alternatives can be seen in Table 2.

Table 2. Aggregate inventory.

Inventory	Alternat. 1	Alternat. 2	Alternat. 3	Alternat. 4
Fossil fuels (MJ/t)	108.91	22.64	0.58	22.35
Electricity (MJ/t)	30.22	0.25	-18.83	9.67

Transport distances to the asphalt plant

Transport distances used in this research are shown in Table 3. It should be mentioned that limestone and slag are always assumed to be used locally while the transport distance of ophite can vary depending on the goal of the analysis.

Table 3. Transport distances.

Material	Transport distance (km)
Ophite	Variable
Limestone	30
Slag	30
RAP	30
Bitumen	100

Asphalt mixture production

The manufacturing energy of asphalt mixtures is mainly conditioned by two aspects: the specific heat of the aggregates and their humidity. Both properties were studied in 3 types of coarse aggregate: one ophite and 2 EAFS with very different water absorption rates.

The specific heat capacity of each material was evaluated by means of the differential scanning calorimetry (DSC) technique. The mean and standard deviation of specific heat capacity of each material can be seen in Figure 1. Ophite is the material which requires most energy to be heated, followed by slag 1 and slag 2. Nevertheless, ophite is also the material with the highest standard deviation. In fact, the lowest ophite specific heat is smaller than the highest slag 1 specific heat. Therefore, three specific heat capacity values were considered for each material (see Table 4).

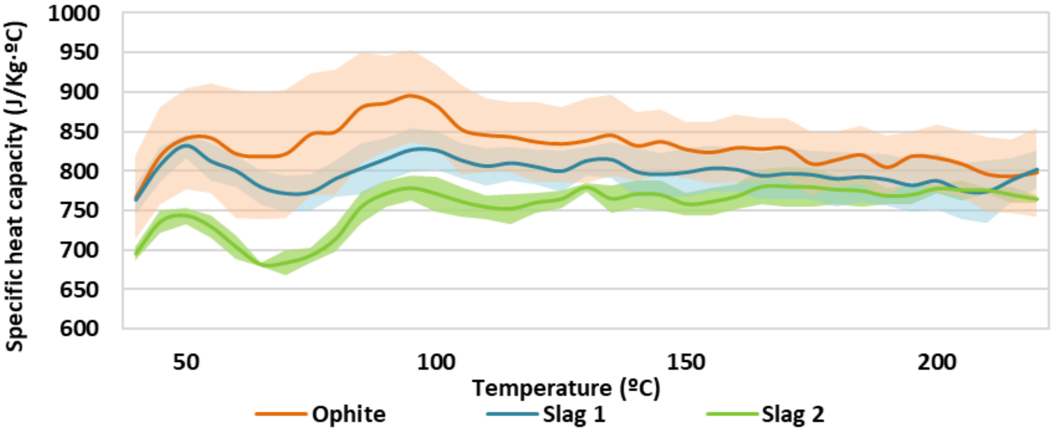


Figure 1. Coarse aggregates specific heat capacity.

Table 4. Specific heat capacity employed (kJ/kg·°C).

Material	C Mean	C Min	C Max
Slag 1	0.798	0.768	0.829
Slag 2	0.757	0.726	0.788
Ophite	0.831	0.772	0.889

The water content of the aggregates is another aspect that affects the energy required in producing the asphalt mix. This water content depends on the ambient humidity, on whether the aggregate is covered and its porosity. Moreover, different void geometries could also affect the aggregate drying process since the larger the specific surface area, the greater the heat transfer. To evaluate this aspect, the drying process of water-saturated aggregates was simulated and monitored at lab level (see Figure 2). However, according to the results the drying speed is practically the same for all the aggregates (0.07 %/min, 0.08 %/min, 0.10 %/min the ophite, slag 1 and slag 2, respectively). Therefore, at least in this case, the drying time only depends on the amount of water retained in the aggregate. For this reason, three moisture contents were taken into account to evaluate their influence on the asphalt mixture energy consumption: the maximum calculated in the test, 50% of the maximum calculated humidity and 1% in all the materials).

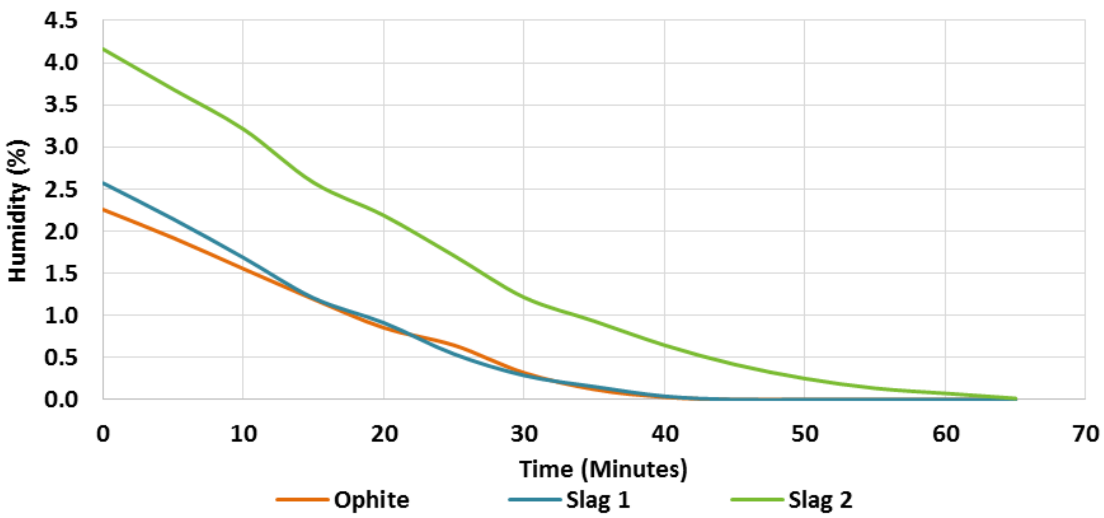


Figure 2. Loss of aggregate moisture over time.

The energy consumed in the asphalt plant was calculated based on the thermodynamic study of an asphalt plant's rotatory dryer carried out by Peinado et al. [83]. However, the model was modified to take into account different types of aggregates. Furthermore, unlike the heavy fuel oil employed in the original model, natural gas was assumed for this work. In addition to this energy, which accounts for 85% of the total consumption of the asphalt plant according to Stotko [84], 12% of electricity and 3% of diesel have to be added to include other sources of energy consumption such as the bitumen heaters or the drum dryer motor. The achieved results are shown in Table 5. As the moisture of the aggregate affects the results at least 3 times more than the variation of the specific heat capacity and evaluating all the options would result in a large number of alternatives, the LCA was performed considering only the average specific heat capacity of each aggregate, but several different moisture contents.

Table 5. Asphalt plant energy consumption per ton of asphalt mix.

Energy	Ref			Slag 1			Slag 2		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Maximum humidity									
E. burned (MJ/t)	239.55	231.92	247.05	246.36	242.05	250.81	277.57	273.2	281.95
Electricity (MJ/t)	33.82	32.74	34.88	34.78	34.17	35.41	39.19	38.57	39.81
Diesel (MJ/t)	8.45	8.19	8.72	8.69	8.54	8.85	9.80	9.64	9.95
50% of the maximum humidity									
E. burned (MJ/t)	198.09	190.46	205.59	200.64	196.34	205.28	212.20	207.83	216.58
Electricity (MJ/t)	27.97	26.89	29.03	28.33	27.72	28.95	29.96	29.34	30.58
Diesel (MJ/t)	6.99	6.72	7.26	7.08	6.93	7.24	7.49	7.34	7.64
1% humidity									
E. burned (MJ/t)	193.32	185.69	200.83	191.71	187.40	196.16	183.37	178.99	187.74
Electricity (MJ/t)	27.29	26.21	28.35	27.06	26.46	27.69	25.89	25.27	26.50
Diesel (MJ/t)	6.82	6.55	7.09	6.77	6.61	6.92	6.47	6.32	6.63

6.2.1.2. **Construction stage**

This stage includes the transportation of the asphalt mix from the plant to the roadwork (which is assumed to be 30 km away), as well as the construction of the road.

According to an industrial partner 1.56 litres of diesel are required to pave and compact 1 ton of conventional asphalt mix. However, as the compaction energy can be affected by the addition of alternative materials, compaction tests were carried out in the laboratory with the rotatory machine. However, the energy obtained in this test is a merely comparative value that does not correspond to the compaction energy required on site. For this reason, the diesel consumption of each mixture was calculated by applying to the available consumption data (the 1.56 litres) the same ratio detected between the compaction energies (see Figure 3). Furthermore, in the WMA mixtures (both with PMB and CB bitumen) a consumption of 1.56 l/t was assumed since no difference was found with respect to the HMA.

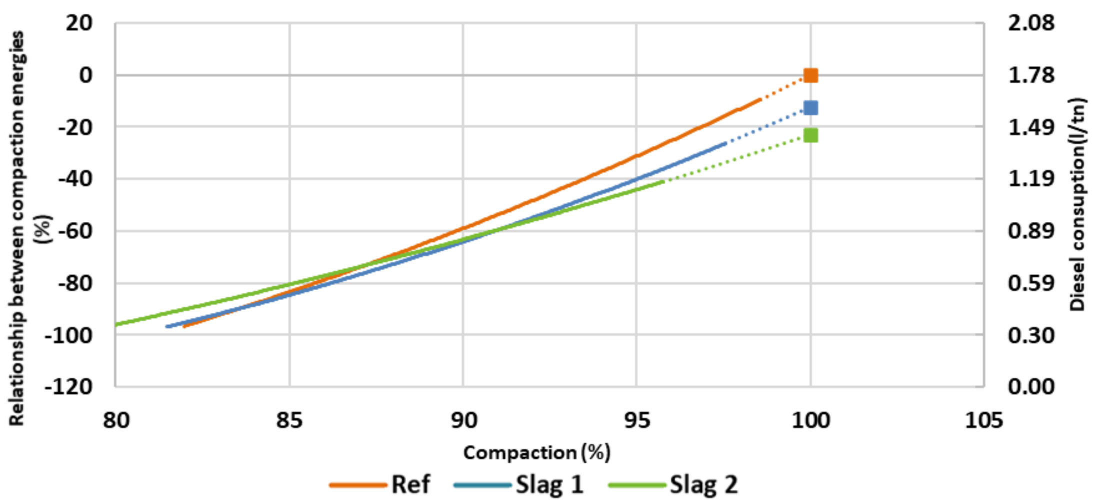


Figure 3. Compaction energy.

