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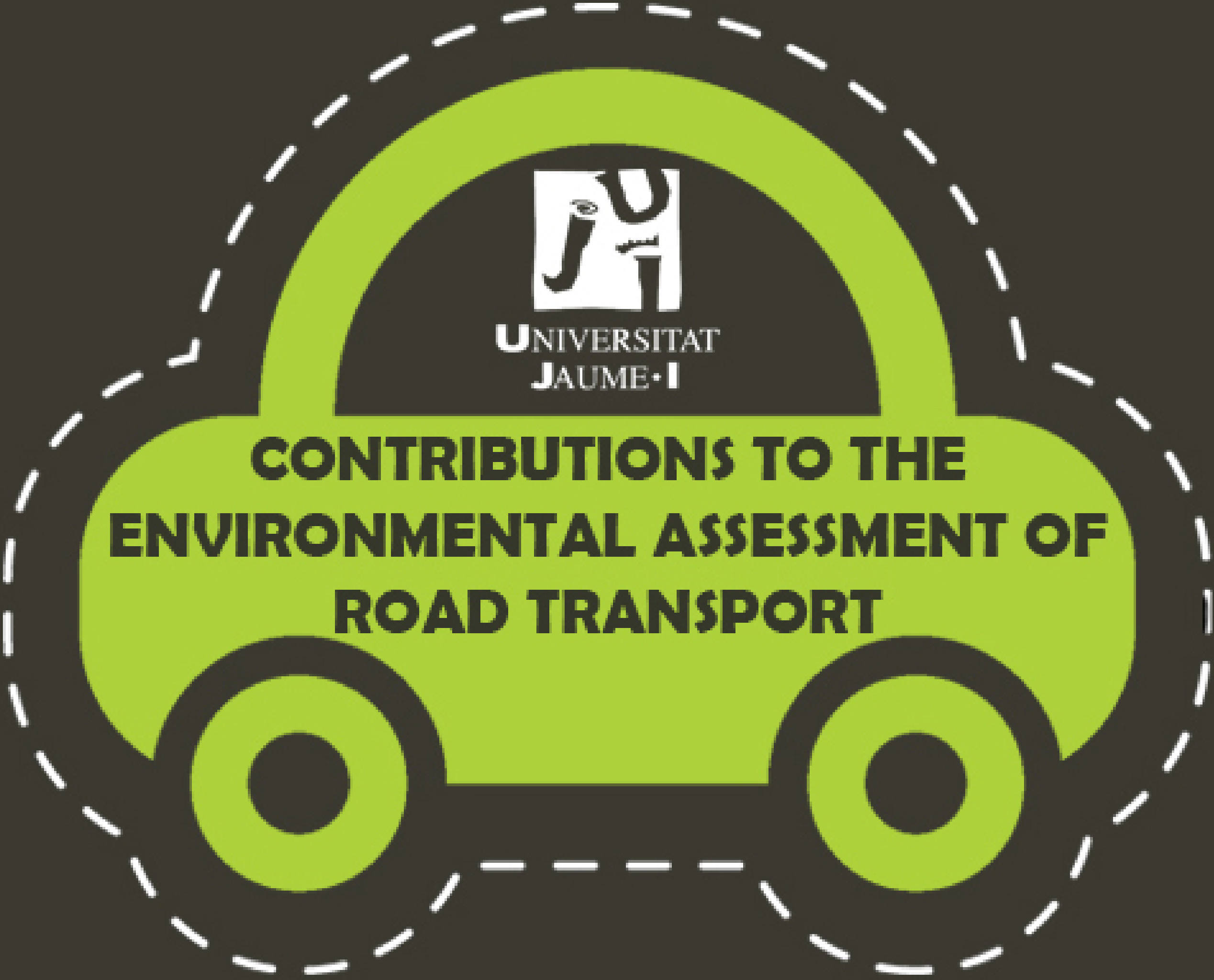
Department of Mechanical Engineering and Construction



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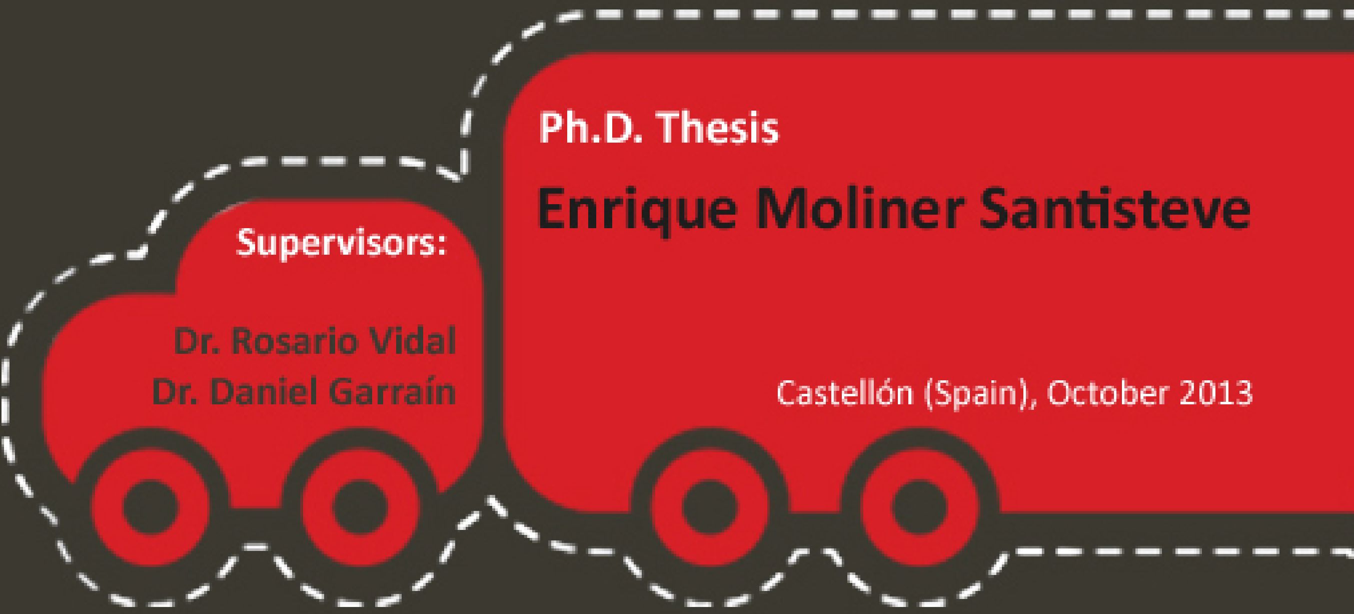
CONTRIBUTIONS TO THE ENVIRONMENTAL ASSESSMENT OF ROAD TRANSPORT



Ph.D. Thesis

Enrique Moliner Santisteve

Supervisors:

Dr. Rosario Vidal
Dr. Daniel Garraín

Castellón (Spain), October 2013

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Ph.D. Thesis

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Castellón (Spain), October 2013

Initial declaration

This thesis is organized as a series of papers published in indexed journals and in a peer-reviewed publication of selected papers from an international conference. The references of the research papers are listed below:

Vidal R, Moliner E, Martínez G, Rubio MC. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resources, Conservation and Recycling 2013;74:101–14.

Garraín D, Franco V, Vidal R, Moliner E, Casanova S. The noise impact category in life cycle assessment. In: Selected Proceedings from the 12th International Congress on Project Engineering; 2009. p. 211–21.

Moliner E, Vidal R, Franco V, Garraín D. A method to assess the impact of road transport noise within the framework of life cycle assessment. DYNA (accepted for publication 16 September 2013).

Moliner E, Vidal R, Franco V. A fair method for the calculation of the external costs of road traffic noise according to the Eurovignette Directive. Transportation Research Part D: Transport and Environment 2013;24:52–61.

All authors have given permission for the papers to be included in this thesis.

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Abstract

The aim of this thesis is to provide more insight into certain environmental issues of road transport that have not yet been investigated in depth. Specifically, the thesis addressed the following lines of research: life cycle assessment (LCA) of road pavements, LCA of noise from road transport, and valuation of external costs of noise from road transport.

The environmental assessment of road transport has usually focused on the environmental impacts of air pollutant emissions from vehicles on the roads, whereas the impacts of construction, maintenance and end-of-life of the roads have not received much attention. The LCA methodology can be useful to overcome this gap, since it is aimed at assessing the environmental impacts associated with all the life cycle stages of a product or service from the cradle to the grave. A comprehensive LCA of road pavements was conducted in this thesis, and an LCA-based tool was developed to automatically calculate the environmental impacts of road pavements. Different types of pavements were investigated, including hot mix asphalt (HMA, manufactured at 165 °C), warm mix asphalt (WMA, manufactured at 135 °C) with the addition of synthetic zeolites, and asphalt mixes with reclaimed asphalt pavement (RAP). The environmental impacts associated with energy consumption and air emissions were assessed, as well as other environmental impacts resulting from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic on the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. Monte Carlo simulations were also conducted to take into account the variability of critical input parameters. Taking into account the entire life cycle, it was found that the impacts of zeolite-based WMA pavements are almost equal to the impacts of HMA pavements with the same RAP content. The reduction in the impacts of WMA resulting from the lowering of the manufacturing temperature is offset by the greater impacts of the materials used, especially the impacts of the synthetic zeolites. Moreover, by comparing asphalt mixes with different RAP contents, it was shown that the impacts of asphalt mixes are significantly reduced when RAP is added. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% of RAP. A key advantage of WMA is the potentially greater use of RAP. Therefore, the decrease in the impacts achieved by adding large amounts of RAP to WMA could turn these asphalt mixes into a good alternative to HMA in environmental terms.

Unlike other pollutants from road transport (e.g., gaseous emissions), noise has rarely been addressed in LCA studies because it has special characteristics (dependence on local factors, lack of linear additivity of emissions, and so forth) that complicate the assessment of its impact. The lack of data on noise has been an additional problem for the impact assessment. However, the recent publication of the strategic noise maps offers the opportunity to overcome these limitations. A method was developed in this thesis to assess the impact of noise from road transport and to incorporate it into the framework of LCA. This method overcomes the methodological limitations found in previous work and uses data from strategic noise maps to perform the assessments. The impacts on health due to noise are quantified in DALYs (disability-adjusted life years), thus allowing the comparison and aggregation of noise with other pollutants harmful to health. A case study was conducted where the method was applied to calculate the noise impact caused by an additional heavy vehicle on three different roads. The noise impact caused by the heavy vehicle differed significantly (up to twofold) between roads due to the dependence of noise impact on local factors, such as traffic conditions and population density close to the roads. The extrapolation of the results obtained for a particular road to other roads may therefore lead to substantial under- or overestimation of noise impacts, the error involved being difficult to predict. For this reason, noise impact assessments differentiated for each particular case are recommended, provided that traffic and noise exposure data are available. The method provided here allows such assessments to be performed in a simple yet effective way based on publicly available data from strategic noise maps. Moreover, the noise impact caused by the heavy vehicle was compared and aggregated with the health impacts due to fuel consumption and air pollutant emissions from the same vehicle. The noise impact accounted for between 2.58% and 4.96% of the total impact caused by the additional heavy vehicle. Noise was the third most significant impact category in terms of damage to human health, being surpassed only by climate change and particulate matter formation. Noise from road transport may therefore have a significant impact in comparison with other impact categories typically assessed in LCA, which justifies its inclusion as a usual impact category in LCA studies of road transport.

An efficient way to reduce the environmental impacts of road transport is to internalise the external costs of such impacts by means of pricing instruments; e.g., charges to road users according to the pollution they produce. These charges may encourage users to use cleaner vehicle technologies and optimize their logistic behaviour, whilst the revenues from charges can be used to reduce pollution at source and promote sustainable mobility. The Eurovignette Directive allows EU Member States to levy infrastructure charges in order to compensate for the external costs of noise caused by heavy goods vehicles (HGVs). To this end, it provides a method for the calculation of the external costs of road traffic noise. This method requires the use of noise weighting factors for vehicle classes and times of the day to allow for differentiation in noise costs, but the Eurovignette Directive does not provide specific values or guidelines to calculate these factors. For this reason, an alternative method was developed in this thesis to calculate the external costs of road traffic noise in Europe. It also included the development of improved noise weighting factors to be used in the method. These factors are more reliable than those found in earlier studies, as they are highly differentiated to better account for the influence of key cost drivers, namely vehicle class, speed and time of the day. The method provided here allows distance-based charges to be calculated for any vehicle class (passenger cars, vans, HGVs, mopeds and motorcycles) and time of the day (day, evening and night), whereas the method of the Eurovignette Directive only applies to HGVs for day and night. A case study was conducted where the alternative method was applied to calculate the average noise costs per vehicle-kilometre by vehicle class and time of the day for three different roads. The noise costs differed significantly (up to almost threefold) between roads due to the dependence of noise costs on local factors. If a top-down approach had been applied, as laid down in the Eurovignette Directive, the noise costs would have been equal for all roads, which is inconsistent with the 'polluter pays' principle that should guide the charging for the use of road infrastructure. Moreover, it was found that the lack of differentiation by vehicle speed in the weighting factors given in previous studies may lead to a misjudgement of the noise costs attributable to vehicles of different classes. If weighting factors from another study had been used in the case study instead the improved factors, the error involved would have ranged from −37.36% to −24.27% for one passenger car and from 30.24% to 57.46% for one HGV, depending on the road. The charges to be borne by HGVs would have thus been highly overestimated, which is also inconsistent with the polluter pays principle.

Resumen

El objetivo de esta tesis es proporcionar un mayor grado de conocimiento sobre ciertos aspectos medioambientales del transporte por carretera que aún no han sido investigados en profundidad. En concreto, la tesis aborda las siguientes líneas de investigación: análisis del ciclo de vida (ACV) de los pavimentos de carreteras, ACV del ruido del transporte por carretera, y valoración de los costes externos del ruido del transporte por carretera.

La evaluación ambiental del transporte rodado se ha centrado fundamentalmente en los impactos ambientales de las emisiones atmosféricas de los vehículos que circulan por las carreteras, mientras que los impactos de la construcción, mantenimiento y fin de vida de las carreteras no han recibido demasiada atención. La metodología del ACV puede ser útil para abordar esta limitación, ya que tiene como objetivo evaluar los impactos ambientales asociados a todas las etapas del ciclo de vida de un producto o servicio desde la cuna hasta la tumba. En esta tesis se ha realizado un ACV exhaustivo de pavimentos de carreteras, y se ha desarrollado una herramienta de ACV para calcular de forma automática los impactos ambientales de los pavimentos. Se han analizado distintos tipos de pavimentos, incluyendo mezclas bituminosas en caliente (MBC, fabricadas a 165 °C), mezclas bituminosas templadas (MBT, fabricadas a 135 °C) mediante la adición de zeolitas sintéticas, y mezclas bituminosas con pavimento asfáltico reciclado (PAR). De este modo, se han evaluado los impactos ambientales asociados al consumo de energía y a las emisiones atmosféricas, así como otros impactos ambientales debidos a la extracción y procesado de minerales, betunes y aditivos químicos; fabricación de asfaltos; transporte de materiales; pavimentación; tráfico durante la vida útil del pavimento; transformación y ocupación del suelo; desmantelamiento del pavimento al final de su vida útil y su reciclaje o eliminación en vertedero. También se han realizado simulaciones mediante el método de Monte Carlo para tener en cuenta la variabilidad de ciertos parámetros de entrada críticos. Al considerar todo el ciclo de vida, se ha observado que los impactos de los pavimentos de MBT a base de zeolita son casi idénticos a los impactos de los pavimentos de MBC con el mismo contenido de PAR. La reducción de los impactos que se obtiene en las MBT al disminuir la temperatura de fabricación queda contrarrestada por los mayores impactos de los materiales utilizados, sobre todo los impactos de las zeolitas sintéticas. Por otro lado, al comparar mezclas bituminosas con distintos contenidos de PAR, se ha observado que los impactos de las mezclas se reducen de forma significativa al añadir PAR. Todos los impactos en las categorías "de punto final", así como los impactos en las categorías de cambio climático, agotamiento de recursos fósiles y demanda de energía acumulada, se han reducido un 13–14% mediante la adición de un 15% de PAR. Una ventaja clave de las MBT es el uso potencialmente mayor de PAR. Por lo tanto, la reducción de los impactos que se consigue añadiendo grandes cantidades de PAR a las MBT podría convertirlas en una buena alternativa a las MBC desde el punto de vista medioambiental.