6.2.1.3. **Use stage**

Leaching

One potential hazard that can arise from the replacement of natural aggregates by slags is an increase in the chemical elements or compounds released to the environment because of contact with rainwater. However, when they are used in asphalt mixtures this contact could decrease because of the coating that bitumen provides. To take this effect into account, the test defined in the standard EN 12457-4:2002 (UNE-EN, 2002), was applied to the granular material and to the loose asphalt mixture.

Figure 4 shows the relationship between the leachate generated by slag 1 when analysed as a granular material and embedded within the asphalt mixture. In general, the amount of chemical elements released to the environment decrease due to bitumen and only those below the detection limit remain unchanged. Still, 3 of the 18 substances analysed increase: dissolved organic carbon (DOC), nitrates (NO_3^-) and copper (Cu). However, this could be caused by the limestone and/or the bitumen contained in the mixture.

The leachate values used for each of the mixtures are shown in Table 6. It should be noted that beryllium (Be), cobalt (Co), cadmium (Cd) and mercury (Hg) were considered to be zero since they were below the detection limit in all the samples despite the high accuracy of the equipment employed to perform the tests.

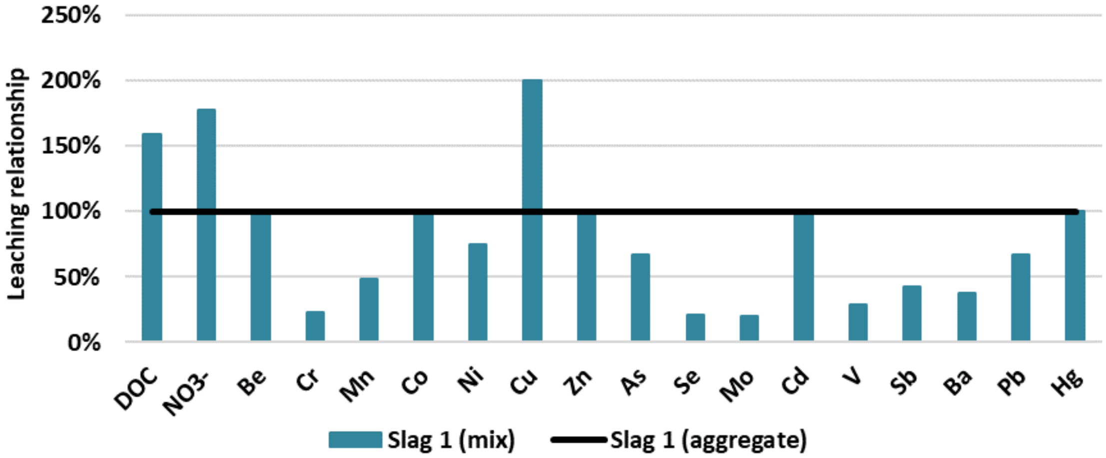


Figure 4. Effect of bitumen in asphalt mixture leachates.

Table 6. Leaching results per kg of loose asphalt mixture.

Mix	DOC	NO3-	Cr	Mn	Ni	Cu	Zn	As	Se	Mo	V	Sb	Ba	Pb
Ref	31.6	1.3	0.009	0.001	0.003	0.005	0.066	0.001	0.006	0.022	0.033	0.002	0.025	0.001
Slag 1	25.1	0.6	0.01	0.002	0.002	0.002	0.001	0.001	0.002	0.018	1.246	0.001	0.218	0.001
Slag 2	19.2	0.25	0.016	0.002	0.001	0.001	0.001	0.001	0.004	0.048	1.006	0.005	0.312	0.001

Maintenance

Maintenance activities involve milling the deteriorated layer (which consumes 0.41 l/t), transporting the reclaimed asphalt to the recovery centre (located 30 km away) and producing and constructing a new layer. However, the maintenance schedule will depend on the mixes to be repaired.

For conventional pavements, experience indicates that the durability of the wearing course can vary between 10 and 15 years depending on whether it is a porous or a dense mixture [88-90]. In addition, in year 30 a complete rehabilitation of the pavement is usually necessary. However, predicting the behaviour of newer mixes and pavements makes the use of calculation software necessary. Two software packages were selected for this research: Alize and 3D-Move. In both cases, a single axle dual tire was selected to load the pavement: tire pressure of 900 kPa, tire load of 32 KN, tire radius of 0.106 m and center to center tire spacing of 0.3192 m.

Congestion

Making recommendations implies the analysis of a wide range of situations from which to draw conclusions. Thus, to evaluate the relevance of the environmental impact produced by congestion, aspects such as the Annual Average Daily Traffic (AADT), the existence of alternative routes, the geometry of the road or the traffic characteristics should be considered. However, this 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.

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. 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. 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 7) 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. The AADT of each scenario was calculated based on the Highway Capacity Manual [91] considering the characteristics of the roads provided by the Spanish Ministry of Public Works [92].

Table 7. 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

Traffic Modelling

To calculate the congestion produced by traffic delay during road maintenance, 2 traffic simulation software packages were used, which apply 2 different approaches: macro and micro simulation.

The Kentucky Highway User Cost Program v1.0 (KyUCP) was selected for the macro-simulation. This software 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 to enable the rerouting of 30% of the demand when a 1-km queue is detected [93–96].

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 [97], what implies the reduction of the adjacent lane width by 0.30 m and the speed from 120 km/h to 80 km/h.

Emissions calculation

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 [98] is already incorporated in the software to calculate the pollutant emissions produced by the simulated traffic. This model provides the emissions for 4 pollutants 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 do this, the relevance of different atmospheric emissions within the impact categories of the ReCiPe methodology was first analyzed. The contaminants selected for the analysis were CO_2, CO, NOx, CH_4, C_6H_6, NH_3, VOC and $PM_{2.5}$. According to the results, the emissions of VOC and CH_4 could be neglected while still guaranteeing the accuracy of the environmental assessment.

Then, the Panis model was recalibrated to fit the MOVES emission model. For this end, traffic simulations were carried out in Aimsun by introducing several traffic light timings, which resulted in different vehicle acceleration and deceleration patterns. These instantaneous speeds and accelerations were fed into MOVES methodology to calculate the emissions related to each trajectory. Finally, trajectory speeds, accelerations and emissions were correlated according to the Panis function eq. (1)[98] by performing a regression analysis with Minitab 17 Statistical Software (see Table 8).

$$\text{Emission (t)} = \max\,[E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)] \qquad (1)$$

Table 8. Environmental impact results for the six scenarios, two approaches and two simulation models used.

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

6.2.1.4. End-of-life stage

This stage includes the milling of the asphalt layer and the transportation of the reclaimed asphalt to the recovery centre. Nevertheless, the processing of the RAP has not been contemplated here since the National Asphalt Pavement Association [101] recommends considering the impact of crushing and screening the RAP in the material supply stage.

6.2.2. Life Cycle Impact Assessment

Once the inventory was completed, the resources consumed and emissions detected were transformed into impact by using the ReCiPe 2016 Hierarchical characterization method, which calculates the impact at two levels: midpoint and endpoint. 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, when performing an LCA, results may change depending on the method used to calculate the impacts. For that reason, the LCA was recalculated also using the CML 2001 (January 2016 update) characterization method. The only way to reduce the number of impacts to facilitate interpretation of the results and the decision making when applying the CML method is to perform 2 additional steps: normalization and weighting. Impacts where normalized by dividing the scores by the impact produced by the 28 member states of the European Union in 2000 and they were weighted using a mean of the factors recommended by the EPA, BEES, NOGEPA and BREE [104,105].

6.3. Results and discussion

6.3.1. Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures

The aim of this part of the research is to evaluate the environmental impact of replacing ophite by EAFS as high-quality coarse aggregates in asphalt mixtures. As the production process and post-treatment directly influence the final properties, two EAFS were selected for this study. Furthermore, conventional aggregate (limestone) was employed in the filler fraction of the mixes.

Firstly, three asphalt concrete mixtures (ref, slag 1 and slag 2) were designed according to the Marshal Design method using a conventional 50/70 penetration grade bitumen. The particle size distribution of the three mixtures was defined by volume due to the higher specific weight of slags and mixtures with 5.8% voids were selected based on the results.

The percentage of bitumen used in the mixtures is highly influenced by the specific weight of slags and their absorption rate. Slag 1 mixture, with similar absorption to ophite, needs practically the same amount of bitumen as the reference mix for the same volume of asphalt mixture, while slag 2 requires 32% more (see Table 9).

Table 9. Characteristics of the asphalt mixtures used in the study of the environmental impact of the EAFS.