A diferencia de otros contaminantes del transporte rodado (por ejemplo, las emisiones gaseosas), el ruido rara vez se incluye en los estudios de ACV, debido a que tiene ciertas particularidades (dependencia de factores locales, imposibilidad de agregar linealmente sus emisiones, etc.) que dificultan la evaluación de su impacto. La escasez de datos sobre ruido ha supuesto un inconveniente añadido para evaluar su impacto. Sin embargo, la publicación reciente de los mapas estratégicos de ruido ofrece la oportunidad de superar estas limitaciones. En esta tesis se ha desarrollado un método para evaluar el impacto del ruido del transporte rodado e integrarlo en el marco del ACV. Este método resuelve las limitaciones metodológicas observadas en otros trabajos previos y permite realizar las evaluaciones a partir de datos de los mapas estratégicos de ruido. Los impactos del ruido sobre la salud se cuantifican en DALYs (años de vida ajustados por discapacidad), posibilitando la comparación y agregación del ruido con otros contaminantes nocivos para la salud. La tesis también incluye un caso de estudio donde el método propuesto se ha aplicado para calcular el impacto del ruido causado por un vehículo pesado adicional en tres carreteras distintas. El impacto del ruido causado por el vehículo pesado varía considerablemente de una carretera a otra (hasta el punto de doblarse), debido a la dependencia del impacto del ruido de factores locales, como las condiciones de tráfico y la densidad de población cercana a las carreteras. La extrapolación de los resultados obtenidos para una carretera determinada a otras carreteras puede, por lo tanto, conducir a estimaciones erróneas de los impactos del ruido, siendo difícil predecir el error incurrido. Por esta razón, se recomienda realizar evaluaciones específicas del impacto del ruido para cada caso particular, siempre que haya datos de tráfico y de exposición al ruido. El método propuesto permite realizar tales evaluaciones de forma sencilla y eficaz a partir de datos públicos disponibles en los mapas estratégicos de ruido. Además, el impacto del ruido causado por el vehículo pesado se ha comparado y agregado con los impactos sobre la salud debidos al consumo de combustible y a las emisiones atmosféricas de ese mismo vehículo. El impacto del ruido ha supuesto entre el 2,58% y el 4,96% del impacto total causado por el vehículo pesado adicional. El ruido ha resultado ser la tercera categoría de impacto más significativa en términos de daños a la salud, únicamente superado por el cambio climático y por la formación de partículas. Por lo tanto, el ruido del transporte rodado puede tener un impacto significativo comparado con otras categorías de impacto evaluadas normalmente en el ACV, lo que justifica su inclusión como categoría de impacto habitual en los estudios de ACV del transporte rodado.

Una solución eficaz para reducir los impactos ambientales del transporte rodado es internalizar los costes externos de tales impactos mediante instrumentos de tarificación; por ejemplo, tasas a los usuarios de las carreteras según la contaminación que producen. Estas tasas pueden alentar a los usuarios a utilizar tecnologías del automóvil más limpias y a optimizar sus comportamientos logísticos, mientras que los ingresos de las tasas pueden destinarse a reducir la contaminación en su origen y a fomentar la movilidad sostenible. La Directiva Euroviñeta permite a los Estados miembros de la UE aplicar tasas a los vehículos pesados con el fin de compensar los costes de la contaminación acústica que originan. Para ello, proporciona un método para el cálculo de los costes externos del ruido del tráfico rodado. Este método requiere el uso de factores de ponderación para cada categoría de vehículo y para cada período del día con vistas a permitir la diferenciación de los costes del ruido, sin embargo, la Directiva Euroviñeta no proporciona valores específicos o directrices para el cálculo de tales factores. Por esta razón, en esta tesis se ha desarrollado un método alternativo para calcular los costes externos del ruido del tráfico rodado en Europa. Asimismo, se han desarrollado factores de ponderación mejorados que constituyen la base del método propuesto. Estos factores son más fiables que los que se aportan en otros estudios, ya que están altamente diferenciados para reflejar de forma precisa la influencia de los factores clave, como la categoría de vehículo, la velocidad y el período del día. El método propuesto permite obtener tasas basadas en la distancia para cualquier categoría de vehículo (turismos, furgonetas, vehículos pesados, ciclomotores y motocicletas) y período del día (día, tarde y noche), mientras que el método de la Directiva Euroviñeta solo es aplicable a los vehículos pesados en los períodos diurno y nocturno. La tesis también incluye un caso de estudio donde el método propuesto se ha aplicado para calcular los costes medios del ruido por vehículo-kilómetro según la categoría de vehículo y el período del día para tres carreteras distintas. Los costes del ruido difieren considerablemente de una carretera a otra (hasta el punto de casi triplicarse), debido a la dependencia de los costes del ruido de factores locales. Si se hubiera aplicado un enfoque "top-down", como establece la Directiva Euroviñeta, los costes del ruido habrían sido iguales en todas las carreteras, lo cual no es coherente con el principio de "quien contamina paga", que debe regir la tarificación por el uso de la infraestructura vial. Por otro lado, se ha comprobado que la falta de diferenciación en base a la velocidad, que presentan los factores de ponderación aportados en otros estudios previos, puede llevar a errores significativos de los costes del ruido atribuibles a los vehículos de las distintas categorías. Si en el caso de estudio se hubieran aplicado los factores de ponderación de otro estudio, el error cometido habría variado entre −37,36% y −24,27% para los turismos y entre 30,24% y 57,46% para los vehículos pesados, dependiendo de la carretera. Por lo tanto, las tasas aplicadas a los vehículos pesados se habrían sobrestimado considerablemente, lo cual también es incoherente con el principio de quien contamina paga.

Resum

L’objectiu d’aquesta tesis es proporcionar un major grau de coneixement sobre determinats aspectes mediambientals del transport per carretera que encara no han sigut investigats en profunditat. En concret, la tesis aborda les següents línees d’investigació: anàlisi del cicle de vida (ACV) dels paviments de carreteres, ACV del soroll del transport per carretera, i la valoració dels costos externs del soroll del transport per carretera.

L’avaluació ambiental del transport rodat s’ha centrat sobretot en els impactes ambientals de les emissions atmosfèriques dels vehicles que circulen per les carreteres, mentre que els impactes de la construcció, manteniment i fi de vida de les carreteres no han rebut massa atenció. La metodologia de l’ACV pot ser útil per a abordar aquesta limitació, ja que té com a objectiu avaluar els impactes ambientals associats a totes les etapes del cicle de vida d’un producte o servei des del bressol fins a la tomba. En aquesta tesis s’ha realitzat un ACV exhaustiu de paviments de carreteres, i s’ha desenvolupat una ferramenta d’ACV per a calcular de forma automàtica els impactes ambientals dels paviments. S’han analitzat diferents tipus de paviments, incloent mescles bituminoses en calent (MBC, fabricades a 165 °C), mescles bituminoses temperades (MBT, fabricades a 135 °C) mitjançant l’adició de zeolites sintètiques, i mescles bituminoses amb paviment asfàltic reciclat (PAR). D’aquesta manera s’han avaluat els impactes ambientals associats al consum d’energia i a les emissions atmosfèriques, així com altres impactes ambientals deguts a la extracció i processat de minerals, betums i additius químics; fabricació d’asfalts; transport de materials; pavimentació; tràfic durant la vida útil del paviment; transformació i ocupació del sòl; desmantellament del paviment a la fi de la seva vida útil i el seu reciclatge o eliminació en abocador. També s’han realitzat simulacions mitjançant el mètode Monte Carlo per tenir en compte la variabilitat de determinats paràmetres d’entrada crítics. Al considerar tot el cicle de vida, s’ha observat que els impactes dels paviments de MBT a base de zeolita son casi idèntics als impactes dels paviments de MBC amb el mateix contingut de PAR. La reducció dels impactes que s’obté en les MBT al reduir la temperatura de fabricació queda contrarestada pels majors impactes dels materials utilitzats, sobretot els impactes de les zeolites sintètiques. Per altra banda, al comparar mescles bituminoses amb distints continguts de PAR, s’ha observat que els impactes de les mescles es redueixen de forma significativa al afegir PAR. Tots els impactes en les categories "de punt final", així com els impactes en les categories de canvi climàtic, esgotament dels recursos fòssils i demanda d’energia acumulada, s’han reduït un 13–14% mitjançant l’addició d’un 15% de PAR. Un avantatge clau de les MBT és l’ús potencialment major de PAR. Per tant, la reducció dels impactes que es pot aconseguir afegint grans quantitats de PAR a les MBT podria convertir-les en una bona alternativa a les MBC des del punt de vista mediambiental.

A diferència d’altres contaminants del transport rodat (per exemple, les emissions gasoses), el soroll poques vegades s’inclou en els estudis d’ACV, degut a que té certes particularitats (dependència de factors locals, impossibilitat d’agregar linealment les seues emissions, etc.)

que dificulten l'avaluació del seu impacte. L'escassetat de dades sobre soroll ha suposat un inconvenient afegit per avaluar el seu impacte. Però, la recent publicació dels mapes estratègics de soroll ofereix l'oportunitat de superar aquestes limitacions. En aquesta tesis s'ha desenvolupat un mètode per avaluar l'impacte del soroll del transport rodat i integrar-lo en el marc de l'ACV. Aquest mètode resol les limitacions metodològiques observades en altres treballs previs i permet realitzar les avaluacions a partir de dades dels mapes estratègics de soroll. Els impactes del soroll sobre la salut es quantifiquen en DALYs (anys de vida ajustats per discapacitat), possibilitant la comparació i agregació del soroll amb altres contaminants nocius per a la salut. La tesis també inclou un cas d'estudi on el mètode proposat s'ha aplicat per a calcular l'impacte del soroll causat per un vehicle pesat addicional en tres carreteres distintes. L'impacte del soroll provocat pel vehicle pesat varia considerablement d'una carretera a altra (fins al punt de doblar-se), degut a la dependència de l'impacte del soroll de factors locals, com les condicions de tràfic i la densitat de població propera a les carreteres. La extrapolació dels resultats obtinguts per una carretera determinada a altres carreteres pot, per tant, conduir a estimacions errònies dels impactes del soroll, sent difícil predir l'error incorregut. Per aquesta raó, es recomana realitzar avaluacions específiques de l'impacte del soroll per a cada cas particular, sempre que hi haja dades de tràfic i d'exposició al soroll. El mètode proposat permet realitzar aquestes avaluacions de forma senzilla i eficaç a partir de dades públiques disponibles en el mapes estratègics de soroll. A més, l'impacte del soroll causat pel vehicle pesat s'ha comparat i agregat amb els impactes sobre la salut deguts al consum de combustible i a les emissions atmosfèriques d'aquest mateix vehicle. L'impacte del soroll ha suposat entre el 2,58% i el 4,96% de l'impacte total causat pel vehicle pesat addicional. El soroll ha resultat ser la tercera categoria d'impacte més significativa en termes de danys a la salut, únicament superat pel canvi climàtic i per la formació de partícules. Per tant, el soroll del transport rodat pot tenir un impacte significatiu en comparació amb altres categories d'impacte avaluades normalment en l'ACV, el que justifica la seva inclusió com a categoria d'impacte habitual en el estudis d'ACV del transport rodat.

Una solució eficaç per a reduir els impactes ambientals del transport rodat es internalitzar els costos externs d'aquests impactes mitjançant instruments de tarifació; per exemple, tasses als usuaris de les carreteres segons la contaminació que produeixen. Aquestes tasses poden animar als usuaris a utilitzar tecnologies de l'automòbil més netes i a optimitzar els seus comportaments logístics, mentre que els ingressos de les tasses es poden destinar a reduir la contaminació en el seu origen i a fomentar la mobilitat sostenible. La Directiva Eurovinyeta permet als Estats membres de la UE aplicar tasses als vehicles pesats a fi de compensar els costos de la contaminació acústica que provoquen. Per això, proporciona un mètode per al càlcul dels costos externs del soroll del tràfic rodat. Aquest mètode requereix l'ús de factors de ponderació per a cada categoria de vehicle i per a cada període del dia amb vistes a permetre la diferenciació dels costos del soroll, però, la Directiva Eurovinyeta no proporciona valors específics o directrius per al càlcul d'aquests factors. Per aquest motiu, en aquesta tesis s'ha desenvolupat un mètode alternatiu per a calcular els costos externs del soroll del tràfic rodat en Europa. Així mateix, s'han desenvolupat factors de ponderació millorats que constitueixen la base del mètode proposat. Aquests factors son més fiables que els que s’aporten en altres estudis, ja que estan altament diferenciats per a reflectir de forma precisa la influència dels factors clau, com la categoria del vehicle, la velocitat i el període del dia. El mètode proposat permet obtenir tasses basades en la distància per a qualsevol categoria de vehicle (turismes, furgonetes, vehicles pesats, ciclomotors i motocicletes) i període del dia (dia, vesprada i nit), mentre que el mètode de la Directiva Eurovinyeta només es aplicable als vehicles pesats en el períodes diürn i nocturn. La tesis també inclou un cas d’estudi on el mètode proposat s’ha aplicat per a calcular els costos mitjans del soroll per vehicle-quilòmetre segons la categoria de vehicle i el període del dia per a tres carreteres distintes. Els costos del soroll difereixen considerablement d’una carretera a altra (fins al punt de que quasi es tripliquen), degut a la dependència dels costos del soroll de factors locals. Si s’haguera aplicat un enfocament "top-down", com estableix la Directiva Eurovinyeta, els costos del soroll hagueren sigut iguals en totes les carreteres, cosa que no es coherent amb el principi de "qui contamina paga", que deu regir la tarifació per l’ús de la infraestructura vial. Per altra banda, s’ha comprovat que la falta de diferenciació en base a la velocitat, que presenten els factors de ponderació aportats en altres estudis previs, pot provocar errors significatius dels costos del soroll atribuïbles als vehicles de les diferents categories. Si en el cas d’estudi s’hagueren aplicat els factors de ponderació d’altre estudi, l’error comés haguera variat entre −37,36% i −24,27% per als turismes i entre 30,24% i 57,46% per als vehicles pesats, depenent de la carretera. Per tant, les tasses aplicades als vehicles pesats s’hagueren sobreestimat considerablement, cosa que també es incoherent amb el principi de qui contamina paga.