Details	%w/w			%v/v		
	Ref	**Slag 1**	**Slag 2**	**Ref**	**Slag 1**	**Slag 2**
Ophite	61.60	-	-	56.38	-	-
Limestone	34.20	29.40	29.19	33.69	33.87	33.89
Slag	-	67.30	66.21	-	56.68	53.00
Binder	4.20	3.30	4.60	9.93	9.45	13.11
Density (t/m3)	2.43	2.95	2.94	2.43	2.95	2.94
Voids (%)	-	-	-	5.80	5.80	5.70

The LCA of the 3 mixtures was carried out considering 4 allocation procedures and different ophite transport distances. In addition, the aggregates were considered to have the highest moisture content (2.26%, 2.57% and 4.16% the ophite, slag 1 and slag 2, respectively). The functional unit was defined as a 1-km lane with a width of 3.75 m and a wearing course of 0.04 m thickness. An analysis period of 30 years was also selected. Regarding the system boundaries, the material production, construction, use (maintenance and leaching) and end-of-life stages were taken into account.

The results of comparing the impacts of slag mixtures with the reference mixture when using ReCiPe (H) characterization method are shown in Figure 5. The x-axis represents the transport distance of ophite while the y-axis represents the increase or decrease of the slag mixtures' environmental impact with respect to the reference mix.

Results show that alternative 2 always remains in a middle position between the other allocation methods. Moreover, it has the advantage of directly fulfilling the mass conservation and not requiring debate about future potential uses or the product which should receive the credit. Consequently, alternative 2 was selected for the rest of the work.

When comparing the two slags, the better performance of slag 1 can be seen due to the higher absorption rate of slag 2, which increases the amount of bitumen needed as well as the aggregate water content. In fact, while slag 1 could replace ophite aggregate located 177 km away, achieving improvements in the HH and ED impacts, slag 2 could replace those located more than 296 km away. Regarding the RA impact, the results do not seem to vary too much despite changing the ophite transport distance. In fact, slag 1 always proves to be a good alternative to ophite while slag 2 always produces a greater impact.

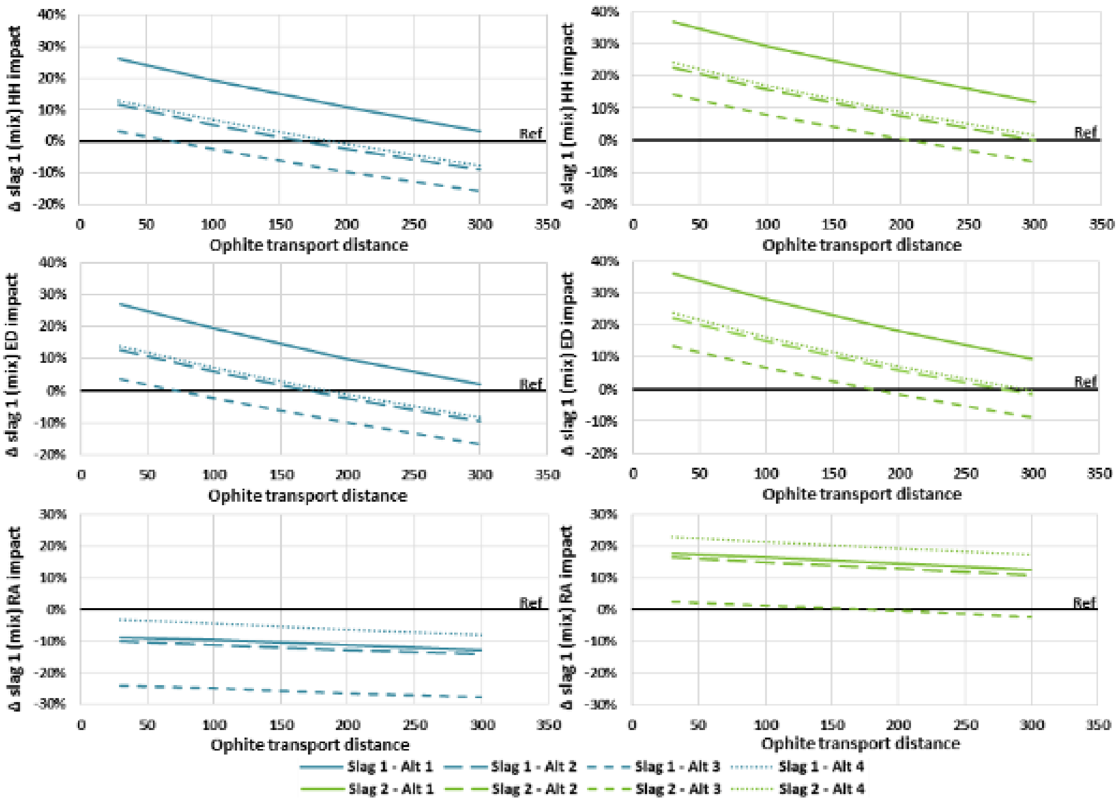


Figure 5. LCA considering 4 allocation procedures and maximum aggregate humidity.

To further understand these results, the process's contribution to the LCA results were evaluated focussing on a specific case in which the ophite transportation distance was assumed to be 200 km (see Figure 6). As expected, the asphalt mixture production is the process that contributes most to the HH and ED impacts. Regarding RA impact, bitumen is the most important process meaning more than 67% in all the mixtures. This explains the results observed above. Slag 1, needing the least bitumen, always produces less RA impact than ophite. However, slag 2, containing more bitumen, always produces more RA impact. Finally, leachate is negligible in all the three endpoint categories.

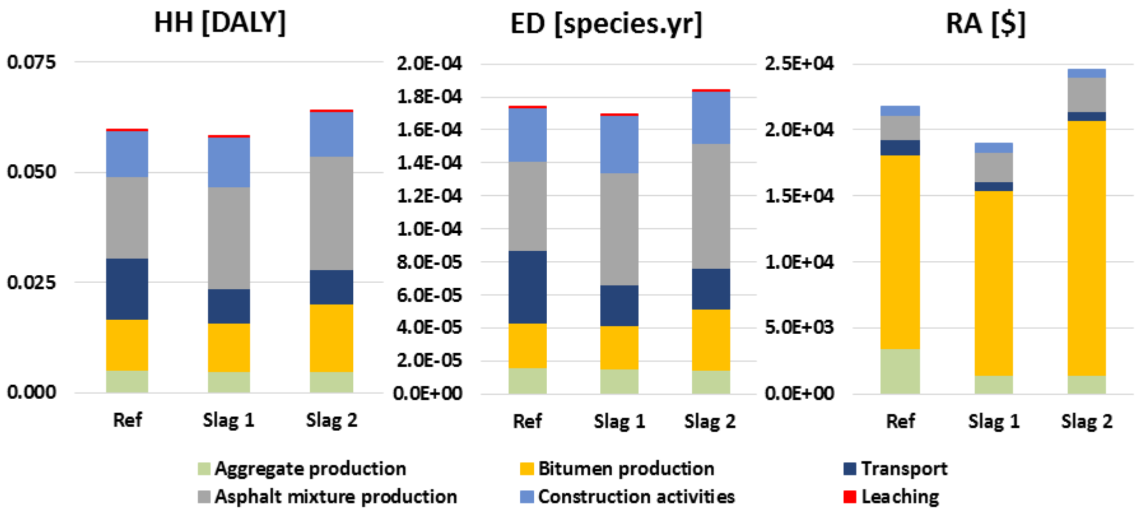


Figure 6. Process contribution to the LCA results. Allocation method: Alternative 2.

Considering the great importance of the asphalt mix production in the HH and ED impacts and the possible reduction of the aggregates' moisture with their covering, the distance from which using slag is beneficial was re-evaluated. In this sense, the analysis was repeated considering 50% of the humidity employed before (1.13%, 1.29% and 2.08%) and also 1% moisture in all the aggregates. The results show that in this way, slag 1 and 2 could replace natural aggregates located more than 149 km and 190 km away respectively. However, the RA impact does not change significantly.

Finally, the sensitivity of the analysis was studied by applying the CML 2001 characterization method (January 2016 update) to the specific case described above where the maximum humidity of the aggregates and 200 km transport distance was selected.

ReCiPe evaluates more impact categories than CML but the variation of the impact of the slag with respect to the reference has the same sign and a similar order of magnitude in all common impacts. However, the greatest differences occur when comparing ReCiPe's end-point impacts with the normalized and weighted impacts of CML: while ReCiPe calculates similar impacts for slag and reference mixtures, CML predicts 145% and 137% higher impacts for slag 1 and 2 mixtures, respectively.

When the contribution of each process to the total LCA impact is analysed, the difference between the two methods can be seen (Figure 7). Leaching, which was negligible according to the ReCiPe method, accounts for 61% and 53% of the total impact in slag 1 and 2 mixtures. Over 90% of this impact is caused by vanadium, a chemical element that is only included in the leaching limit standards for waste-derived aggregates of 4 of the 10 countries studied in Saveyn et al. [108]. In fact, the asphalt mixtures under study fulfil those 4 legislations. Therefore, taking into account that when comparing the midpoint impacts with both methods the results are not so different, the variation of the final results may be caused by the way these impacts are aggregated, in other words, by the normalization and weighting.

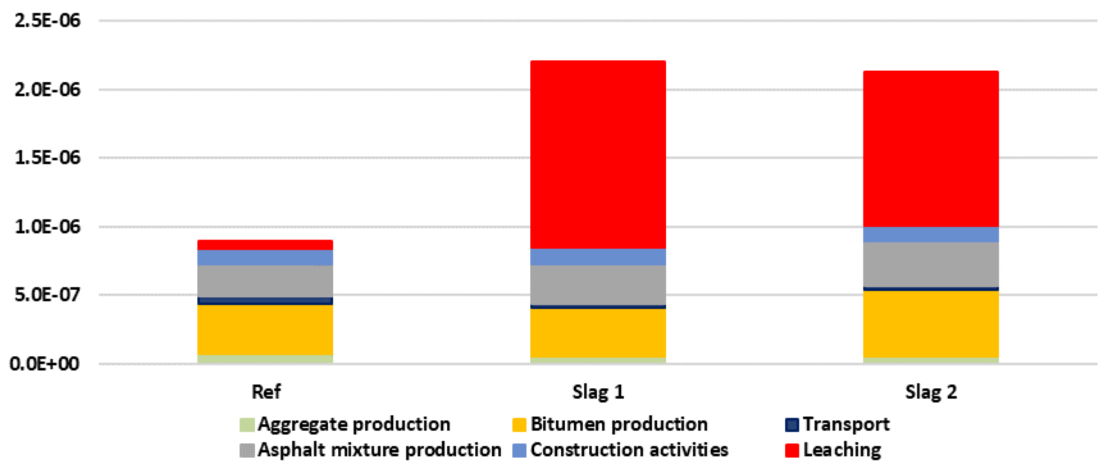


Figure 7. Process contribution to the LCA results. CML characterization method. Total impact (normalised and weighted).

6.3.2. Analysis of the influence of asphalt pavement durability on the LCA results

To evaluate the influence of asphalt pavement durability on LCA results, 3 porous mixes were designed combining 3 technologies: namely replacement of natural aggregates, reduction in manufacturing temperature and use of a nanomodified binder (see Table 10). The mixtures were developed introducing changes sequentially: firstly, a hot mix asphalt (HMA) was designed containing EAFS and RAP and using a polymer modified bitumen PMB 45/80-65; then, a warm mix asphalt (WMA) was manufactured incorporating Evotherm into the previous mix to reduce the production temperature; and finally, a nanomodified binder (NB) developed by ACCIONA Infrastructure [34] containing carbon black (CB) and styrene-butadiene-styrene (SBS) was used instead of the PMB to produce another WMA.

Table 10. Characteristics of the asphalt mixtures used in the study of the influence of durability on the LCA.

Details	HMA - PMB	WMA - PMB	WMA- NB
Aggregates (%)	0.0	0.0	0.0
Limestone filler (%)	2.0	2.0	2.0
Virgin bitumen (%)	3.6	3.6	3.6
Slags (%)	80.4	80.4	80.4
RAP (%)	14.0	14.0	14.0
Evotherm	0.000	0.018	0.018
Density (t/m3)	2.554	2.555	2.539
Voids (%)	20.8	20.7	21.1

Regarding the manufacturing temperatures, HMA samples were mixed at about 165°C and compacted at 155°C following the indications of the bitumen manufacturer. In contrast, WMA were designed by varying the manufacturing temperature until the same air void content as the HMA mixture was reached, resulting in 12% reduction in manufacturing temperature for the WMA-PMB mixture and 6% reduction for the WMA-NB. However, the manufacturing energy of the mixtures was not reduced to the same extent as the temperature due to the aggregates' moisture content, but decreased by 8.8% and 4.4% according to the model developed by Peinado et al. [83].

The analysis was performed considering as a functional unit a 1-km lane with a width of 3.5 m and a pavement thickness of 25 cm (5 cm wearing course, 10 cm binder course and 10 cm base layer). Furthermore, the material, construction, maintenance, use (leaching) and end-of life stages were included in the analysis. The analysis was performed considering different service life extensions for the WMA-PMB and WMA-NB pavements. However, 2 maintenance actions on the wearing course were considered necessary before the failure of the whole pavement due to the durability of PA mixes. Moreover, to compare the results of the mixtures under equal conditions, the impacts calculated were annualized by dividing them by their service life.

In this part of the research a LCCA of the technologies was also carried out to apply an economic approach in addition to the environmental one, but in this case only the agency costs (those assumed by the owner of the road) were taken into account. Furthermore, since the value of money does not remain constant over time, a 4% discount rate was applied to calculate the present value of future costs [109].

Finally, as the sustainability results are highly dependent on the service life of the road, a simulation of the pavement performance was carried out. The main failure mechanism of the binder and base layers is fatigue damage and ravelling is the most common failure of porous mixtures. The Cantabro test can shed light on the particle loss that a porous mixture could undergo in the future. However, a direct correlation between the laboratory test results and the durability of the mixture does not exist. Therefore, the pavement was assumed to fail by fatigue cracking and it was simulated using two software packages: Alize and 3D-Move.

Results after comparing the LCA and LCCA of both WMA with the HMA are shown in Figure 8. As is obvious, the greater the service life of the road, the smaller the economic and environmental impacts.

When the analysis is performed considering only the wearing course, the differences between the mixtures are more obvious. The reduction in the manufacturing temperature of the WMA-PMB leads to a decrease of 1.0%, 2.9% and 3.3% in the RA, HH and ED impacts, respectively when no service life extension is considered. However, the addition of Evotherm increases the cost of the mixture, WMA-PMB needing 0.5% life extension to equalize the HMA cost. Regarding WMA-NB, the addition of NB results in a higher environmental and economic impact if no service life extension takes place. Again, the economic impact is the most restrictive one with 8.8% higher cost than the HMA, RA only increasing 0.5 %.

When the whole pavement section is included in the system boundaries the effect of the technology (only applied on the wearing course) is attenuated. In this sense, the economic aspect is still the most restrictive impact, WMA-PMB needing 0.2% service life extensions to be considered as profitable, whereas the WMA-NB needs at least a 3.0% increase. On the other hand, WMA-PMB technology obtains improvements in the 3 environmental impacts even if the life of the pavement is reduced by 0.3%. However, WMA-NB requires 2.3% increase to be considered as environmentally friendly due to the HH impact generated during the CB production.

Nevertheless, as calculating the durability of porous asphalt mixtures is not possible with the tools currently available (at least at laboratory level), the durability of the whole pavement was calculated assuming fatigue failure (see Table 11).

When a static approach is applied, Alize provides more conservative results than 3D-Moves. However, the relationship between the mixture's durability is very similar whichever software is used. In this sense, WMA-PMB and WMA-NB increase the durability of HMA by around 5% and 17%. On the other hand, the effect of vehicle speed on the pavement deterioration can be clearly observed when the dynamic analysis is carried out: the lower the speed, the greater the damage. Nevertheless, as the relationship between the mixtures' durability is barely affected by the speed selected, the service life increase of the WMA-PMB and WMA-MB is 4% and 11%. Therefore, smaller increments in the service life are calculated when performing a dynamic analysis.

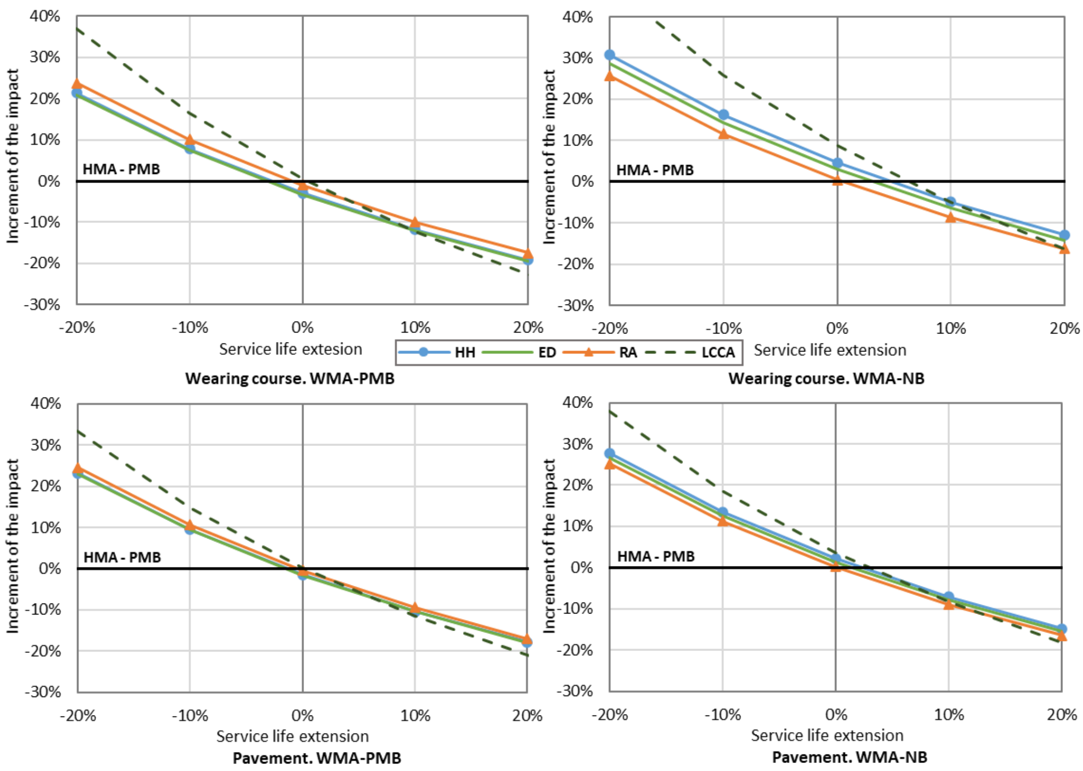


Figure 8. LCA and LCCA results comparison considering the road surface and the whole pavement.

Table 11. PA mixture durability.

Mix	Alize Static	3D-MOVE					Static (mean	Dynamic (mean)
		Static	10 km/h	20 km/h	60 km/h	100 km/h		
Absolute value (years)								
HMA-PMB	11.8	15.3	10.0	14.2	23.8	29.2	-	-
WMA-PMB	12.5	16.1	10.3	14.8	24.9	30.5	-	-
WMA-NB	13.9	17.8	11.1	15.9	26.4	32.2	-	-
Durability increase compared to the HMA-PMB mix (%)								
HMA-PMB	0%	0%	0%	0%	0%	0%	0%	0%
WMA-PMB	6%	5%	3%	4%	5%	5%	5%	4%
WMA-NB	17%	16%	12%	12%	11%	11%	17%	11%

Considering the service life extension calculated with the software, significant improvements are obtained with both mixes. WMA-PMB, achieving a smaller increment in the service life, enables a reduction between 5.2% and 6.3% in the environmental impact when the static approach is applied and between 4.1% and 5.2% with the dynamic analysis. Bigger improvements are achieved with the nanomodified binder. When the dynamic analysis is carried out, reductions between 8.2% and 10.0% are possible, reaching between 12.3% and 14.0% reduction when the static analysis is performed.