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List of symbols and abbreviations

$\%HA$	Percentage of highly annoyed persons
$\%HSD$	Percentage of highly sleep disturbed persons
ΔHA	Variation of the number of highly annoyed persons
ΔHH	Variation of noise damages to human health
ΔHH_{HA}	Variation of noise damages to human health related to high annoyance
ΔHH_{HSD}	Variation of noise damages to human health related to high sleep disturbance
ΔHSD	Variation of the number of highly sleep disturbed persons
ΔLA_{eq}	Variation of noise emission level of a road (in the road traffic noise model from the SAEFL)
ΔL_{den}	Variation of day-evening-night noise level
ΔL_{night}	Variation of night noise level
ΔL_{W}	Variation of noise emission level of a road (in the road traffic noise model from the CNOSSOS-EU project)
ΔQ_{CATi}	Variation of the vehicle flow of the class i
Δv_{CATi}	Variation of the average speed of the vehicle flow of the class i
€$_{2006}$ PPP	Euro adjusted to year 2006 for purchasing power parity
€ct	Euro cent
€ct$_{2006}$ PPP	Euro cent adjusted to year 2006 for purchasing power parity
ADT_{CATi}	Average daily traffic for the vehicle class i during the day-evening-night period
$ADT_{T,CATi}$	Average daily traffic for the vehicle class i during the time period T
CATi	Vehicle class i (where CAT1 are light motor vehicles, CAT2 are medium heavy vehicles, CAT3 are heavy vehicles, CAT4a are mopeds, and CAT4b are motorcycles)
CATref	Vehicle class taken as a reference (CAT1)
CC	Climate change
Cd	Cadmium
CED	Cumulative energy demand
cf.	Consult
CH_4	Methane
Cl	Cloride
CNOSSOS-EU	Common Noise Assessment Methods in Europe
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
D	Average duration of disability in years
DALY	Disability-adjusted life year (as the unit to express the damage to human health)
dB	Decibel
dBA	A-weighted decibel
den	Day-evening-night
DW	Disability weight

DW_{HA}	Disability weight for high annoyance
DW_{HSD}	Disability weight for high sleep disturbance
e	Equivalence factor between HGVs and passenger cars, as defined in the Eurovignette Directive
EAPA	European Asphalt Pavement Association
EC	Energy consumption of paving and milling machines
e_{CATi}	Weighting factor for the vehicle class i
ED	Ecosystem diversity
e.g.	For example
$EP(L_{den})$	Number of persons exposed to a 5 dBA interval of L_{den} (55–60, 60–65, 65–70, 70–75, >75)
$EP(L_{night})$	Number of persons exposed to a 5 dBA interval of L_{night} (50–55, 55–60, 60–65, 65–70, >70)
eq	Equivalent
$e_{T,CATi}$	Weighting factor for the vehicle class i according to the time of the day T
EU	European Union
EW	Effective width of paving and milling machines
FD	Fossil depletion
f_T	Weighting factor for time of the day T
$f_{T,CATi}$	Weighting factor for the time of the day T according to the vehicle class i
$f_{T,CATref}$	Weighting factor for the time of the day T according to the reference vehicle class
GVW	Gross vehicle weight
HEATCO	Developing Harmonised European Approaches for Transport Costing and Project Assessment
HGV	Heavy goods vehicle
HH	Human health
HMA	Hot mix asphalt
i	Slope of the road (in the road traffic noise model from the SAEFL)
I	Number of incident cases
i.e.	That is
IMAGINE	Improved Methods for the Assessment of the Generic Impact of Noise in the Environment
IMPACT	Internalisation Measures and Policies for All external Cost of Transport
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
K	Background noise level
LA_{eq}	Noise emission level of a road (in the road traffic noise model from the SAEFL)
LCA	Life cycle assessment
LCI	Life cycle inventory
L_{day}	Day noise indicator that represents the A-weighted long-term average sound level determined over all the day periods (12 h) of a year
L_{den}	Day-evening-night noise indicator that represents the A-weighted long-term average sound level determined over all the 24-h periods of a year
$LE1$	Noise emission level of the flow of trucks
$LE2$	Noise emission level of the flow of cars

$L_{evening}$	Evening noise indicator that represents the A-weighted long-term average sound level determined over all the evening periods (4 h) of a year
LF	Load factor
L_{night}	Night noise indicator that represents the A-weighted long-term average sound level determined over all the night periods (8 h) of a year
L_P	Noise level of a single car at a speed of 50 km/h measured at a distance of 7.5 m from the car (in the method of Doka)
$L_P(d)$	Noise level at a specific distance d from a point noise source (in the method of Nielsen and Laursen)
LPG	Liquefied petroleum gas
L_W	Sound power level
$\mathrm{L}_{W,0,CATi}$	Instantaneous sound power level emitted by a single vehicle of the class i
$L_{W,den}$	Day-evening-night sound power level
$L_{W,T}$	Equivalent sound power level per unit length emitted by the traffic during a time period T
$L_{W,T,CATi}$	Equivalent sound power level per unit length emitted by a flow of vehicles of the class i during a time period T
$\mathrm{m^2y}$	Square metre years
N	Number of passes of paving and milling machines
$N1$	Number of cars per hour
$N2$	Number of trucks per hour
N_2O	Dinitrogen monoxide
NC_{den}	Total noise cost per day and kilometre of road during the day-evening-night period
NC_{jk}	Noise cost per day per person exposed to daily noise level k from road type j, as defined in the Eurovignette Directive
NC_k	Noise cost per day per person exposed to noise level k by 5 dBA intervals of L_{den}
NC_T	Total noise cost per day and kilometre of road during the time period T
$NC_{T,CATi}$	Noise cost per day and kilometre of road for the vehicle flow of the class i during the time period T
$NCV_{den,CATi}$	Average noise cost per vehicle-kilometre for a vehicle of the class i during the day-evening-night period
$NCV_{den,CATref}$	Average noise cost per vehicle-kilometre for the reference vehicle class during the day-evening-night period
$NCV_{j,daily}$	Average daily noise cost per vehicle-kilometre for a HGV on road type j, as defined in the Eurovignette Directive
$NCV_{j,day}$	Average noise cost per vehicle-kilometre for a HGV on road type j during the day period, as defined in the Eurovignette Directive
$NCV_{j,night}$	Average noise cost per vehicle-kilometre for a HGV on road type j during the night period, as defined in the Eurovignette Directive
$NCV_{T,CATi}$	Average noise cost per vehicle-kilometre for a vehicle of the class i during the time period T
$NCV_{T,CATref}$	Average noise cost per vehicle-kilometre for the reference vehicle class during the time period T
NH_3	Ammonia
Ni	Nickel
NMVOC	Non-methane volatile organic compounds

NN_d	Noise nuisance at a specific distance d from a point noise source
NNF_{Lp}	Noise nuisance factor specific for the noise level L_p relative to the background noise level
NN_{proc}	Total noise nuisance caused by a specific process
NN_{prod}	Total nuisance from a product or service
NOISE	Noise Observation and Information Service for Europe
NO_X	Nitrogen oxides
OECD	Organisation for Economic Cooperation and Development
P	Power of paving and milling machines
PAH	Polycyclic aromatic hydrocarbons
P_d	Number of persons within a specific distance d from a point noise source
PM	Particulate, unspecified
$PM_{2.5}$	Particulates < 2.5 µm
POP_k	Number of persons exposed to noise level k by 5 dBA intervals of L_{den}
p_s	Yearly average proportion of light vehicles equipped with studded tyres
QALY	Quality-adjusted life year
Q_{CATi}	Number of vehicles of the class i per hour
$Q_{T,CATi}$	Number of vehicles of the class i per hour during the time period T
$Q_{T,CATref}$	Number of vehicles of the reference vehicle class per hour during the time period T
r^2	Coefficient of determination
RA	Resource availability
RAP	Reclaimed asphalt pavement
ReportNet–EIONET	European Environment Information and Observation Network
RF	Reduction factor of paving and milling machines
s	Slope of the road (in the road traffic noise model from the CNOSSOS-EU project)
$	Dollar (as the unit to express the damage to resource availability)
Se	Selenium
SE	Standard error
SETAC	Society of Environmental Toxicology and Chemistry
SICA	Spanish Information System on Noise Pollution
SO_2	Sulfur dioxide
SO_4	Sulfate
species.year	Species per year (as the unit to express the damage to ecosystem diversity)
T	Time of the day or time period (day, evening, or night)
T_{air}	Air temperature
T_{proc}	Duration of the noisy process (i.e., the time required to produce one unit of the product or service according to the functional unit)
v	Speed of paving and milling machines
$V1$	Average speed of the flow of cars
$V2$	Average speed of the flow trucks
v_{CATi}	Average speed of the vehicle flow of the class i
v_{CATref}	Average speed of the vehicle flow of the reference vehicle class
vkm	Vehicle-kilometre

VOC	Volatile organic compounds
$v_{T,CATi}$	Average speed of the vehicle flow of the class *i* during the time period *T*
$v_{T,CATref}$	Average speed of the vehicle flow of the reference vehicle class during the time period *T*
W	Sound power
W_0	Instantaneous sound power
$W_{0,CATi}$	Instantaneous sound power emitted by a single vehicle of the class *i*
$W_{0,CATref}$	Instantaneous sound power emitted by a single vehicle of the reference vehicle class
WADT	Weighted average daily traffic
W_{den}	Day-evening-night sound power
WMA	Warm mix asphalt
W_{ref}	Reference sound power of 10^{-12} W
W_T	Sound power for the time period *T*
$W_{T,CATi}$	Sound power per unit length emitted by a flow of vehicles of the class *i* for the time period *T*
$W_{T,CATref}$	Sound power per unit length emitted by a flow of vehicles of the reference vehicle class for the time period *T*
x	Distance to the nearest crossing with traffic lights or roundabout
YLD	Years lived with disability
YLL	Years of life lost due to premature mortality
Zn	Zinc

1

Introduction

1.1. Aim and scope

The aim of this thesis is to make a significant contribution to the field of environmental assessment of road transport. This contribution may well be useful in the planning and management of sustainable mobility policies.

The environmental assessment of road transport has usually focused on the environmental impacts of air pollutant emissions from vehicles on the roads, whereas the impacts of construction, maintenance and end-of-life of the roads have not received much attention. The life cycle assessment (LCA) methodology was used in the thesis to assess the environmental impacts of road pavements throughout their entire life cycle, including extraction and processing of raw materials, production and transportation of materials, construction, use, maintenance, and end-of-life. An LCA-based tool was also developed to automatically calculate the impacts of road pavements. Different types of asphalt pavements were thus evaluated to determine the best alternatives in environmental terms.

Unlike other pollutants (e.g., gaseous emissions), noise has rarely been addressed in LCA studies because it has special characteristics that complicate the assessment of its impact. A simple yet effective method was developed in the thesis to assess the impact of noise from road transport and to incorporate it into the framework of LCA. This method quantifies the impact of noise in such a way that it can be compared and aggregated with other impacts from road transport that are typically assessed in LCA.

The environmental assessment of noise from road transport was not only limited to the impact assessment, but it was also extended to the valuation of the external costs of noise.

A reliable method for the calculation of the external costs of noise from road transport was also developed in the thesis. This method allows distance-based charges to road users to be applied in order to cover the costs of noise pollution they produce according to the road, vehicle class and time of the day involved.

1.2. Background and need for research

This thesis has its origin in the research project 'Indicadores de impacto y vulnerabilidad de las infraestructuras de transporte' (Vidal et al., 2006), which was conducted by the Engineering Design Group of the Universitat Jaume I and funded by the Spanish Ministry of Public Works and Transport. This project addressed the methodological development of impact indicators for transport infrastructure based on LCA, risk analysis, and valuation of external costs. A total of 37 indicators were developed and grouped into the following categories: health damage due to accidents, material damage, noise, air quality, water and soil pollution, land occupation and transformation, and external costs. These indicators were then used to assess the impacts of road infrastructure in Spain. Moreover, certain issues requiring further research and methodological development were identified:

- LCA of road pavements.
- LCA of noise from road transport.
- Valuation of external costs of noise from road transport.

These are the lines of research of this thesis. Below are described in detail the limitations encountered in each line of research and how these were dealt with in the thesis.

1.2.1. Need for life cycle assessment of road pavements

The manufacturing, spreading and conservation of asphalt mixes are among the sources of environmental pollution resulting from the construction of road infrastructure. Lowering the manufacturing temperature of asphalt mixes and adding reclaimed asphalt pavement (RAP) to the mixes are some solutions to reduce the environmental impacts of road pavements (Moulthrop et al., 2007). A cleaner production of asphalt mixes requires lowering the manufacturing temperature without reducing the level of mechanical performance of the mixes. A conventional hot mix asphalt (HMA) is manufactured at a temperature of 150–190 °C, while an equivalent warm mix asphalt (WMA) is manufactured at a temperature around 20–40 °C lower. WMA is the result of recently developed technologies that involve the use of organic additives, chemical additives, water-based foaming processes, or water-containing foaming processes (Rubio et al., 2012; Zaumanis, 2010). The advantages of WMA are the following: lower energy consumption in mix production, reduced emissions, better working conditions because of the absence of harmful gases, quicker turnover to traffic, longer hauling distances, and extended paving window (Rubio et al., 2012). Another key advantage of WMA is the potentially greater use of RAP; some studies have reported RAP percentages above 50% (D’Angelo et al., 2008;

Vaitkus et al., 2009). The use of RAP in asphalt pavements can help to offset increased initial costs, conserve natural resources and avoid disposal problems (Rubio et al., 2012).

Several studies have been conducted to evaluate the potential benefits of WMA (Barthel et al., 2004; Button et al., 2007; D'Angelo et al., 2008; Kvasnak and West, 2009; Nazzal et al., 2010; Vaitkus et al., 2009). These studies have shown that emissions during the production and placement of WMA were reduced in comparison to HMA. In addition, WMA pavements have exhibited similar performance to those constructed with HMA. These studies have quantified some of the potential environmental impacts of WMA in terms of resource consumption and emissions. However, the role of the upstream supply chain, related to the production of minerals, asphalt binders and chemical additives used in asphalt mixes, and related environmental impacts associated with the transportation of materials have rarely been included in the scope of the above studies (Tatari et al., 2012).

The LCA methodology can be useful to overcome the above gaps, since it assesses the environmental impacts associated with all the life cycle stages of a product. Santero et al. (2010) provides a critical review of existing literature and modelling tools related to LCA of road pavements. Among the most cited works are the studies by Mroueh et al. (2000) and Stripple (2001), and the LCA-based tools PaLATE (Horvath, 2003), ROAD-RES (Birgisdóttir, 2005) and UK asphalt pavement LCA model (Huang et al., 2009). Most literature and tools have been focused on conventional asphalt pavements, whilst WMA pavements have rarely been considered due to the novelty of the technique. Moreover, there are some LCA studies that consider the use of RAP in asphalt pavements, such as those by Jullien et al. (2006) and Chiu et al. (2008), as well as LCA-based tools, such as PaLATE (Horvath, 2003), UK asphalt pavement LCA model (Huang et al., 2009) or the LCA model of Tatari et al. (2012).

A comprehensive LCA of road pavements is presented in this thesis. The pavements investigated include HMA and zeolite-based WMA, both with and without RAP content. As in most LCA studies of road pavements, the environmental impacts associated with energy consumption and air emissions are included, but other environmental impacts are also considered from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic during the service life of the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. Additionally, an LCA-based tool is provided to automatically calculate the environmental impacts of different road pavements.

1.2.2. Need for life cycle assessment of noise from road transport

Environmental noise is a growing concern among both the general public and policymakers in Europe. A report published by the World Health Organization (2011) indicates that at least one million healthy life years are lost every year in Western Europe due to traffic noise. Sleep disturbance and annoyance, mostly related to road traffic noise, constitute the main burden of environmental noise; one in three individuals is annoyed during the daytime and one in five has disturbed sleep at night because of traffic noise in the Western European countries.

In order to provide a common basis for tackling the problem of environmental noise across the EU, the Directive 2002/49/EC (European Commission, 2002) –also known as the Environmental Noise Directive– was adopted. In this respect, the use of harmonised indicators and methods for assessing environmental noise has a key role. According to the Environmental Noise Directive, the determination of exposure to noise must be conducted through noise mapping by using the common indicators of noise levels: L_{den} (day-evening-night noise indicator), to assess annoyance, and L_{night} (night-time noise indicator), to assess sleep disturbance. The EU Member States have made strategic noise maps for their major roads whose contents have been published recently. Although the Environmental Noise Directive refers to annoyance and sleep disturbance as indicators of the harmful effects of noise exposure, it does not provide specific methods to assess such effects. Hence, methods are still needed for quantifying the effects of noise on human health and properly attributing them to their sources.

Noise has special characteristics (dependence on local factors, lack of linear additivity of emissions, and so forth) that complicate the assessment of its impact on human health. Nevertheless, some valuable contributions towards the methodological development of the impact assessment of noise from road transport have been made in the past decade, especially in the context of LCA (Müller-Wenk, 2002, 2004; Doka, 2003; Nielsen and Laursen, 2005; Althaus et al., 2009; Franco et al., 2010). The work of Müller-Wenk (2002, 2004) is especially remarkable, since he was first to devise a comprehensive methodology to link a road transportation event to its noise impacts on health. This methodology helped raise awareness about the relevance of noise as a major source of global health impairment. However, it showed limited applicability in the context of everyday practice, and it assumed simplifications that lead to overestimation of the overall health impacts caused by transport noise (Franco et al., 2010). Bearing in mind these drawbacks, Franco et al. (2010) developed an alternative calculation method that incorporates an advanced noise emission model for road traffic, thus allowing for better accuracy in the computation of health impacts. This method was devised to be consistent with the Environmental Noise Directive (European Commission, 2002), since it uses data from strategic noise maps to calculate the effects of noise on health in terms of annoyed persons. The method of Franco et al. (2010), however, has two drawbacks: it does not consider the effects on health due to sleep disturbance, and it does not convert the effects of noise into their corresponding damage to human health.

Building upon the work of Franco et al. (2010), an extended method is provided in this thesis to assess the impact of noise from road transport and to incorporate it into LCA. The extended method quantifies not only the health effects due to annoyance but also those due to sleep disturbance. In addition, the method quantifies the damage to human health associated with the harmful effects of noise. To this end, it includes the calculation of the environmental burden of disease associated with annoyance and sleep disturbance, thus quantifying the health impact of noise in DALYs (disability-adjusted life years). The DALY indicator allows the impact of noise to be compared and aggregated with the health impacts from other pollutants that are usually assessed in LCA of road transport.

1.2.3. Need for valuation of external costs of noise from road transport

Transport gives rise to negative effects such as congestion, accidents and environmental impacts. The costs of such effects are generally labelled as external costs because these are rarely borne by the transport users. The internalisation of external costs means making such effects part of the decision-making process of transport users. The internalisation of external costs by means of pricing instruments (e.g., user charges) may encourage users to use cleaner vehicle technologies and optimize their logistic behaviour. Moreover, revenues generated from charges can be used to reduce pollution at source and mitigate its effects, improve the environmental performance of vehicles, develop alternative infrastructure for transport users, optimize logistics, and promote sustainable mobility in general.

The estimation and internalisation of external costs of transport has been an important issue in transport research and policy in Europe for many years. The European Commission addressed the matter of cost internalisation in several strategy papers (European Commission, 1995, 1998, 2001, 2006a, 2011). Pricing instruments for the internalisation of external costs of transport have been implemented through a number of EU Directives. The Eurovignette Directive (European Commision, 1999) was initially adopted to allow EU Member States to charge heavy goods vehicles (HGVs) for the use of motorways to cover construction, maintenance and operation costs. It was later amended (European Commission, 2006b) to extend the charges to all roads in the trans-European road network and to allow a limited differentiation of charges according to the amount of congestion and certain environmental criteria. It also mandated the development of a reliable model for the assessment of all external costs to serve as the basis for future calculations of infrastructure charges. To this end, the European Commission commissioned the IMPACT project (Maibach et al., 2008), which provided an overview of the state of the art and best practice in the estimation of external costs of transport. Based on this overview, the Eurovignette Directive was amended (European Union, 2011) to allow Member States to charge HGVs for the costs of air pollution and noise, providing methods for calculating these costs. In the case of noise, the calculation method provides average costs per vehicle-kilometre, which are differentiated according to a set of key cost drivers, namely location, vehicle class and time of the day. The location of the roads is taken into account by distinguishing two types of road: suburban roads, which are subject to higher noise costs as they are located close to populated areas; and interurban roads, which are subject to lower noise costs as they are located in sparsely populated areas. The calculation method requires the use of weighting factors for different vehicle classes to account for differences in noise costs among vehicle classes. The use of weighting factors for different times of the day is also required to distinguish between noise costs for day and night.

The latest revision of the Eurovignette Directive (European Union, 2011), however, has some drawbacks. Most notably, it refers to the use of weighting factors for vehicle classes and times of the day, but it does not provide specific values or guidelines to calculate such factors. Moreover, each Member State can only determine a single specific charge for each combination of vehicle class, type of road and time of the day. The method of the Eurovignette Directive applies a top-down approach to calculate the noise costs for two different types of road. This approach uses aggregated data from a large set of roads of the same type to compute the total noise costs, which are then divided by the total amount of traffic on these roads to obtain the average noise costs to be applied to all such roads. A bottom-up approach might be preferable to assess the noise costs of each particular road, or at least more detailed differentiation should be made between roads to take into account other key drivers influencing noise costs (e.g., speed on the roads).

An alternative method is provided in this thesis to calculate the external costs of noise from road transport in compliance with the Eurovignette Directive (European Union, 2011). It also includes the development of noise weighting factors to be used in the method. These factors are highly differentiated in order to account for the influence of key cost drivers, namely vehicle class, speed and time of the day. The method of the Eurovignette Directive only focuses on the charging of HGVs for day and night, while the method provided here makes it possible to extend the calculation of noise costs to any vehicle class (passenger cars, vans, HGVs, mopeds and motorcycles) and time of the day (day, evening and night).

1.3. Research objectives

The aim of this thesis is to provide more insight into certain environmental issues of road transport that have not yet been investigated in depth. In order to achieve this overall aim, the following specific research objectives were set:

Research objective 1: to provide an LCA-based tool for road pavements. This tool is aimed at quantifying and comparing the environmental impacts of various asphalt pavements (including HMA, WMA, and asphalt mixes with RAP) to determine the best alternatives in environmental terms.

Research objective 2: to provide an LCA method for the assessment of the health impact of noise from road transport. This method is aimed at comparing and adding the impact of noise with other health impacts from road transport to determine the importance of noise with respect to other impact categories typically assessed in LCA.

Research objective 3: to provide a method for the valuation of the external costs of noise from road transport. This method is aimed at calculating distance-based charges to be applied to road users according to the road, vehicle class and time of the day.

1.4. Hypotheses

Through the fulfilment of the research objectives, this thesis seeks to validate the following hypotheses:

Hypothesis 1: if the entire life cycle of road pavements is considered, the environmental benefit of WMA pavements compared to HMA pavements may not be as great as shown in many studies, due to the high impact of producing the chemical additives used in WMA.

Hypothesis 2: the environmental benefit of pavements containing RAP may be significant if the entire life cycle of road pavements is considered, because the use of RAP avoids the extraction and processing of virgin raw materials and the disposal of asphalt to landfill, but it does not significantly affect the asphalt manufacturing process.

Hypothesis 3: noise from road transport may have a significant impact in comparison with other impact categories typically assessed in LCA, and therefore it must be included as a usual impact category in LCA studies of road transport.

Hypothesis 4: the method provided by the Eurovignette Directive to calculate the external costs of noise from road transport has some drawbacks that may lead to significant inaccuracies, but it can be improved on the basis of publicly available models and datasets.

1.5. Thesis organization

This thesis is organized as a series of papers published in indexed journals and in a peer-reviewed publication of selected papers from an international conference (Table 1). A total of four research papers were written, which constitute the main body of the thesis in four self-contained chapters (from Chapter 2 to Chapter 5). Each of these chapters is organized as a research paper, including introduction, main body, conclusions, and references. The thesis also includes a final chapter containing the overall conclusions of the research and suggestions for further research. A brief summary of the contents of each of the main chapters is presented below.

1.5.1. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement

Chapter 2 presents a comprehensive LCA of road pavements, which includes HMA, WMA with the addition of synthetic zeolites, and asphalt mixes with RAP. The environmental impacts associated with energy consumption and air emissions are included, as well as other environmental impacts resulting from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic on the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. It also includes Monte Carlo simulations to take into account the variability of critical input parameters. The impacts of zeolite-based WMA pavements are thus compared to the impacts of HMA pavements with the same RAP content. The impacts of asphalt mixes with different RAP contents are also compared. Additionally, an LCA-based tool to automatically calculate the environmental impacts of different road pavements is presented.

1.5.2. The noise impact category in life cycle assessment

Chapter 3 presents a critical review of existing methods for the assessment of the impact of road transport noise on human health. It includes a discussion of the methods of Müller-Wenk (1999, 2002, 2004), Doka (2003), and Nielsen and Laursen (2003). As a result of this review, the guidelines for incorporating the noise impact into LCA are provided, and the DALY is supported as the best unit for measuring the impacts of noise on human health.

1.5.3. A method to assess the impact of road transport noise within the framework of life cycle assessment

Chapter 4 provides a method to assess the impact of road transport noise and integrate it into LCA. The way in which this method overcomes the methodological limitations found in earlier methods is explained. The health impacts due to noise are quantified in DALYs, thus allowing the comparison and aggregation of noise with other pollutants harmful to health. A case study is presented to illustrate the application of the method. The noise impact caused by an additional heavy vehicle on three different roads is thus calculated and compared with the health impacts due to fuel consumption and air emissions from the same vehicle. Through the case study, the need for specific noise impact assessments for each particular case is justified, and the importance of noise compared to other impact categories is exposed.

1.5.4. A fair method for the calculation of the external costs of road traffic noise according to the Eurovignette Directive

Chapter 5 provides a method to calculate the external costs of noise from road transport as an alternative to the method of the Eurovignette Directive (European Union, 2011). It also includes the development of improved noise weighting factors for vehicle classes and times of the day to be used in the method. A case study is presented to demonstrate the application of the alternative method. The average noise costs per vehicle-kilometre by vehicle class and time of the day are thus calculated for three different roads. Through the case study, the advantages of the alternative method compared to the method of the Eurovignette Directive are demonstrated.

Table 1. Thesis as a series of research papers.

Chapter	Research paper	Impact Factor	Quartile in Category
Chapter 2	Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resources, Conservation and Recycling 2013;74:101–14.	2.319	Q2
Chapter 3	The noise impact category in life cycle assessment. In: Selected Proceedings from the 12th International Congress on Project Engineering; 2009. p. 211–21.	-	-
Chapter 4	A method to assess the impact of road transport noise within the framework of life cycle assessment. DYNA (accepted for publication 16 September 2013).	0.237	Q4
Chapter 5	A fair method for the calculation of the external costs of road traffic noise according to the Eurovignette Directive. Transportation Research Part D: Transport and Environment 2013;24:52–61.	1.291	Q2

Note: Impact Factor and Quartile in Category were obtained from the Journal Citation Reports®.

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2

Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement

Resources, Conservation and Recycling 74 (2013) 101–114

2.1. Introduction

The asphalt paving industry is constantly looking for solutions to improve pavement performance, increase construction efficiency, conserve resources and advance environmental stewardship. Lowering the manufacturing temperature of the asphalt mixes and adding reclaimed asphalt pavement (RAP) to the mixes are among the solutions identified to reduce the environmental impacts of asphalt pavements (Moulthrop et al., 2007).

A cleaner production of asphalt mixes requires lowering the manufacturing temperature of these mixes without reducing their level of mechanical performance. This temperature reduction has led to the following temperature-based classification of asphalt mixes: hot mix asphalt (150–190 °C), warm mix asphalt (100–140 °C), half-warm mix asphalt (60–100 °C), and cold mixes (0–40 °C) (EAPA, 2010; Vaitkus et al., 2009). A typical warm mix asphalt (WMA) is manufactured at a temperature around 20–40 °C lower than an equivalent hot mix asphalt (HMA). The temperature reduction in WMA is the result of recently developed technologies that involve the use of organic additives (e.g., Sasobit®), chemical additives (e.g., Evotherm®), water-based foaming processes (e.g., Double Barrel Green®) or water-containing foaming processes (e.g., Aspha-Min®) (Rubio et al., 2012; Zaumanis, 2010). Water-containing technologies produce a foaming process by using synthetic zeolites, which are composed of aluminosilicates of alkali metals and have been hydro-thermally crystallized. The crystallization is approximately 20% water, which is released from the zeolite structure as the temperature rises. This causes a micro-foaming effect in the asphalt mix: when the water is mixed with the hot bitumen, the high temperatures cause it to evaporate and the steam is entrapped, thus generating a large volume of foam, which temporarily increases the volume of the binder and reduces the viscosity of the mix. This effect improves the coating of the aggregates by the binder remarkably and also improves the workability of the asphalt mix at lower temperatures.

Most of the literature consulted highlights the advantages of WMA, which include the following: lower energy consumption in mix production, reduced emissions, better working conditions because of the absence of harmful gases, quicker turnover to traffic, longer hauling distances, and extended paving window (Rubio et al., 2012). Another key advantage of WMA is the potentially greater use of RAP. The improved workability of WMA leads to a lower production temperature, with less ageing of the binder, thus counteracting the stiffer RAP binder (Rubio et al., 2012). Some studies have reported even higher percentages of 50% RAP (D’Angelo et al., 2008; Vaitkus et al., 2009).

Recycling of asphalt pavements is a valuable approach for technical, economic and environmental reasons. The use of RAP has been favoured over virgin materials due to the increasing cost of asphalt, the scarcity of quality aggregates and the pressing need to preserve the environment (Al-Qadi et al., 2007). Many studies claim that the use of RAP in asphalt pavements can help to offset increased initial costs, conserve natural resources and avoid disposal problems (Rubio et al., 2012).

Several studies have been conducted to evaluate the potential benefits of using WMA (e.g., Barthel et al., 2004; Button et al., 2007; D’Angelo et al., 2008; Kvasnak and West, 2009; Nazzal et al., 2010; Vaitkus et al., 2009). In general, the results of these studies have shown that the emissions during the production and placement of WMA were reduced in comparison to HMA. In addition, WMA pavements have exhibited similar performance to those constructed with HMA. These studies have successfully quantified some of the potential environmental impacts of WMA in terms of resource consumption and emissions. Generally the role of the upstream supply chain, related to the production of minerals, asphalt binders and chemical additives used in different asphalt mixes, and related environmental impacts associated with the transportation of these materials have not been included in the scope of the above-mentioned studies (Tatari et al., 2012).

The life cycle assessment (LCA) methodology can be useful to overcome the gaps outlined above, since this methodology is aimed at assessing the environmental impacts associated with all the stages of a product's life from the cradle to the grave. Santero et al. (2010) provides a critical review of existing literature and modelling tools related to the LCA of road pavements. Among the most cited works are the studies conducted by Mroueh et al.

(2000) and Stripple (2001), and the LCA-based tools PaLATE (Horvath, 2003), ROAD-RES (Birgisdóttir, 2005) and UK asphalt pavement LCA model (Huang et al., 2009). Most literature and tools have been focused on conventional asphalt pavements, whilst WMA pavements have rarely been considered due to the novelty of the technique. One exception is the hybrid LCA model developed by Tatari et al. (2012), which assesses the environmental impacts of different types of WMA pavements and compares them to those of a conventional HMA pavement. Moreover, there are some LCA studies that consider the use of RAP in asphalt pavements, such as those conducted by Jullien et al. (2006) and Chiu et al. (2008), as well as LCA-based tools, such as PaLATE (Horvath, 2003), UK asphalt pavement LCA model (Huang et al., 2009) or the LCA model by Tatari et al. (2012).