Economic advantages are also obtained with these technologies and again, WMA-NB is the most profitable pavement. When an optimistic service life extension is assumed, WMA-NB achieves 15.0% cost reduction while WMA-PMB achieves 5.9%. Considering a more conservative scenario, WMA-NB can reduce 9.8% the agency costs whereas WMA-PMB only reduces them 4.5%.

6.3.3. Analysis of the relevance of the congestion produced during the maintenance activities on the LCA of a road

The relevance for the environment of the traffic delay produced during road maintenance for the 6 scenarios defined before was evaluated by considering a 1-km lane of the Spanish A-8 Motorway and an analysis period of 30 years as a functional unit.

Normally, when comparing two roads in which the only difference is the wearing course, the model is simplified analysing only the distinctive aspects [15,115]. However, when 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. The characteristics of the asphalt mixtures considered can be seen in Table 12 [112].

Table 12. Characteristics of the asphalt mixtures employed in the analysis of the relevance of congestion.

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 (t/m^3)	2.459	2.357	2.371

The LCA was performed considering the product, construction, maintenance, congestion, leaching and end-of-life stages. Maintenance activities involve closing the lane for 24 hours every 15 years due to the average life span of a dense wearing course [89,107].

Traffic simulations were carried out for the 6 scenarios defined above with 2 different programs (micro with AINSUM and macro with KyUCP).

When the lane closure is performed in a road with an “A” LOS in its peak-hour, no congestion is created in any of the models employed. Furthermore, no speed variation is produced (Figure 9), 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 in the micro-simulation model. 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. 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.

Queues become longer as 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 9 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 worsens when the traffic flow quality decreases, producing almost 60% speed reduction in the most trafficked hours when scenario 6 (C LOS) is considered.

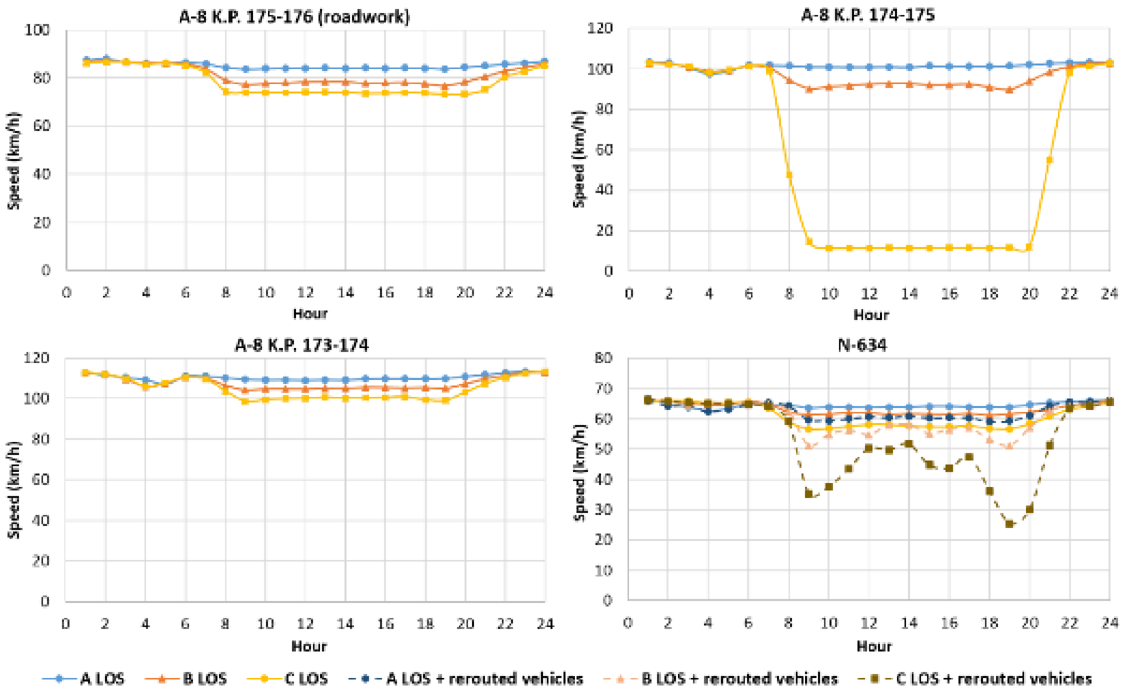


Figure 9. Aimsun average speed variation.

Speed variation and queue creation affect the emissions generated by vehicles and thus, the LCA results. Figure 10 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 NH3 since the minimum emission is generated at 50 km/h. Consequently, 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 NH3. Moreover, when similar queues are predicted, the differences between the roadwork and normal traffic conditions are 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 are more detrimental for the environment. This situation changes in the other scenarios due to the much longer queues calculated with the macro-simulation model.

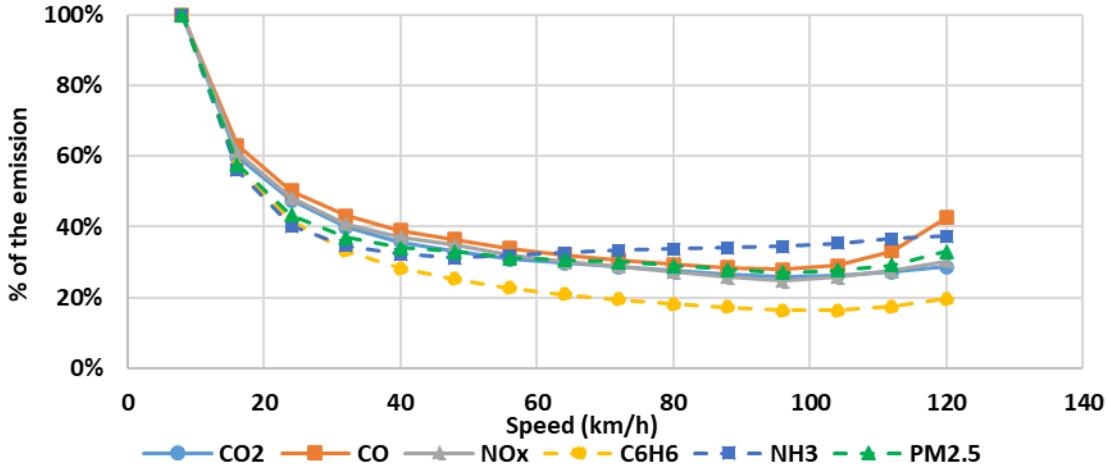


Figure 10. Relationship between vehicle emissions and speed.

The contribution of congestion to the three endpoint impacts when considering the wearing course (WC) and the whole pavement section (PS) is shown in Figure 11.

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 WC 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% in "C" LOS (S4, S5 and S6). In fact, this stage is relevant even when PS is taken into account, only being negligible (<1%) in scenario 1 when the KyUCP software is used.

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 around 2%. However, applying this same concept to the A-8 Motorway it results in an increase of more than 43% in the LCA for WC, and 18% when the results are referred to PS.

The dissimilarity between the simulation's models (micro and macro) changes with the AADT of the Motorway. 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 characterization method and 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 WC is being analysed.

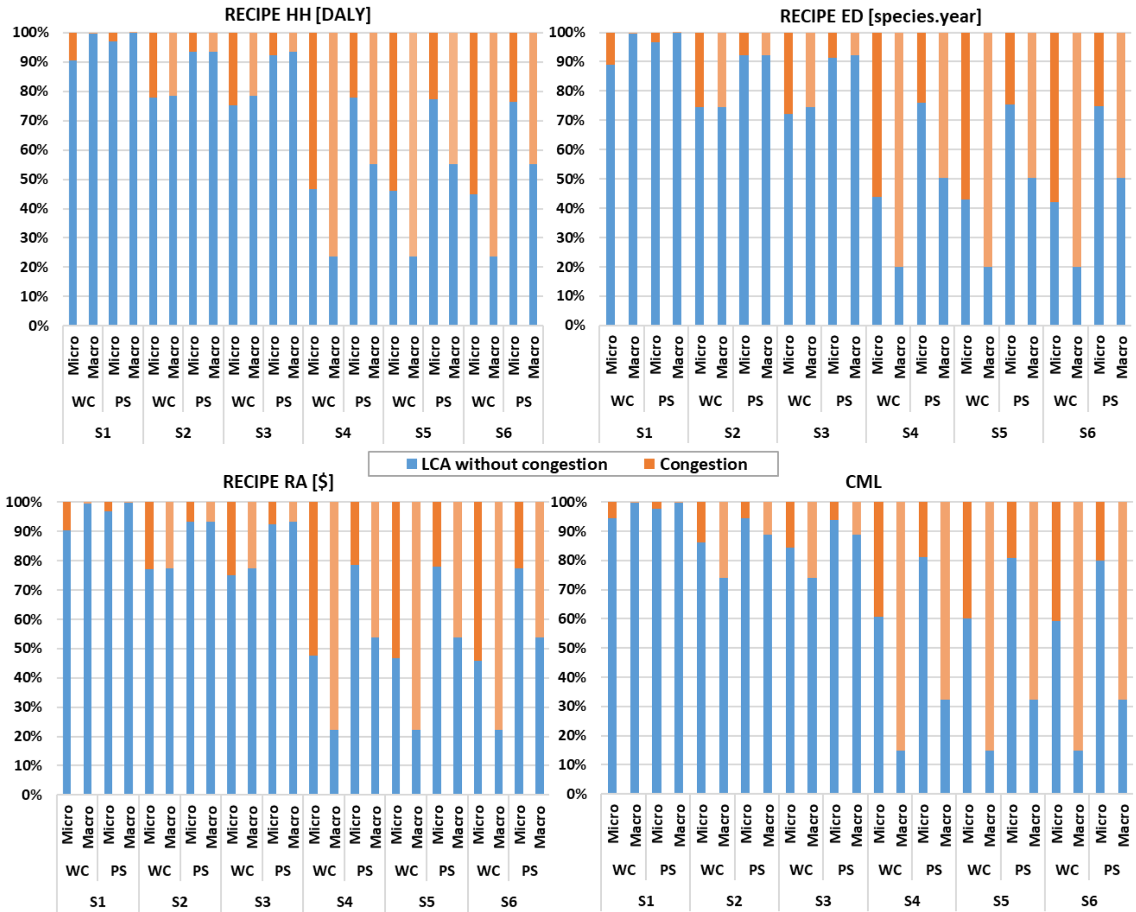


Figure 11. Contribution of congestion to the LCA of a road.