The aim of the present study was to perform a comprehensive LCA of road pavements including HMA and zeolite-based WMA, both with and without RAP content. As in most LCA studies of road pavements, the environmental impacts associated with energy consumption and air emissions were assessed, but other environmental impacts were also assessed (at the midpoint and endpoint levels) from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic during the service life of the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling.

2.2. Materials and methods

The LCA methodology was used in this study to calculate and compare the environmental impacts of different road pavements during their entire life cycle. LCA was applied according to the guidelines provided by ISO 14040:2006 (ISO, 2006a, 2006b). The LCA software application SimaPro® was used to tackle the development of the study more effectively. Field data for the study were supplied by the company UCOP Construcciones, SA (Spain). In those cases where no field data were available from the company, data were gathered from LCA databases and from the scientific literature. Additionally, an LCA-based tool was developed and implemented in a spreadsheet software application to automatically compute the impacts of road pavements within the framework of LCA. An uncertainty assessment was finally conducted to determine the uncertainties in the LCA results.

2.2.1. Life cycle assessment

LCA is a methodology to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, which encompasses: extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use and maintenance; recycling and final disposal (SETAC, 1993). According to ISO standards, LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a). The goal and scope definition determines the guidelines to be followed during the rest of the study by specifying the reason for conducting the study, intended use of the results, intended audience, system boundaries, functional unit, data requirements, and study limitations. The inventory analysis involves collecting data to create a life cycle inventory (LCI) of the inputs (energy and materials) and outputs (environmental releases and waste) associated with each stage of the life cycle. The impact assessment translates the LCI data into potential environmental impacts. To this end, the impact categories under study must be defined (categorization), the inventory data must be assigned to specific impact categories (classification), and the level of impact must be evaluated according to predefined assessment methods (characterization). Impact assessment may also include other additional steps (normalization, grouping and weighting) to facilitate the interpretation phase, but these are not mandatory according to ISO standards. Finally, the interpretation phase combines and summarizes the results from inventory analysis and impact assessment (consistent with the defined goal and scope) in order to reach conclusions and recommendations.

2.2.2. Goal and scope definition

The present study aimed to calculate the environmental impacts of different road pavements during their entire life cycle. The pavements investigated include HMA and zeolite-based WMA, both with and without RAP content. In this way, the results for the different asphalt pavements could be compared with each other to determine the best alternatives in environmental terms.

2.2.2.1. System description and boundaries

Normally, the life cycle of road pavements is divided into five major stages or sub-systems: material production, construction, use, maintenance, and end-of-life (Santero et al., 2010). However, asphalt production was treated in this study as a separate sub-system in order to highlight the influence of asphalt production technology on the overall impact. Transportation of asphalt mixes to the construction site was also dealt with separately. Therefore, the overall system under study was divided into the following sub-systems (Fig. 1):

1. *Materials*. The life cycle of road pavements starts with the extraction of raw materials. The asphalt mixes consist mainly of natural aggregates and binder constituents, although other materials could also appear to a lesser extent (cement, lime products, zeolites, RAP, and so forth). The environmental burdens associated with this stage arise from mining operations, manufacturing of materials, and transportation of materials to the asphalt plant.
2. *Asphalt production*. The different materials composing the asphalt are screened, dried and mixed at the asphalt plant. The environmental burdens associated with this stage

are due to land use, infrastructure and machinery, fuel and electricity consumption, and emissions to air from the machinery used in asphalt production.

3. *Transportation*. The asphalt mixes produced at the asphalt plant are delivered by road transport to the construction site. The environmental burdens associated with this stage arise from fuel consumption and emissions to air from the heavy goods vehicles used.
4. *Construction*. The construction of a road comprises diverse processes: site clearing, excavation, foundation reinforcement, construction of the sub-base and base layers, paving with asphalt, and adding the different kinds of equipment needed on roads (road lighting, signs, safety fences, and so forth). Only asphalt paving processes were considered in this study. The environmental burdens associated with this stage are due to fuel consumption and emissions to air from the asphalt paving machinery, air emissions and leaching of pollutants from the asphalt pavement, and transformation of land.
5. *Use*. After the construction stage, the road moves onto a use stage which lasts until the end of the service life of the infrastructure. The use of the road includes the operation of the different types of vehicles driven on it. The environmental burdens associated with this stage are due to fuel consumption and emissions to air from the road traffic, and also due to land occupation.
6. *Maintenance*. The maintenance stage also lasts until the end of the service life of the infrastructure, since it is related to the wear of the pavement. The maintenance of the road includes the replacement of the wearing course. The environmental burdens associated with the dismantling of the worn asphalt layer are the same as those in the end-of-life stage, whilst the environmental burdens associated with the placement of a new layer of asphalt are the same as those in the materials, asphalt production, transportation and construction stages.
7. *End-of-life*. The last stage is the end-of-life, which occurs when the infrastructure reaches the end in its service life. When a road reaches this stage, the general procedure is either to leave the pavement materials in place or to demolish the road and then dispose of or recycle the pavement materials. The environmental burdens associated with this stage can be quite different depending on the end-of-life strategy that is chosen.

2.2.2.2. Functional unit

The functional unit is a reference unit to which the results of the LCA are related, and which should represent the function of the analyzed system. In order to compare different road pavements, it is important to use the same functional unit for all the systems compared. The functional unit for road pavements is defined herein by their geometry, service life, and levels of traffic supported. In the case study presented later, the section of road concerned is 1 km long with a width of 13 m and a thickness of the asphalt layer of 0.08 m; the service life of the road is 40 years; and the average daily traffic is 1000 vehicles per day with 8% of heavy vehicles. This is a two-lane road with two-way traffic whose pavement was sized according to the Spanish instruction for designing pavement sections (Spanish Ministry of Public Works, 2003), which takes into account the type of soil and the volume of heavy traffic expected.

A major drawback of LCA of pavements as a whole is the lack of consensus upon a single functional unit upon which to assess pavements. This is due to the fact the pavement structure (i.e., the type and thickness of materials) is heavily influenced by the traffic, environmental conditions, design life, and other project-specific details (Santero et al., 2010). Therefore, our results emphasize the variability between the four pavements studied under the same functional unit, while other results from the literature are difficult to compare because they respond to other functional units.

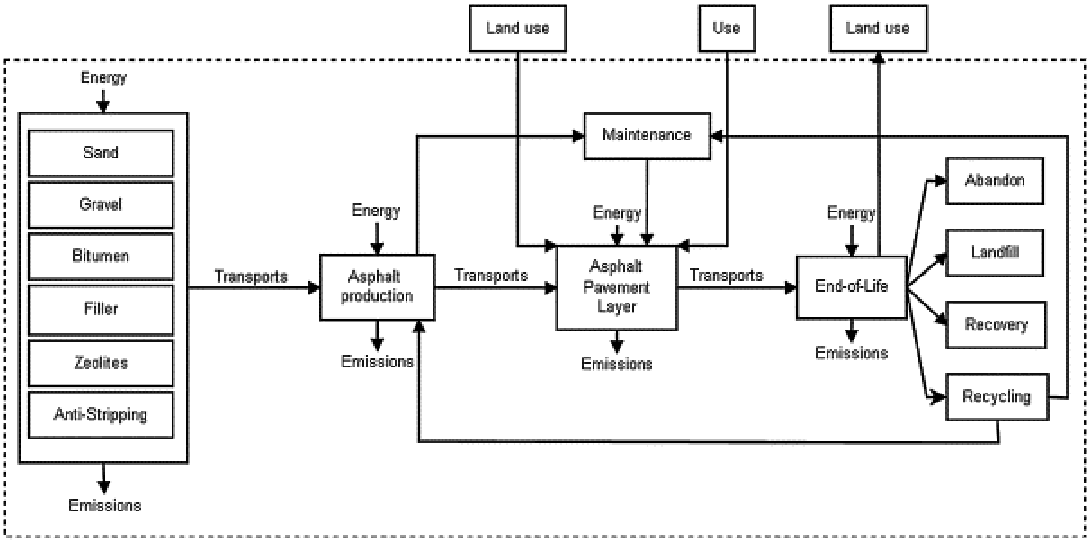

Fig. 1. System boundaries.

2.2.3. Inventory analysis

The inventory analysis is based on the life cycle sub-components that have emerged from the various sub-systems considered. At a later phase in the assessment process, these sub-components together with the functional unit and other input variables make up the core of the calculation model. The sub-components are made up of factors which show energy consumption, resource consumption and emissions for different basic activities, expressed per number of kilometers driven (km) or per amount of materials extracted and/or processed (kg), for example. These units were chosen based on practical applicability. Field data supplied by the company were used to gather information about the inputs and outputs for each sub-component. For those sub-components where no field data were available from the company, data were collected from LCA databases and from the scientific literature. After completing the gathering of data, each sub-component was modeled using the SimaPro® software application.

2.2.3.1. Materials

Asphalt mixes consist mainly of natural aggregates and binder constituents, although other materials may also appear to a lesser extent. RAP can be used to replace a portion of virgin materials.

Sand and gravel are used as fine and coarse aggregates, respectively, while bitumen is used as a binder constituent. Their LCI was taken from the Ecoinvent® database (Jungbluth, 2004; Kellenberger et al., 2003) and adapted to this study.

Cement and lime products (such as limestone and hydrated lime) are typically used as filler. The general effect of adding filler to the mixes is to obtain harder and stiffer asphalt. The addition of hydrated lime can also reduce stripping, rutting, cracking and aging. Cement is also used as an anti-stripping agent. The LCI of the raw materials listed above was also taken from the Ecoinvent® database (Kellenberger et al., 2003) and adapted to this study.

Synthetic zeolites are used for WMA production, since they allow lower manufacturing temperatures of the asphalt mixes to be used without reducing their mechanical performance. LCI of zeolite was based on data from a study conducted by Fawer (1996). This study quantified the environmental burdens associated with the production of synthetic zeolites through the aluminosilicate hidrogel route, which is the process used for the production of commercial zeolites for asphalts. Other LCI present in commercial databases (Ecoinvent® and ETH-ESU 96®) are also based on the same source, but they have errors because they counted twice the energy consumption and emissions of some processes.

Burdens from RAP have not been included in this section because this material is declared as waste and therefore has no direct burdens associated to it. Other auxiliary inputs (such as machinery, electricity, fuels, and so forth) were taken from the Ecoinvent® database, but their associated burdens were attributed to those stages where such inputs emerge. Moreover, the burdens associated with the transport of raw materials to the asphalt plant were also taken into account and were modeled according to the LCI of the transportation stage (cf. Section 2.2.3.3).

2.2.3.2. Asphalt production

This section deals with the LCI of the asphalt production process by considering different types of resulting products, namely HMA and WMA, both with and without RAP content. Besides the production process, the asphalt plant was also inventoried separately. The LCI was based on field data on the production of HMA without RAP content. Data relative to HMA production were used as the basis on which to inventory other asphalt mixes, but taking into account the variations in energy consumption and air emissions due to the variations in composition and manufacturing temperature of the mixes.

2.2.3.2.1. Asphalt plant

The asphalt plant includes the land use, infrastructure and machinery used in asphalt production. The life span of the plant was estimated to be about 50 years and the average yearly production about 114,000 metric tons of asphalt. The asphalt plant used as a reference is divided into two sub-plants with different technologies: a batch mix plant and a continuous mix plant. The continuous mix plant covers 64.3% of total asphalt production, whilst the batch mix plant covers the remaining 35.7%. The machinery used in the asphalt plant includes: 8 cold-feed bins (5 metric tons per bin), 4 sieves (5 metric tons per sieve), 1 rotary dryer (10 metric tons), 1 mixer (10 metric tons), 1 drum mixer (10 metric tons), 2 burners (5 metric tons per burner), 1 boiler (5 metric tons), 2 filtering units (10 metric tons per unit), 4 big silos (10 metric tons per silo), 4 big tanks (10 metric tons per tank), and a conveyor belt (100 m in length and 1.5 m in width). The service life for all machines was assumed to be 25 years, except for the conveyor belt, which was considered to have a service life of 20 years. Several smaller machines such as pumps or motors were not taken into account. Table 2 shows the LCI of the asphalt plant.

Table 2. LCI of the asphalt plant.

Input/output	Amount
Land use	
Transformation, from unknown (m^2)	2.98E+04
Transformation, to industrial area, built up (m^2)	2.13E+03
Transformation, to industrial area, vegetation (m^2)	5.15E+03
Transformation, to traffic area, road network (m^2)	2.26E+04
Occupation, industrial area, built up (m^2y)	1.07E+05
Occupation, industrial area, vegetation (m^2y)	2.58E+05
Occupation, traffic area, road network (m^2y)	1.13E+06
Infrastructure and machinery	
Building, hall (m^2)	1.87E+03
Building, multi-storey (m^3)	3.07E+03
Industrial machine (kg)	4.10E+05
Conveyor belt (m)	1.50E+02

In this study, the asphalt plant was assumed to be common for all asphalt products and is therefore included in the LCI of the different types of asphalt products considered in the study.

2.2.3.2.2. Hot mix asphalt

The production of HMA includes the following processes: screening, drying, mixing, and storing. In the batch mix plant, the aggregates and the filler are dried using a fuel-fired rotary dryer, then they are sorted and finally mixed in a separate pug mill with bitumen that is preheated to 160 °C using a fuel oil boiler. In the continuous mix plant, the dryer is used not only to dry the aggregates and the filler but also to mix the heated and dried aggregates and filler with the preheated bitumen. The initial temperature of the raw materials is 15 °C, whilst the final temperature of the asphalt mixes is 165 °C. All fuel consumption and air pollutant emissions for these processes were based on measured data from the asphalt plant. Moreover, diesel consumption for internal transport and electricity consumption at the plant were also accounted for based on measured data. The batch mix plant and the continuous mix plant were not distinguished by fuel and electricity consumption. However, process emissions are different depending on the manufacturing technology used. Thus, process emissions for HMA production were estimated considering that the continuous mix plant covers 64.3% of total production and the batch mix plant covers the remaining 35.7%. Waste was not taken into account because of a rejection of only about 8–10% of filler occurs, but it was reintroduced into the process. Table 3 shows the LCI of 1 kg of reference HMA (without RAP content).

2.2.3.2.3. Warm mix asphalt

Synthetic zeolites are used for WMA production, since they allow lower manufacturing temperatures of asphalt mixes to be used without reducing their mechanical performance. The addition of zeolites does not increase the mixing time, which means that the production capacity of the asphalt plant can be maintained. The asphalt plant used herein as a reference only manufactures HMA, although some pilot tests have been conducted with WMA. Basically, data relative to HMA production were used as a basis to inventory WMA production, but taking into account the lower energy consumption and the decrease in air emissions due to the reduction in the manufacturing temperature. Firstly, an energy balance was performed on the HMA asphalt plant to estimate the heat loss from the production process. Thus, heat loss coefficients associated with burners and boiler were obtained as a function of the heated mass and the heating temperature. In addition, air pollutant emissions from burners and boiler were estimated as a function of fuel consumption. Secondly, an energy balance was performed again by using the heat loss coefficients mentioned above, but this time taking into account the composition of WMA and a new final temperature for the mixes. In this way, fuel consumption by burners and boiler for WMA production was estimated. Finally, air pollutant emissions from WMA production were calculated according to the new values for fuel consumption.