6.4. Conclusions and future lines of research

6.4.1. General conclusions

Transport infrastructures play an essential role in the social and economic development of nations by enabling the transportation of resources and by boosting trade between regions. However, it also generates environmental problems that worsen as the transport network grows and the effects of climate change increase. However, to palliate this effect not only is it necessary to foster the implementation of more durable, cost-effective and environmentally friendly practices, but it is also necessary to guarantee their sustainability by conducting analyses that take into account the particular circumstances of their implementation.

Life cycle assessment (LCA) is a standardized method that has been used for decades for this purpose but is still under development for road applications. The existence of gaps in knowledge regarding certain life stages and the lack of guidelines and methodologies to facilitate their inclusion in the analysis are leading to simplified LCAs in which aspects which could be decisive in the selection of a technology are not taken into account. For this reason, this doctoral thesis tries to alleviate these deficiencies by analysing more in-depth various aspects of the methodology that are generating uncertainty in its application to asphalt pavements.

The application of the LCA methodology to asphalt mixtures susceptible to be healed by induction heating allowed the identification of those aspects that required a more detailed study and the creation of a database. The tests and models applied to the steel slag production enabled to complete the initial database, as well as to give recommendations both on its use and on the way to perform LCAs of this type of material. The application of pavement behaviour simulation programs made evident the loss of precision obtained when making assumptions about the life of the technologies. Finally, the study of the importance of the congestion created during road maintenance activities revealed both the importance of this phase within the overall results and the importance of faithfully reproducing road geometry and vehicle behaviour.

Therefore, based on the reviewed bibliography and the studies carried out both before and during the development of this doctoral thesis, the importance of certain aspects of road life-cycle that are not usually taken into account when applying the LCA methodology is confirmed. Furthermore, the main objective of the thesis is fulfilled by proposing recommendations that facilitate the proper implementation of asphalt pavement's LCA.

6.4.2. Specific conclusions

The specific conclusions for each aspect of the LCA methodology analyzed in this doctoral thesis are summarized below.

6.4.2.1. **Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures**

- The impact allocation method which only takes into account those processes that are exclusively performed on slags is the most reasonable alternative.
- The absorption rate of slags strongly affects the LCA results, increasing the binder content of the mixture as well as the aggregate humidity.
- Slags can replace high-quality aggregates located between 144 and 296 km depending on their absorption rate and humidity.
- Bitumen coating reduces most of the chemical elements leached by the asphalt mixtures, thus, making this stage negligible when using ReCiPe.
- Using ReCiPE's endpoint impacts is recommended when reducing the number of impacts is necessary to make comparative assertions.

6.4.2.2. **Analysis of the influence of asphalt pavement durability on the LCA results**

- The durability effect is essential to obtain reliable LCA results.
- In general, static simulations provide more conservative results than dynamic analysis when they are expressed in absolute terms but provide more optimistic results when expressed percentage-wise.

- Alize and 3D-Move can be used interchangeable to calculate the relationship between the pavement's durability in a static way but not to calculate the absolute value.
- The analysis of the whole pavement when the technology is only applied in the wearing course attenuates the LCA and LCCA results.

6.4.2.3. Analysis of the relevance of the congestion produced during the maintenance activities on the LCA of a road

- 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, C_6H_6, NH_3 and $PM_{2.5}$.
- Macro-simulation should be used only for rough calculations or for preliminary analysis.
- 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.
- Alternative routes should be included in the traffic analysis.

6.4.3. Future lines of research

The development of this thesis posed the next future lines of research:

- Expanding the system's boundaries in the EAFS study to include other possible uses.
- Determine the variation of LCA results when using more advanced pavement behaviour simulation software.
- Correlating the durability of pavements calculated with computer programs with durability data obtained under more realistic conditions.
- Determine the relevance of the congestion produced during maintenance activities of national roads.
- Explore the best way to incorporate the noise produced by traffic into the LCA.

7. REFERENCIAS

[1] United Nations General Assembly, Report of the world commission on environment and development: Our common future, 1987. https://www.iisd.org/topic/sustainable-development-goals.

[2] United Nations, Sustainable Development Goals, (2015). https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[3] UEPG, European Aggregates Association. A Sustainable Industry for a Sustainable Europe, 2017. http://www.uepg.eu/uploads/Modules/Publications/uepg-ar2016-17_32pages_v10_18122017_pbp_small.PDF.

[4] Eurobitume, The bitumen industry in Europe, (2012). http://www.eurobitume.eu/bitumen/industry/ (accessed December 30, 2017).

[5] European Road Federation, Road Maintenance and Investment 2017, (2017). https://erf.be/statistics/road-maintenance-and-invenstment-2017/.

[6] UK Department for Transport, New government proposals to cut congestion on our busiest roads, (2017). https://www.gov.uk/government/news/new-government-proposals-to-cut-congestion-on-our-busiest-roads (accessed December 30, 2017).

[7] A. Jensen, E. J, K. Christiansen, H. L, M. BT, A. Schmidt, van F, Life cycle assessment (LCA) - a guide to approaches, experiences and information sources, 1998.

[8] I. Boustead, LCA — how it came about, Int. J. Life Cycle Assess. 1 (1996) 147–150. https://doi.org/10.1007/BF02978943.

[9] I.D. Dobson, Life cycle assessment for painting processes: putting the VOC issue in perspective, Prog. Org. Coatings. 27 (1996) 55–58. https://doi.org/https://doi.org/10.1016/0300-9440(95)00519-6.

[10] G.E. Kniel, K. Delmarco, J.G. Petrie, Life cycle assessment applied to process design: Environmental and economic analysis and optimization of a nitric acid plant, Environ. Prog. 15 (1996) 221–228. https://doi.org/10.1002/ep.670150410.

[11] A. Aranda, I. Zabalza, S. Scarpellini, Economic and environmental analysis of the wine bottle production in Spain by means of life cycle assessment, Int. J. Agric. Resour. Gov. Ecol. 4 (2005) 178–191. https://www.scopus.com/inward/record.uri?eid=2-s2.0-21244433946&partnerID=40&md5=01c21f853cb2fc15c899bba0822ee524.

[12] T. Häkkinen, K. Mäkelä, Environmental adaption of concrete. Environmental impact of concrete and asphalt pavements, VTT Tied. - Valt. Tek. Tutkimusk. (1996).

[13] A. Horvath, C. Hendrickson, Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements, Transp. Res. Rec. J. Transp. Res. Board. 1626 (1998) 105–113. https://doi.org/10.3141/1626-13.

[14] U.M. Mroueh, P. Eskola, J. Laine-Ylijoki, K. Wellman, E. Mäkelä, M. Juvankoski, Life cycle assessment of road construction, Finnra Reports 17/2000. (2000).

[15] A. Jullien, P. Monéron, G. Quaranta, D. Gaillard, Air emissions from pavement layers composed of varying rates of reclaimed asphalt, Resour. Conserv. Recycl. 47 (2006) 356–374. https://doi.org/https://doi.org/10.1016/j.resconrec.2005.09.004.

[16] M. Kucukvar, M. Noori, G. Egilmez, O. Tatari, Stochastic decision modeling for sustainable pavement designs, Int. J. Life Cycle Assess. 19 (2014) 1185–1199. https://doi.org/10.1007/s11367-014-0723-4.

[17] G. Lu, Y. Wang, H. Li, D. Wang, M. Oeser, The environmental impact evaluation on the application of permeable pavement based on life cycle analysis, Int. J. Transp. Sci. Technol. 8 (2019) 351–357. https://doi.org/https://doi.org/10.1016/j.ijtst.2019.05.006.

[18] B. Yu, Q. Lu, Life cycle assessment of pavement: Methodology and case study, Transp. Res. Part D Transp. Environ. 17 (2012) 380–388. https://doi.org/https://doi.org/10.1016/j.trd.2012.03.004.

[19] Worldsteel Association, World Steel in Figures 2018, 2018. https://www.worldsteel.org/en/dam/jcr:f9359dff-9546-4d6b-bed0-996201185b12/World+Steel+in+Figures+2018.pdf.

[20] J.R. Arenal, Estudio, análisis y diseño de aplicaciones de áridos procedentes de la valorización de residuos industriales : firmes de carreteras y hormigones, 2016. https://repositorio.unican.es/xmlui/handle/10902/8293.

[21] EUROSLAG, EUROFER, Position paper on the status of ferrous slag complying with the Waste Framework Directive (Articles 5/6) and the REACH Regulation, 2012. http://www.euroslag.com/fileadmin/_media/images/Status_of_slag/Position_Paper_April_2012.pdf.