In this particular case, synthetic zeolites are added to the mix at a rate of about 0.3% by mass, replacing a portion of the filler. Additionally, hydrated lime is added to the mix as an anti-stripping agent at a rate of 1.5% by mass. Thus, the aggregates and the filler are heated up to a temperature level which is 30 °C lower than normal and are then mixed with bitumen, which remains preheated at 160 °C. The initial temperature of the raw materials is 15 °C, whilst the final temperature of the asphalt mixes is now 135 °C. As in the production of HMA, process emissions for WMA production were estimated considering that the continuous mix plant covers 64.3% of total production and the batch mix plant covers the remaining 35.7%. Likewise, no waste was taken into account because the rejected filler is later reintroduced into the process. Table 3 shows the LCI of 1 kg of this particular WMA (without RAP content).

2.2.3.2.4. Asphalt mixes with RAP

In the previous section, the LCI of a particular WMA was conducted based on field data related to the production of a reference HMA. Other asphalt mixes with different RAP percentages or different manufacturing temperatures can also be modeled and inventoried in the same manner. In this study, both HMA and WMA with 15% of RAP were also investigated. Table 3 shows the LCI of 1 kg of each of these asphalt mixes with RAP content.

Table 3. LCI of the production of 1 kg of asphalt mixes.

Input/output	Amount			
	HMA 0% RAP	HMA 15%RAP	WMA 0% RAP	WMA 15% RAP
Land use, infrastructure and machinery				
Asphalt plant (unit)	1.75E−10	1.75E−10	1.75E−10	1.75E−10
Electricity and fuels				
Electricity, medium voltage (kWh)	3.28E−03	3.28E−03	3.28E−03	3.28E−03
Light fuel oil (kg)	6.11E−03	6.38E−03	4.98E−03	5.24E−03
Heavy fuel oil (kg)	8.69E−04	7.40E−04	8.69E−04	7.40E−04
Diesel (MJ)	5.18E−03	5.18E−03	5.18E−03	5.18E−03
Emissions to air				
CO_2 (kg)	1.77E−02	1.80E−02	1.49E−02	1.52E−02
CO (kg)	2.17E−03	2.27E−03	1.77E−03	1.86E−03
NO_X (kg)	8.70E−05	8.92E−05	7.26E−05	7.47E−05
SO_2 (kg)	1.24E−05	1.18E−05	1.12E−05	1.06E−05
$PM_{2.5}$ (kg)	1.99E−05	2.08E−05	1.63E−05	1.71E−05
NMVOC (kg)	1.54E−05	1.60E−05	1.25E−05	1.32E−05
Waste heat (MJ)	1.18E−02	1.18E−02	1.18E−02	1.18E−02

Note: the composition of the asphalt mixes and the moisture content of the raw materials are the same as in the case study (see Table 11).

2.2.3.3. Transportation

The raw materials are transported from the extraction and processing sites to the asphalt plant by road. Likewise, the asphalt mixes produced are delivered to the construction site by road transport. The burdens associated with the transport of raw materials to the asphalt plant were attributed to the materials stage (cf. Section 2.2.3.1), whilst the burdens associated with the transport of asphalt mixes to the construction site were attributed to the transportation stage. To account for the transport of materials, two heavy goods vehicles were modeled in this study: an articulated truck-trailer with a Euro II diesel engine and an articulated truck-trailer with a Euro III diesel engine. Both heavy vehicles have a maximum payload weight of 28.45 metric tons and a maximum technically admissible laden weight of 40–50 metric tons. Fuel consumption and direct airborne emissions of gaseous substances, particulate matters and heavy metals from these vehicles were inventoried based on the 'EMEP/EEA air pollutant emission inventory guidebook' (European Environment Agency, 2009). Fuel consumption and emissions can be calculated as a function of vehicle speed, road gradient and vehicle load. The average vehicle speed was assumed to be 70 km/h, whilst the road gradient was assumed to be 0%. With respect to vehicle load, two different load factors (LF) were considered: an LF of 100% (assuming that the vehicle is fully loaded on the outward journey) and an LF of 0% (assuming that the vehicle is fully unloaded on the return journey). The production of the vehicles themselves was not considered. Table 4 shows the LCI of the operation of one vehicle-kilometer for each of the heavy vehicles modeled.

Table 4. LCI of the operation of one heavy goods vehicle-kilometer.

Input/output	Amount			
	Articulated truck-trailer 40–50 t Euro II		Articulated truck-trailer 40–50 t Euro III	
	LF 0%	LF 100%	LF 0%	LF 100%
Fuel				
Diesel, low-sulfur (g)	1.91E+02	3.42E+02	1.96E+02	3.44E+02
Emissions to air				
CO_2 (kg)	5.99E−01	1.07E+00	6.15E−01	1.08E+00
CO (g)	1.21E+00	2.14E+00	1.36E+00	2.27E+00
NO_X (g)	7.36E+00	1.17E+01	5.83E+00	9.14E+00
$PM_{2.5}$ (g)	1.32E−01	2.48E−01	1.26E−01	1.80E−01
CH_4 (mg)	8.00E+01	8.00E+01	8.00E+01	8.00E+01
NMVOC (g)	2.66E−01	2.86E−01	2.29E−01	2.29E−01
N_2O (mg)	1.50E+01	1.50E+01	9.00E+00	9.00E+00
NH_3 (mg)	3.00E+00	3.00E+00	3.00E+00	3.00E+00
Cd (mg)	1.00E−02	1.00E−02	1.00E−02	1.00E−02
Cu (mg)	1.70E+00	1.70E+00	1.70E+00	1.70E+00
Cr (mg)	5.00E−02	5.00E−02	5.00E−02	5.00E−02
Ni (mg)	7.00E−02	7.00E−02	7.00E−02	7.00E−02
Se (mg)	1.00E−02	1.00E−02	1.00E−02	1.00E−02
Zn (mg)	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Total dioxins (pg)	3.00E+00	3.00E+00	3.00E+00	3.00E+00
Total furans (pg)	7.90E+00	7.90E+00	7.90E+00	7.90E+00
Total PAH (µg)	2.42E+02	2.42E+02	2.42E+02	2.42E+02

2.2.3.4. Construction

Road construction comprises diverse processes, but the present study focused only on asphalt paving processes. The environmental burdens associated with the construction stage arise from fuel consumption and air emissions from the paving machinery, air emissions and leachate from the asphalt pavement, and transformation of land.

2.2.3.4.1. Machinery

Three different machines are normally used by the company to spread and compact the asphalt: an asphalt paver, a heavy vibratory roller, and a rubber tire roller. Basic data on the operating conditions of these machines are shown in Table 5. Energy consumption (*EC*, in kWh) of each machine for paving a road with a given length (*L*, in km) and width (*W*, in m) can be calculated from the operating conditions in Table 5 by applying Eq. (1).

$$EC = P/RF \cdot L/v \cdot W/EW \cdot N \tag{1}$$

Table 5. Basic data for paving and milling machines.

Machine	Power: *P* (kW)	Speed: *v* (km/h)	Effective width: *EW* (m)	Number of passes: *N*	Reduction factor: *RF*
Asphalt paver (VÖGELE)	129	1.50	3.65	1	1.00
Heavy vibratory roller (BOMAG)	100	4.50	2.52	8	0.75
Rubber tire roller (BOMAG)	75	6.00	1.98	1	0.60
Milling machine (MARINI)	179	1.68	1.31	1	1.00

Fuel consumption and air emissions from the paving machines were inventoried as a function of energy consumption based on the 'EMEP/EEA air pollutant emission inventory guidebook' (European Environment Agency, 2009). The production of the machines themselves was not considered. Table 6 shows the LCI of the operation of the paving machines related to an energy consumption of 1 kWh. All paving machines have the same power range (75–130 kW), and thus the inventories are the same.

Table 6. LCI of the operation of paving and milling machines for an energy consumption of 1 kWh.

Input/output	Amount	
	Paving machine (75–130 kW)	Milling machine (130–300 kW)
Fuel		
Diesel, low-sulfur (g)	2.60E+02	2.54E+02
Emissions to air		
CO (g)	5.00E+00	5.00E+00
NO_X (g)	9.20E+00	9.20E+00
PM (g)	4.00E−02	3.00E−02
$PM_{2.5}$ (g)	6.60E−01	5.10E−01
CH_4 (g)	5.00E−02	5.00E−02
NMVOC (g)	1.30E+00	1.30E+00
N_2O (g)	3.50E−02	3.50E−02
NH_3 (g)	2.00E−03	2.00E−03

The above data on the operating conditions of paving machines are based on the construction of pavements with HMA. Because WMA generally has a lower viscosity, each roller pass provides more compaction, thus reducing the number of passes needed to achieve a specified density (Kristjánsdóttir, 2007; Zaumanis, 2010). However, the same operating conditions of paving machines were assumed for pavements with WMA, since there are no accurate data in the literature on the reduction in the number of roller passes that can be achieved by paving with WMA.

2.2.3.4.2. Emissions to air from asphalt pavement

Besides the air emissions from the paving machines, the air emissions from the different asphalt pavements were also considered. The air emissions from HMA pavements are higher than those from WMA pavements. Moreover, these emissions can vary depending on the content of RAP in the asphalt mixes. Eight different asphalt pavements were considered in this study: four HMA pavements, containing 0, 10, 20 and 30% of RAP; and four WMA pavements, containing 0, 10, 20 and 30% of RAP. VOC and PAH emissions from HMA pavements were inventoried based on data from the study conducted by Jullien et al. (2006). Air emissions from WMA pavements were inventoried based on the same data, but assuming reduction rates of 97.0% for VOC and 80.2% for PAH, as stated by Li and Ding (2011). Table 7 shows the LCI relative to the air emissions from 1 kg of asphalt pavement constructed.

Table 7. LCI of emissions to air for 1 kg of asphalt pavement.

Input/output	Amount							
	HMA 0% RAP	HMA 10% RAP	HMA 20% RAP	HMA 30% RAP	WMA 0% RAP	WMA 10% RAP	WMA 20% RAP	WMA 30% RAP
Emissions to air								
VOC (mg)	9.30E−02	1.47E−01	1.42E−01	1.59E−01	2.79E−03	4.41E−03	4.27E−03	4.78E−03
PAH (µg)	7.15E−04	1.76E−03	3.38E−03	4.03E−03	1.42E−04	3.47E−04	6.69E−04	7.98E−04

2.2.3.4.3. Leachate from asphalt pavement

Other environmental burdens associated with road construction arise from the leaching of pollutants from the asphalt pavement. Pollutant concentrations in leachate may vary depending on the content of RAP in asphalt mixes. Three different asphalt pavements, containing 0, 10 and 20% of RAP, were considered in this study. Leaching of heavy metals and PAH were inventoried based on data from the study conducted by Legret et al. (2005). Table 8 shows the LCI relative to the leaching of pollutants from 1 kg of asphalt pavement constructed.

Table 8. LCI of leachate for 1 kg of asphalt pavement.

Input/output	Amount		
	Asphalt pavement 0% RAP	Asphalt pavement 10% RAP	Asphalt pavement 20% RAP
Emissions to water			
Cl (mg)	BDL	4.24E−01	3.77E−01
SO_4 (mg)	BDL	7.07E−01	BDL
Cd (µg)	BDL	7.55E−01	4.72E−01
Cu (µg)	BDL	9.43E+00	9.90E+00
Cr (µg)	BDL	2.36E+00	3.77E+00
Ni (µg)	BDL	5.19E+00	5.19E+00
Zn (µg)	4.18E+01	1.18E+02	1.49E+02
Total hydrocarbons (µg)	BDL	5.66E+01	6.13E+01
Fluoranthene (µg)	BDL	1.65E−02	1.65E−02

Note: BDL means below detection limit and is considered herein as 0.00E+00.

2.2.3.4.4. Land use

Besides the direct burdens from the construction processes, the construction stage implies an additional burden derived from the transformation of land. To account for this burden, the following issues must be specified in the inventory: the area transformed and the nature of the transformation (Lindeijer et al., 2002). The land transformed can be determined as the space occupied by the new road infrastructure. The nature of the transformation takes into account the decrease in quality of the land transformed by comparing the types of land use before and after the construction takes place. Land use is classified as traffic area once the construction of the road finishes, whilst the type of initial land use depends on the site where the road is constructed. Three types of initial land use with different land qualities were considered in this study: forest, urban/industrial, and other. The initial land use was inventoried as a mix of such types of land use.

2.2.3.5. Use

The use stage lasts until the end of the service life of the road infrastructure. The environmental burdens associated with this stage are due to fuel consumption and air emissions from the traffic on the road during its service life, and also due to land occupation.

2.2.3.5.1. Road traffic

Two types of vehicles were considered in order to model the road traffic: an average light vehicle and an average heavy vehicle. These vehicles were modeled according to the vehicle fleet average on Spanish highways for the year 2005 (Ntziachristos et al., 2008). Thus, the average light vehicle is a mix of passenger cars and light-duty vehicles with different technologies (gasoline and diesel engines with various emission standards, such as conventional and Euro I to Euro IV), whilst the average heavy vehicle is a mix of heavy-duty trucks and buses with different technologies (gasoline and diesel engines with various emission standards, such as conventional and Euro I to Euro IV). Fuel consumption and direct airborne emissions of gaseous substances, particulate matters and heavy metals from these vehicles were inventoried based on the 'EMEP/EEA air pollutant emission inventory guidebook' (European Environment Agency, 2009). Fuel consumption and emissions can be calculated as a function of vehicle speed, which was assumed to be 120 km/h for light vehicles and 100 km/h for heavy vehicles. Fuel consumption and emissions for heavy vehicles also depend on road gradient and vehicle load. The road gradient was assumed to be 0%, whilst a load factor of 50% was considered. The production of the vehicles themselves was not taken into account. Table 9 shows the LCI of the operation of one vehicle-kilometer for each of the average vehicles modeled.

2.2.3.5.2. Land use

The use stage also implies an additional burden derived from the occupation of land. To account for this burden, the following issues must be specified in the inventory: the land occupied, the time of occupation and the nature of the occupation (Lindeijer et al., 2002).

The land occupied can be determined as the space occupied by the road infrastructure and the time of occupation is assumed to be the same as the service life of the road. The nature of the occupation takes into account the quality of the land occupied, which has that same quality throughout the entire time of occupation. This quality is determined by the type of land use, which is classified as traffic area during the time of occupation. Land occupation is expressed in terms of square meter years (m^2y), because it is obtained by multiplying the area occupied (in m^2) by the time of occupation (in years).

Table 9. LCI of the operation of one average vehicle-kilometer.

Input/Output	Amount	
	Average light vehicle	Average heavy vehicle
Fuel		
Petrol, low-sulfur (g)	3.23E+01	1.45E−05
Diesel, low-sulfur (g)	3.03E+01	1.80E+02
Emissions to air		
CO_2 (kg)	1.98E−01	5.98E−01
CO (g)	2.47E+00	1.17E+00
NO_X (g)	1.35E+00	5.90E+00
$PM_{2.5}$ (g)	5.20E−02	1.75E−01
CH_4 (mg)	1.17E+01	4.52E+01
NMVOC (g)	1.90E−01	2.21E−01
N_2O (mg)	4.35E+00	1.31E+01
NH_3 (mg)	2.48E+01	3.00E+00
Cd (mg)	1.00E−02	1.00E−02
Cu (mg)	1.70E+00	1.70E+00
Cr (mg)	5.00E−02	5.00E−02
Ni (mg)	7.00E−02	7.00E−02
Se (mg)	1.00E−02	1.00E−02
Zn (mg)	1.00E+00	1.00E+00
Total dioxins (pg)	5.75E+00	3.00E+00
Total furans (pg)	1.18E+01	7.90E+00
Total PAH (µg)	6.39E+02	2.42E+02

2.2.3.6. Maintenance

The maintenance stage takes place periodically throughout the service life of the road infrastructure, since it is related to the wear of the pavement. Maintenance of the road involves the replacement of the wearing course. This includes the dismantling and end-of-life of the worn pavement layer and the placement of a new layer of asphalt. This process of repaving again involves the following stages: materials, asphalt production, transportation, and construction. Thus, the burdens associated with laying a new layer of asphalt were modeled according to the LCI of the stages outlined above (cf. Sections 2.2.3.1–2.2.3.4), and were also attributed to such stages. Likewise, the burdens associated with dismantling and end-of-life of the worn layer of asphalt were modeled according to the LCI of the end-of-life stage (cf. Section 2.2.3.7), and were attributed to such a stage. The burdens due to transformation of land in the construction and end-of-life stages were not taken into account again.