[22] M. Ameri, S. Hesami, H. Goli, Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag, Constr. Build. Mater. 49 (2013) 611–617. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.08.034.

[23] A. Kavussi, M.J. Qazizadeh, Fatigue characterization of asphalt mixes containing electric arc furnace (EAF) steel slag subjected to long term aging, Constr. Build. Mater. 72 (2014) 158–166. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.08.052.

[24] M. Pasetto, N. Baldo, Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags, J. Hazard. Mater. 181 (2010) 938–948. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.05.104.

[25] S. Sorlini, A. Sanzeni, L. Rondi, Reuse of steel slag in bituminous paving mixtures, J. Hazard. Mater. 209–210 (2012) 84–91. https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.12.066.

[26] U.-M. Mroueh, P. Eskola, J. Laine-Ylijoki, Life-cycle impacts of the use of industrial by-products in road and earth construction, Waste Manag. 21 (2001) 271–277. https://doi.org/https://doi.org/10.1016/S0956-053X(00)00100-8.

[27] S. Sayagh, A. Ventura, T. Hoang, D. François, A. Jullien, Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures, Resour. Conserv. Recycl. 54 (2010) 348–358. https://doi.org/https://doi.org/10.1016/j.resconrec.2009.08.011.

[28] Y. Huang, A. Spray, T. Parry, Sensitivity analysis of methodological choices in road pavement LCA, Int. J. Life Cycle Assess. 18 (2013) 93–101. https://doi.org/10.1007/s11367-012-0450-7.

[29] A. Mladenovič, J. Turk, J. Kovač, A. Mauko, Z. Cotič, Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses, J. Clean. Prod. 87 (2015) 683–691. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.10.013.

[30] V.J. Ferreira, A. Sáez-De-Guinoa Vilaplana, T. García-Armingol, A. Aranda-Usón, C. Lausín-González, A.M. López-Sabirón, G. Ferreira, Evaluation of the steel slag incorporation as coarse aggregate for road construction: technical requirements and environmental impact assessment, J. Clean. Prod. 130 (2016) 175–186.

https://doi.org/https://doi.org/10.1016/j.jclepro.2015.08.094.

[31] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm Mix Asphalt: An overview, J. Clean. Prod. 24 (2012) 76–84. https://doi.org/10.1016/j.jclepro.2011.11.053.

[32] R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, R. Velkennedy, A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements, Constr. Build. Mater. 28 (2012) 311–320. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2011.08.031.

[33] C.J. Slebi-Acevedo, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers, Constr. Build. Mater. 234 (2020) 117224. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.117224.

[34] R. Casado-Barrasa, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Assessment of carbon black modified binder in a sustainable asphalt concrete mixture, Constr. Build. Mater. 211 (2019) 363–370. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.03.255.

[35] H. Ajam, P. Lastra-González, B. Gómez-Meijide, G. Airey, A. Garcia, Self-healing of dense asphalt concrete by two different approaches: Electromagnetic induction and infrared radiation, J. Test. Eval. 45 (2017). https://doi.org/10.1520/JTE20160612.

[36] R. Vidal, E. Moliner, G. Martínez, M.C. Rubio, Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement, Resour. Conserv. Recycl. 74 (2013) 101–114. https://doi.org/https://doi.org/10.1016/j.resconrec.2013.02.018.

[37] Q. Aurangzeb, I.L. Al-Qadi, H. Ozer, R. Yang, Hybrid life cycle assessment for asphalt mixtures with high RAP content, Resour. Conserv. Recycl. 83 (2014) 77–86. https://doi.org/https://doi.org/10.1016/j.resconrec.2013.12.004.

[38] W.K. Biswas, Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia, Int. J. Life Cycle Assess. 19 (2014) 732–744. https://doi.org/10.1007/s11367-013-0681-2.

[39] M.R. Mohd Hasan, Z. You, Estimation of cumulative energy demand and green house gas emissions of ethanol foamed WMA using life cycle assessment analysis, Constr. Build. Mater. 93 (2015) 1117–1124. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2015.05.029.

[40] T. Schlegel, D. Puiatti, H.-J. Ritter, D. Lesueur, C. Denayer, A. Shtiza, The limits of partial life cycle assessment studies in road construction practices: A case study on the use of hydrated lime in Hot Mix Asphalt, Transp. Res. Part D Transp. Environ. 48 (2016) 141–160. https://doi.org/https://doi.org/10.1016/j.trd.2016.08.005.

[41] A. Farina, M.C. Zanetti, E. Santagata, G.A. Blengini, Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement, Resour. Conserv. Recycl. 117 (2017) 204–212. https://doi.org/https://doi.org/10.1016/j.resconrec.2016.10.015.

[42] D. Landi, M. Marconi, E. Bocci, M. Germani, Comparative life cycle assessment of standard, cellulose-reinforced and end of life tires fiber-reinforced hot mix asphalt mixtures, J. Clean. Prod. 248 (2020) 119295. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.119295.

[43] R. Díaz, T. Echaveguren, S. Vargas-Tejeda, Heavy load trucks and its impact in life cycle of asphalt pavements , Rev. La Constr. 11 (2012) 101–118. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84869745870&partnerID=40&md5=d8e3fa5ab6264399ad562c0428e309b2.

[44] Y.D. Wang, B. Keshavarzi, Y.R. Kim, Fatigue Performance Prediction of Asphalt Pavements with FlexPAVETM, the S-VECD Model, and DR Failure Criterion, Transp. Res. Rec. 2672 (2018) 217–227.

[45] R.A. Etheridge, Y.D. Wang, S.S. Kim, Y.R. Kim, Evaluation of Fatigue Cracking Resistance of Asphalt Mixtures Using Apparent Damage Capacity, J. Mater. Civ. Eng. 31 (2019) 4019257.

[46] L. Trupia, T. Parry, L.C. Neves, D. Lo Presti, Rolling resistance contribution to a road pavement life cycle carbon footprint analysis, Int. J. Life Cycle Assess. 22 (2017) 972–985. https://doi.org/10.1007/s11367-016-1203-9.

[47] F. Galatioto, Y. Huang, T. Parry, R. Bird, M. Bell, Traffic modelling in system boundary expansion of road pavement life cycle assessment, Transp. Res. Part D Transp. Environ. 36 (2015) 65–75. https://doi.org/https://doi.org/10.1016/j.trd.2015.02.007.

[48] N.J. Santero, E. Masanet, A. Horvath, Life-cycle assessment of pavements. Part I: Critical review, Resour. Conserv. Recycl. 55 (2011) 801–809. https://doi.org/https://doi.org/10.1016/j.resconrec.2011.03.010.

[49] L. Trupia, System Boundary Expansion in Road Pavement Life Cycle Assessment, University of Nottingham, 2018.

[50] J. Anthonissen, W. Van den bergh, J. Braet, Review and environmental impact assessment of green technologies for base courses in bituminous pavements, Environ. Impact Assess. Rev. 60 (2016) 139–147. https://doi.org/https://doi.org/10.1016/j.eiar.2016.04.005.

[51] N. Santero, E. Masanet, A. Horvath, Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research, 2010. https://doi.org/10.2172/985846.

[52] C. Kim, M. Ostovar, A. Butt A, T. Harvey J, Fuel Consumption and Greenhouse Gas Emissions from On-Road Vehicles on Highway Construction Work Zones, Int. Conf. Transp. Dev. 2018. (2018). https://doi.org/doi:10.1061/9780784481561.028.

[53] CEDR, CEDR Transnational Road Research Program. Call 2017, New Mater. Tech. (2017).

[54] E. Lizasoain-Arteaga, I. Indacoechea-Vega, P. Pascual-Muñoz, D. Castro-Fresno, Environmental impact assessment of induction-healed asphalt mixtures, J. Clean. Prod. 208 (2019) 1546–1556. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.223.

[55] E. Lizasoain-Arteaga, P. Lastra-González, I. Indacoechea-Vega, G. Flintsch, Comprehensive analysis of the environmental impact of electric arc furnace steel slag on asphalt mixtures, J. Clean. Prod. 275 (2020) 123121. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.123121.

[56] I. Rodríguez-Fernández, E. Lizasoain-Arteaga, P. Lastra-González, D. Castro-Fresno, Mechanical, environmental and economic feasibility of highly sustainable porous asphalt mixtures, Constr. Build. Mater. 251 (2020) 118982. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.118982.

[57] E. Lizasoain-Arteaga, I. Indacoechea-Vega, B. Alonso, D. Castro-Fresno, Influence of

traffic delay produced during maintenance activities on the life cycle assessment of a road, J. Clean. Prod. 253 (2020). https://doi.org/10.1016/j.jclepro.2020.120050.

[58] ISO, ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework, 2 nd. International Organization for Standardization, 2006.

[59] ISO, ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standardization, 2006.

[60] UNE-EN, UNE-EN 15804:2012+A1:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2012.

[61] NREL, U.S. Life Cycle Invent. Database. (2012). https://www.lcacommons.gov/nrel/search (accessed November 19, 2012).

[62] A. Jullien, C. Proust, T. Martaud, E. Rayssac, C. Ropert, Variability in the environmental impacts of aggregate production, Resour. Conserv. Recycl. 62 (2012) 1–13. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.02.002.

[63] UNPG, Module d'informations environnementales de la production de granulats issus de roches meubles., 2011.

[64] UNPG, Module d'informations environnementales de la production de granulats issus de roches massives, 2011.

[65] H. Stripple, Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis, 2001.

[66] RE-ROAD, Life Cycle Assessment of Reclaimed Asphalt, 2012.

[67] Y. Huang, Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements, 2007.

[68] Athena, Cement and Structural Concrete Oroducts: Life Cycle Inventory Update #2, 2005.

[69] M.L. Marceau, M. a Nisbet, M.G. Vangeem, Life Cycle Inventory of Portland Cement Concrete, Cycle. (2007).

[70] UNPG, Module d'informations environnementales de la production de granulats recyclés, (2011).

[71] A. Di Maria, M. Salman, M. Dubois, K. Van Acker, Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag, Int. J. Life Cycle Assess. 23 (2018) 2091–2109. https://doi.org/10.1007/s11367-018-1440-1.

[72] R.I. Iacobescu, G.N. Angelopoulos, P.T. Jones, B. Blanpain, Y. Pontikes, Ladle metallurgy stainless steel slag as a raw material in Ordinary Portland Cement production: a possibility for industrial symbiosis, J. Clean. Prod. 112 (2016) 872–881. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.06.006.

[73] EU, Directive 2008/98/EC of the European parliament and of the council on waste and repealing certain directives, (2008).

[74] G. Habert, A method for allocation according to the economic behaviour in the EU-ETS for by-products used in cement industry, Int. J. Life Cycle Assess. 18 (2013) 113–126. https://doi.org/10.1007/s11367-012-0464-1.

[75] M. Saade, M. Silva, V. Silva, Environmental impact allocation methods and their

reflection on the attractiveness of blast furnace slag in cement industry, 2013.

[76] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete, Resour. Conserv. Recycl. 54 (2010) 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001.

[77] PE International, Harmonization of LCA Methodologies for Metals, 2014. http://www.world-aluminium.org/media/filer_public/2017/06/29/harmonization-lca-methodologies-metals.pdf.

[78] B. Reza, R. Sadiq, K. Hewage, Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads, Clean Technol. Environ. Policy. 16 (2014) 251–266.

[79] B. Weidema, Avoiding Co-Product Allocation in Life-Cycle Assessment, 4 (2001).

[80] M. Martin, N. Svensson, M. Eklund, Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis, J. Clean. Prod. 98 (2015) 263–271. https://doi.org/10.1016/j.jclepro.2013.06.024.

[81] M. Maldonado, Suben los precios del alambrón en el sur de Europa, (2018). https://es.linkedin.com/pulse/suben-precios-del-alambrón-en-el-sur-de-europa-manuel-maldonado.

[82] Letsrecycle, Ferrous scrap metal prices, (2018). https://www.letsrecycle.com/prices/metals/ferrous-metal-prices/ferrous-scrap-metal-prices-2018/.

[83] D. Peinado, M. de Vega, N. García-Hernando, C. Marugán-Cruz, Energy and exergy analysis in an asphalt plant's rotary dryer, Appl. Therm. Eng. 31 (2011) 1039–1049. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.11.029.

[84] O. Stotko, Energy and Related Carbon Emission Reduction Technologies for Hot Mix Asphalt Plants, 10th Conf. Asph. Pavements South. Africa - CAPSA. 8000 (2011) 1–9.

[85] N. Bueche, Évaluation des performances et des impacts des enrobés bitumineux tièdes, EPFL PP - Lausanne, 2011. https://doi.org/10.5075/epfl-thesis-5169.

[86] I. Gillespie, Quantifying the Energy Used in an Asphalt Coating Plant, (2012) 164.

[87] UNE-EN, UNE-EN 12457-4:2002 Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size re, (2002).

[88] J.. Nicholls, I. Carswell, C. Thomas, B. Sexton, Bituminous surfacing material and techniques – how suitable are they for urban conditions?, 2012.

[89] EAPA, Long-Life Asphalt Pavements. Technical version, 2007. https://eapa.org/wp-content/uploads/2018/07/llp_technical2007.pdf.

[90] CEDR, CEDR Transnational Road Research Programme Call 2012: Recycling: Road construction in a post-fossil fuel society., (2012).

[91] National Research Council (U.S.). Transportation Research Board., HCM 2010 : highway capacity manual., (2010).

[92] Ministerio de Fomento, Mapas de tráfico, (2017). https://www.fomento.gob.es/carreteras/trafico-velocidades-y-accidentes-mapa-estimacion-y-evolucion/mapas-de-trafico/2017.

[93] A. Erke, F. Sagberg, R. Hagman, Effects of route guidance variable message signs (VMS) on driver behaviour, Transp. Res. Part F Traffic Psychol. Behav. 10 (2007) 447–457. https://doi.org/https://doi.org/10.1016/j.trf.2007.03.003.

[94] R. Koo, Y. Yim, Commuter Response to Traffic Information on an Incident, Transp. Res. Rec. 1621 (1998) 36–42. https://doi.org/10.3141/1621-05.

[95] V. Knoop, S. Hoogendoorn, H. van Zuylen, Rerouting behaviour of travellers under exceptional traffic conditions — an empirical analysis of route choice, Procedia Eng. 3 (2010) 113–128. https://doi.org/10.1016/j.proeng.2010.07.012.

[96] R. Kucharski, G. Gentile, Simulation of rerouting phenomena in Dynamic Traffic Assignment with the Information Comply Model, Transp. Res. Part B Methodol. 126 (2019) 414–441. https://doi.org/https://doi.org/10.1016/j.trb.2018.12.001.

[97] Ministerio de Fomento, Norma de carreteras 8.3-IC. Señalización de obras, 1989.

[98] L. Int Panis, S. Broekx, R. Liu, Modelling instantaneous traffic emission and the influence of traffic speed limits, Sci. Total Environ. 371 (2006) 270–285. https://doi.org/https://doi.org/10.1016/j.scitotenv.2006.08.017.

[99] J.L. Jiménez-Palacios, Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing, PhD dissertation. Massachusetts Institute of Technology, Cambridge, Mass, 1999.

[100] J. Koupal, M. Cumberworth, H. Michaels, M. Beardsley, D. Brzezinski, Design and Implementation of MOVES: EPAís New Generation Mobile Source Emission Model, 2003.

[101] NAPA, Product Category Rules (PCR) For Asphalt Mixtures, 2016.

[102] RIVM, ReCiPe 2016 V1.1, 2016.

[103] PE International, Best Practice LCA: Impact Assessment, (2014).

[104] G. Huppes, L. Van Oers, Evaluation of Weighting Methods for Measuring the EU-27 Overall Environmental Impact, 2011.

[105] O. Abbe, L. Hamilton, BRE Global Environmental Weighting for Construction Products using Selected Parameters from EN 15804, 2017.

[106] Dirección General de Carreteras, Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Spanish General Technical Specifications for Roads and Bridge Works, PG-3), 2017. https://fomento.gob.es/NR/rdonlyres/7E090150-7354-4F83-8D4E-E4BA2BE70717/141045/PG3_PARTE_5.pdf.

[107] J.. Nicholls, I. Carswell, C. Thomas, B. Sexton, Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring, 674 TRL Rep. (2010).

[108] H. Saveyn, P. Eder, E. Garbarino, L. Muchova, O. Hjelmar, H. van der Sloot, R. Comans, A. van Zomeren, J. Hyks, A. Oberender, Study on methodological aspects regarding limit values for pollutants in aggregates in the context of the possible development of end-of-waste criteria under the EU Waste Framework Directive, 2014. https://doi.org/10.2791/1125.

[109] European Commission, Guide to Cost-Benefit Analysis of Investment Projects, 2014.

[110] M. de Fomento, Ordin Circular 37/2016. Base de precios de referencia de la Dirección General de Carreteras., 2016.

[111] CYPE Ingenieros, Generador de Precios. España, (2019). http://www.generadordeprecios.info/.

[112] A. Moral Quiza, La herramienta ambiental Análisis del Ciclo de Vida en el estudio de secciones de firme., 2016.

[113] G.W. Flintsch, A. Loulizi, S.D. Diefenderfer, K.A. Galal, B.K. Diefenderfer, Asphalt materials characterization in support of implementation of the proposed mechanistic-empirical pavement design guide, Final Contract Rep. VTRC 07-CR10. (2007).

[114] Ministerio de Fomento., Norma 6.1-IC. Secciones de firme, 2003.

[115] C.-T. Chiu, T.-H. Hsu, W.-F. Yang, Life cycle assessment on using recycled materials for rehabilitating asphalt pavements, Resour. Conserv. Recycl. 52 (2008) 545–556. https://doi.org/https://doi.org/10.1016/j.resconrec.2007.07.001.

[116] Caltrans, Life-Cycle Cost Analysis Procedures Manual, 2007.

[117] N. Geroliminis, C.F. Daganzo, Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings, Transp. Res. Part B Methodol. 42 (2008) 759–770. https://doi.org/https://doi.org/10.1016/j.trb.2008.02.002.

[118] B. Alonso, A. Ibeas, G. Musolino, C. Rindone, A. Vitetta, Effects of traffic control regulation on Network Macroscopic Fundamental Diagram: a statistical analysis of real data., Transp. Res. Par A Policy Pract. (2019).

[119] I.I. Sirmatel, N. Geroliminis, Economic Model Predictive Control of Large-Scale Urban Road Networks via Perimeter Control and Regional Route Guidance, IEEE Trans. Intell. Transp. Syst. 19 (2018) 1112–1121. https://doi.org/10.1109/TITS.2017.2716541.

[120] X. Wu, H.X. Liu, N. Geroliminis, An empirical analysis on the arterial fundamental diagram, Transp. Res. Part B Methodol. 45 (2011) 255–266. https://doi.org/https://doi.org/10.1016/j.trb.2010.06.003.

[121] M. Yildirimoglu, I.İ. Sırmatel, N. Geroliminis, Hierarchical control of heterogeneous large-scale urban road networks via path assignment and regional route guidance, 2018. https://doi.org/10.1016/j.trb.2018.10.007.