2.2.3.7. End-of-life

When a road reaches the end-of-life stage, the general procedure is either to leave the road in place or to dismantle it and then dispose of or recycle the pavement materials. On the one hand, when a road is abandoned and the materials are not removed from the site, no environmental burdens are taken into account (it is assumed that there will be no significant transformation in land use). On the other hand, when a road is dismantled and the pavement materials are disposed of or recycled as RAP, various burdens must be considered.

2.2.3.7.1. Machinery

A milling machine is used by the company to dismantle the asphalt pavement layer. Basic data on the operating conditions of this machine are shown in Table 5. Energy consumption (*EC*, in kWh) of the milling machine for removing an asphalt pavement layer with a given length (*L*, in km) and width (*W*, in m) can be calculated from the operating conditions in Table 5 by applying Eq. (1). Fuel consumption and air emissions from the milling machine were inventoried as a function of energy consumption based on the 'EMEP/EEA air pollutant emission inventory guidebook' (European Environment Agency, 2009). The production of the machine itself was not considered. Table 6 shows the LCI of the operation of the milling machine related to an energy consumption of 1 kWh.

2.2.3.7.2. Disposal and recycling

The asphalt resulting from dismantling the road can be either disposed of in a sanitary landfill or recycled as RAP. Both the transport of waste to the landfill and the transport of RAP to the asphalt plant were taken into account and modeled according to the LCI of the transportation stage (cf. Section 2.2.3.3).

The LCI of the disposal of asphalt in a sanitary landfill was taken from the Ecoinvent® database (Doka, 2003). This inventory includes the environmental burdens due to land use, infrastructure and machinery, waste-specific short-term emissions to air via landfill gas incineration and landfill leachate, long-term emissions from landfill to groundwater (after base lining failure), and treatment of short-term leachate in wastewater treatment plant.

No burdens were attributed to the recycling of asphalt. However, the use of RAP to replace a portion of the virgin materials results in a twofold environmental benefit (which is transferred to other life cycle sub-components), since it avoids the disposal of asphalt to landfill, as well as the extraction of virgin raw materials.

2.2.3.7.3. Land use

The dismantling of the road may also involve a benefit derived from the transformation of land, since land may recover some of its original quality (i.e., before the road was constructed). To account for this benefit, the following issues must be specified in the inventory: the land transformed and the nature of the transformation (Lindeijer et al., 2002). The land transformed can be determined as the space occupied by the road infrastructure that is removed. The nature of the transformation takes into account the increase in quality of the land transformed by comparing the types of land use before and after the removal of the road takes place. Land use is classified as traffic area before the removal of the road. The type of final land use depends on the site where the road was constructed. Three types of final land use with different land qualities were considered in this study: forest, urban/industrial, and other. The final land use was inventoried as a mix of such types of land use.

2.2.4. Impact assessment

The impact assessment of each life cycle sub-component was conducted by applying the impact assessment method ReCiPe (Goedkoop et al., 2009), which is incorporated within the SimaPro® software application. ReCiPe assesses the environmental impacts according to two sets of impact categories: midpoint categories and endpoint categories. Eighteen impact categories can be assessed at the midpoint level: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion. These midpoint impact categories are further converted and aggregated into three endpoint categories: damage to human health, damage to ecosystem diversity, and damage to resource availability. The environmental impacts can be assessed according to three cultural perspectives: egalitarian, hierarchist, and individualist. Both midpoint and endpoint impacts were assessed in this study according to hierarchist perspective, which is based on scientific consensus with regards to time horizon and other issues (adaptation capacity, technology development, and so forth). ReCiPe also allows normalization, grouping and weighting of environmental impacts. All midpoint impacts were in this study normalized according to the normalization factors for Europe in year 2000. Such normalization factors express the annual impact scores of an average European citizen for every midpoint impact category. The abstract impact scores of asphalt pavements were thus translated into a more understandable form by showing the magnitude of each midpoint impact relative to the annual impacts of an average European citizen. Since the different impact scores were normalized to a common reference, it was easier to make comparisons between impact scores of different impact categories.

The cumulative energy demand (CED) was also assessed in order to ease energy comparisons. CED assessment was based on the method published by Ecoinvent® (Frischknecht et al., 2004) and expanded within the SimaPro® software application.

2.2.5. LCA-based tool

An LCA-based tool was developed and implemented in a spreadsheet software application (Microsoft® Excel®) to automatically calculate the environmental impacts of road pavements within the framework of LCA. Only the functional unit and other input variables must be specified by the user (Table 10). The tool uses these inputs as a starting point to quantify the amount of each life cycle sub-component produced. Each sub-component, together with its associated amount, is linked to its corresponding LCI to compute the total environmental burdens due to such a sub-component. The environmental burdens are then automatically assessed by applying the impact assessment method ReCiPe. Finally, the environmental impacts thus obtained for the different sub-components are aggregated into the different stages of the life cycle of road pavements.

Table 10. Input variables required by the LCA-based tool.

Category	Input variable	Unit
Functional unit	Road length	km
	Road width	m
	Asphalt layer thickness	m
	Road service life	years
	Annual average daily traffic	veh/day
	Percentage of heavy vehicles	%
Materials	Sand, type	% by dry weight
	Gravel, type	% by dry weight
	Bitumen	% by dry weight
	Filler, type	% by dry weight
	Zeolite	% by dry weight
	Anti-stripping agent, type	% by dry weight
	RAP	% by dry weight
	Moisture content of each material	%
	Distance from supplier of each material to asphalt plant	km
Asphalt production	Production in continuous mix plant	%
	Production in batch mix plant	%
	Initial temperature of raw materials	°C
	Final temperature of asphalt mix	°C
Transportation	Distance from asphalt plant to construction site	km
Construction	Percentage of each type of initial land use	%
Use	–	–
Maintenance	Frequency of maintenance	years
	Percentage of road dismantled	%
	Percentage of road repaved	%
End-of-life	Percentage of road abandoned	%
	Percentage of asphalt recycled as RAP	%
	Distance from construction site to asphalt plant	km
	Percentage of asphalt disposed to landfill	%
	Distance from construction site to landfill	km
	Percentage of each type of final land use	%

2.2.6. Case study

The environmental impacts of four different road pavements were assessed by using the LCA-based tool. The functional unit comprises the entire life cycle of the asphalt pavement of a particular road: the section of road concerned is 1 km long; the total width is 13 m; the thickness of the asphalt layer is 0.08 m; the service life of the road is 40 years; the average daily traffic is about 1000 vehicles per day with 8% of heavy vehicles. This is a two-lane road with two-way traffic whose pavement was sized according to the Spanish instruction for designing pavement sections (Spanish Ministry of Public Works, 2003), which takes into account the type of soil and the volume of heavy traffic expected.

The asphalt pavements evaluated in this study included HMA and zeolite-based WMA, both with and without RAP content. Table 11 shows the composition of each asphalt mix, as well as the moisture content of each raw material and the distances from the suppliers of raw materials to the asphalt plant.

Table 11. Composition of asphalt mixes and other input variables relative to materials.

Material	Composition of asphalt mixes (% by dry weight)				Moisture content (%)	Distance to asphalt plant (km)
	HMA 0% RAP	HMA 15 % RAP	WMA 0% RAP	WMA 15% RAP		
Sand, dolomite	48.53	41.25	48.53	41.25	1.16	26
Gravel, ophite	43.04	36.58	43.04	36.58	0.56	73
Bitumen	4.49	3.82	4.49	3.82	0.00	280
Filler, Portland calcareous cement	3.94	3.35	2.20	1.61	0.00	103
Zeolite	0.00	0.00	0.24	0.24	21.00	2243
Anti-stripping agent, hydrated lime	0.00	0.00	1.50	1.50	0.30	197
RAP	0.00	15.00	0.00	15.00	2.90	50

The allocation of asphalt production is the same for all asphalt mixes: 64.3% in the continuous mix plant and 35.7% in the batch mix plant. The initial temperature of the raw materials is 15 °C for all asphalt mixes, whilst the final temperature of the asphalt mixes depends on the production technology. Thus, the final temperature of HMA is 165 °C, whilst the final temperature of WMA is 135 °C. All asphalt mixes are transported 50 km from the asphalt plant to the construction site.

The maintenance conditions are also common to all the road pavements to be compared. It was assumed that maintenance is conducted every 15 years and involves dismantling and repaving about 50% of the asphalt pavement.

No section of the road pavement will be abandoned in this case when the road reaches the end of its service life, but all pavement materials will be removed from the site and disposed of or recycled as RAP. Two different end-of-life strategies were considered here in order to analyze the full environmental benefit of recycling asphalt pavements (i.e., benefits of avoiding both the extraction of virgin raw materials and the disposal of asphalt to landfill). On the one hand, 15% of the asphalt in the pavements without RAP was to be disposed of in a landfill, whilst the remaining 85% would be recycled. On the other hand, the asphalt pavements with 15% of RAP were to be entirely recycled. The distance to the landfill and the distance to the asphalt plant are both 50 km.

The initial and final land uses must also be specified to account for the burdens due to land transformation. The initial land use was defined herein as a mix of the following land uses:

3% forest, 85% urban/industrial, and 12% other. Likewise, the final land use was defined as a mix of the following land uses: 1% forest, 95% urban/industrial, and 4% other.

2.2.7. Uncertainty assessment

An uncertainty assessment was also conducted as part of the study to determine the uncertainties in the LCA results. Various uncertainties related to the LCI data were handled to take into account variability of such data due to measurements, process specific variations, temporal and spatial variations, and so forth. Data uncertainties had already been quantified for the various LCI taken from the Ecoinvent® database. The uncertainties for the LCI based on field data or literature data were treated and quantified according to the considerations given in the Ecoinvent® project (Frischknecht et al., 2004). Lognormal distributions were used to represent the LCI data and a simplified standard procedure was applied to estimate data uncertainties as a function of data quality, which was assessed through the pedigree matrix devised by Weidema and Wesnaes (1996). For example, transport distances received an uncertainty factor of 2, which represents values between half and twice the mean values. Uncertainty values were assigned to 72.4% of the total LCI data. Monte Carlo simulations were then performed to estimate the variability with a 95% confidence interval for the environmental impacts of each of the asphalt pavements assessed. Each simulation consisted of 1000 samples.

2.3. Results and discussion

Four different asphalt pavements were evaluated by using the LCA-based tool. The environmental impacts of such pavements were assessed both at the midpoint level and the endpoint level.

As a first result, it was observed that the use stage caused most of the impact, with a contribution to the overall impact ranging between 79% and 91%, depending on the asphalt pavement and the endpoint impact category that were assessed. This result was expected, since the impact of the use stage includes the impacts due to fuel consumption and airborne emissions from millions of vehicles driven on the road throughout its entire service life. The impact of the use stage varies depending on traffic conditions on the road. Because traffic conditions were equal for all cases studied, the impact of the use phase was the same and was excluded from further analysis in order to avoid masking other lower impacts that may vary from one asphalt pavement to another.

Moreover, the impacts of land transformation were also significant in the construction and end-of-life stages. Such impacts vary depending on land use before road construction and after road dismantling. However, land use was assumed to be equal for all roads, and the impacts of land transformation were therefore the same for all cases. Like the impact from the use stage, the impacts due to land transformation from the construction and end-of-life stages were excluded from further analysis to avoid masking other results.

By not taking into account the above impacts, the materials stage became the stage of the life cycle with by far the greatest impact, followed by asphalt production, end-of-life, transportation, and construction. The contribution of each stage of the life cycle to the overall impact varied moderately among the different asphalt pavements investigated.

2.3.1. Impacts on human health, ecosystem diversity and resource availability

The environmental impacts of each asphalt pavement were assessed at the endpoint level according to three endpoint impact categories: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA). In this way, the impacts of each life cycle stage, as well as the overall impact, were aggregated into these three impact categories as shown in Fig. 2.

On comparing HMA and zeolite-based WMA, it was observed that the overall impacts of WMA were almost equal to the overall impacts of HMA with the same RAP content. There were no significant differences between the impacts of HMA and WMA in the transportation, construction and end-of-life stages. With respect to the asphalt production stage, the impacts of WMA were about 14–15% lower than the impacts of HMA, due to the reduction of manufacturing temperature. However, the impacts of the materials stage were higher in WMA: damage to HH was increased by 6–7%, damage to ED was increased by 4–5%, and damage to RA was increased by 2–3%. Thus, the reduction in manufacturing temperature of WMA produced a benefit in the asphalt production stage, which was offset by the increase in the impacts of the materials stage as a result of the more complex composition of WMA compared to HMA. Consequently, the decrease in the overall impacts of WMA regarding HMA was less than 1% for every endpoint impact category.

In addition, by comparing the same type of asphalt mixes (i.e., mixes with the same manufacturing temperature) with different RAP contents, it was observed that the overall impacts of mixes were significantly reduced when 15% of RAP was added. The reduction in the impacts was mainly attributable to the materials and end-of-life stages. The impacts of the materials stage were reduced about 15–16% by adding 15% of RAP. Likewise, the impacts of the end-of-life stage were reduced as follows: damage to HH was decreased by 42%, damage to ED was decreased by 41%, and damage to RA was decreased by 45%. Conversely, there were no significant differences between the impacts of mixes with different RAP contents in the transportation, asphalt production and construction stages. As a result, the decrease in the overall impacts by adding 15% of RAP to the mixes was as follows: 13% both for damage to HH and for damage to ED, and 14% for damage to RA.

The results discussed above refer to the mean impacts of a particular case study, which means that uncertainties have not been taken into account in such results. However, an uncertainty assessment was conducted to determine the variability of the results due to uncertainties in LCI data. The effect on the results due to the potential variability of certain input variables (composition of asphalt mixes, transportation distances, and so forth) was also taken into account through the uncertainty assessment. The variability with a 95%

confidence interval for the endpoint impacts of each asphalt pavement is shown in Fig. 2 as lines. The variability for each endpoint impact was very similar for the different asphalt pavements; the coefficient of variation was 6–7% for damage to HH, 11% for damage to ED, and 5% for damage to RA.

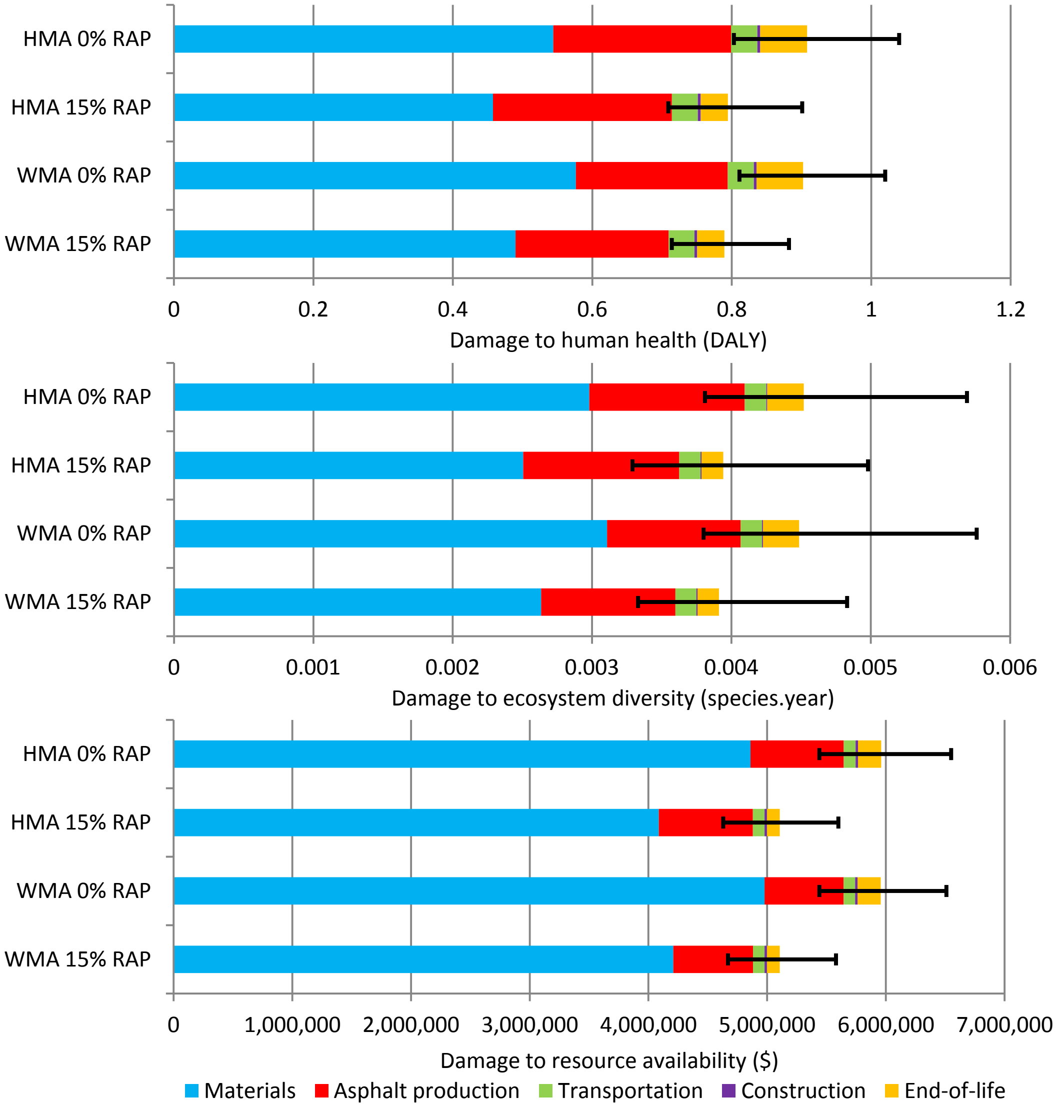

Fig. 2. Damages to human health, ecosystem diversity, and resource availability of asphalt pavements (endpoint impact assessment by using the ReCiPe Endpoint (H) V1.06/Europe ReCiPe H/A method).

2.3.2. Impacts on climate change and fossil depletion

The environmental impacts of each asphalt pavement were assessed at the midpoint level according to eighteen impact categories. The impacts on climate change (CC) and fossil depletion (FD) are presented and discussed because CC and FD are two of the most widely studied impact categories in the scientific literature on asphalt mixes (Muench et al., 2011). Fig. 3 shows the impacts of each life cycle stage as well as the overall impact for these midpoint impact categories.

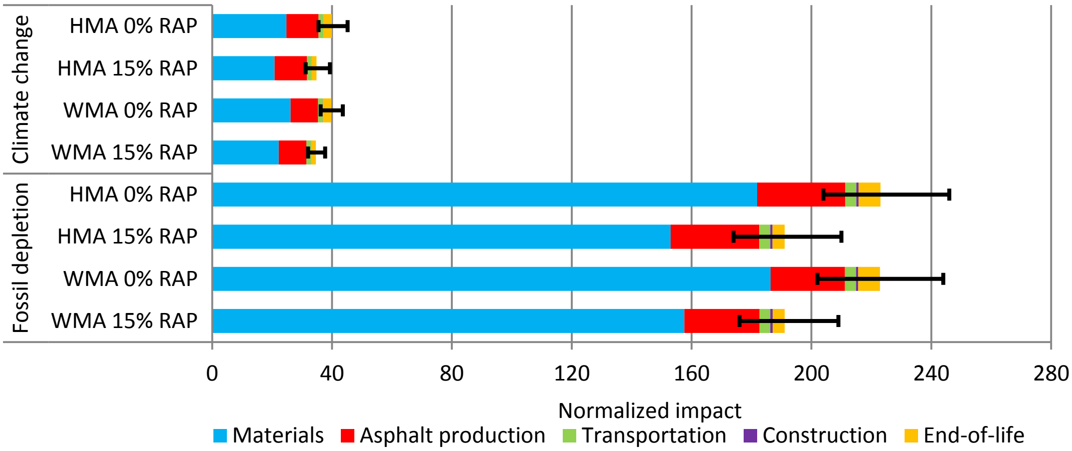

Fig. 3. Impacts on climate change and fossil depletion of asphalt pavements (midpoint impact assessment by using the ReCiPe Midpoint (H) V1.06/Europe ReCiPe H method).

The results obtained from the midpoint impact assessment were similar to those obtained from the endpoint impact assessment. The impacts on CC and FD were almost equal in HMA and WMA with the same RAP content, whilst the addition of RAP reduced both impacts. The impact on CC was decreased by 13% (from 4.48E+05 kg CO_2 eq for HMA and 4.45E+05 kg CO_2 eq for WMA, both with 0% RAP) and the impact on FD was decreased by 14% (from 3.71E+05 kg oil eq for HMA and WMA, both with 0% RAP) by adding 15% of RAP.

The variability with a 95% confidence interval for the midpoint impacts of each asphalt pavement is also shown in Fig. 3. The coefficient of variation was 4–6% for impact on CC and 4–5% for impact on FD. To infer more certainty to the results, comparisons were made again through Monte Carlo simulations. The probability that the impacts of HMA were higher than the impacts of WMA was 54.1% for CC and 50.9% for FD. Moreover, the impacts on CC and FD were reduced with a probability of 99.7% and 98.8% by adding 15% of RAP.

The results obtained from the CED assessment showed that the total energy for the asphalt mixes depends almost only on the RAP content. The total energy was 1.63E+07 MJ eq for asphalt mixes without RAP and 1.40E+07 MJ eq for asphalt mixes with 15% of RAP, which means a decrease of 14% by adding 15% of RAP.

The most significant differences in impacts among the asphalt pavements were mainly attributable to the materials, asphalt production and end-of-life stages. The environmental impacts of each of these stages were assessed in more detail to identify the main sub-components that cause such differences. Thus, the impacts on CC and FD related to each stage were broken down into various sub-components, as shown in Fig. 4.

It should be noted that bitumen was the material with the highest impact on FD (88–92% in top graph of Fig. 4). According to ISO 14044 standard (ISO, 2006b), feedstock energy was included in our LCI. For the case of pavements, the most notable input material affected by feedstock energy is bitumen (Santero et al., 2010). As a hydrocarbon, bitumen has a significant amount of chemical energy, which was estimated at 40.2 MJ/kg by the IPCC (Garg et al., 2006). Thus, the feedstock energy of the asphalt pavements investigated was about 1.8 MJ/kg.

As previously noted, the impacts of WMA were lower than the impacts of HMA (with the same RAP content) in the asphalt production stage. This is due to the reduction in manufacturing temperature, which is 165 °C for HMA and 135 °C for WMA. This temperature reduction of 30 °C led to a fuel saving of 15–16%, which is within the 10–30% range reported in the literature (Gandhi, 2008). The reduction in fuel consumption produced a twofold environmental benefit: the impact on CC due to air emissions from the asphalt production process was decreased in the same proportion, whilst the impacts on CC and FD associated with the life cycle of the fuel were both decreased (see middle graph in Fig. 4). Conversely, the impacts of WMA were higher than the impacts of HMA in the materials stage. This is due to the differences in composition between HMA and WMA. The composition of both asphalt mixes is very similar in this case, except that synthetic zeolites and hydrated lime are added to the WMA at a rate of 0.24% and 1.5% by dry weight, respectively, replacing the same proportions of cement. The hydrated lime has slightly greater impacts than the cement being replaced, and thus hardly contributed to increase the impacts of WMA with respect to HMA. However, the production of synthetic zeolites is highly intensive in energy and resources, the impacts of zeolites being much greater than the impacts of cement. Consequently, the synthetic zeolites caused the greatest part of the increase in the impacts of WMA with respect to HMA in the materials stage, despite the fact that they were added in very small proportions (see top graph in Fig. 4). There were not significant differences between the impacts of HMA and WMA in other stages of the life cycle. The increase in the impacts of WMA due to the addition of zeolites offset the decrease in the impacts resulting from the reduction in manufacturing temperature. Therefore, the overall impacts of WMA were almost equal to the overall impacts of HMA with the same RAP content.

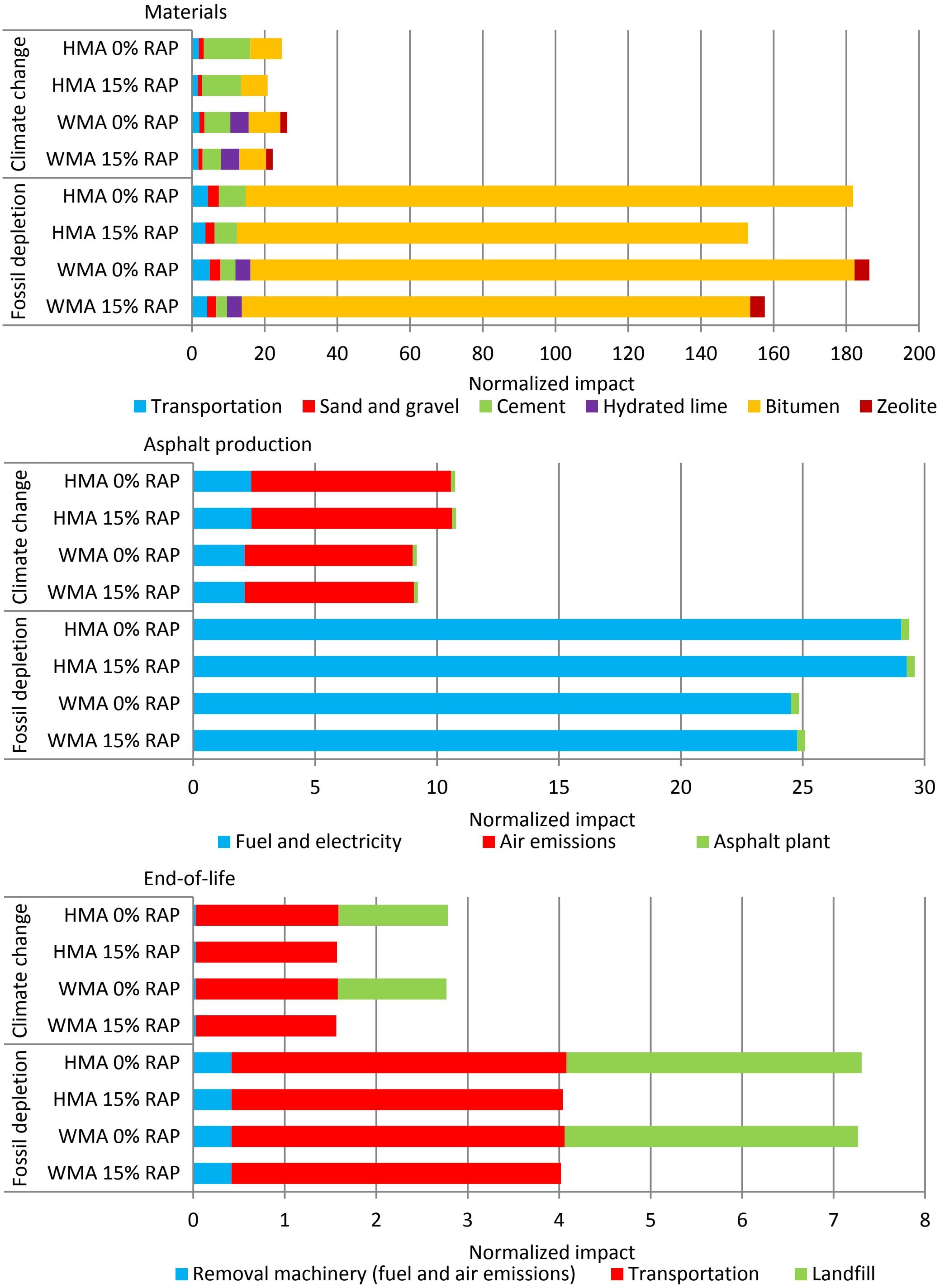

Fig. 4. Impacts on climate change and fossil depletion of materials, asphalt production and end-of-life (midpoint impact assessment by using the ReCiPe Midpoint (H) V1.06/Europe ReCiPe H method).

Most studies comparing WMA and HMA have shown that the emissions during the production and placement of WMA are reduced in comparison to HMA. These studies have successfully quantified some of the potential environmental impacts of WMA in terms of resource consumption and emissions. However, the role of the upstream supply chain related to the production of the minerals, asphalt binders and chemical additives used in different asphalt mixes, and related environmental impacts associated with the transportation of these materials have generally not been included in the scope of the above-mentioned studies (Tatari et al., 2012). By considering the entire life cycle, the WMA are not as advantageous over the HMA, because the impact of the materials stage counteracts the benefit in the production stage.

It was also previously noted that the impacts of asphalt pavements could be reduced by adding RAP. The reduction in the impacts was mainly attributable to the materials and end-of-life stages. Conversely, there were no significant differences between the impacts of mixes with different RAP contents in other stages of the life cycle. The use of RAP as a raw material avoided the need to extract a portion of the virgin raw materials, such as sand and gravel, and also made the processing of a portion of the bitumen unnecessary. The impacts of the materials stage were thus decreased in the same proportion as the percentage of RAP that was added (see top graph in Fig. 4). In addition, the use of RAP also avoided disposal of asphalt to landfill, which reduced the impacts of the end-of-life stage (see bottom graph in Fig. 4).

At this point, it is worth noting that one of the main advantages of WMA is the potentially greater use of RAP as a result of the increased workability of WMA compared to HMA. The improved workability of WMA leads to a lower production temperature, with less ageing of the binder, thus counteracting the stiffer RAP binder (Rubio et al., 2012). Certain studies have even reported RAP percentages of over 50% (D'Angelo et al., 2008 and Vaitkus et al., 2009). Therefore, the decrease in the impacts resulting from the addition of large amounts of RAP in WMA could turn them into a good alternative to HMA in environmental terms.

2.4. Conclusions

A comprehensive LCA of asphalt pavements, which includes HMA and zeolite-based WMA both with and without RAP, was conducted. For this purpose, an LCA-based tool was developed and implemented in a spreadsheet software application, which computes the impacts of asphalt pavements automatically.

The life cycle of road pavements was divided into seven major stages: (1) materials, including extraction and processing of aggregates, bitumen, filler, synthetic zeolites, anti-stripping agent and RAP, and also transportation of materials to the asphalt plant; (2) asphalt production, including land use, infrastructure and machinery, fuel and electricity consumption and air emissions from the asphalt plant; (3) transportation of asphalt mixes to the construction site; (4) construction, including fuel consumption and air emissions from asphalt paving machinery, air emissions and leachate from the asphalt pavement, and transformation of land; (5) use, including fuel consumption and air emissions from road traffic, and occupation of land; (6) maintenance, including dismantling of the worn asphalt layer and paving a new asphalt layer; and (7) end-of-life, including fuel consumption and air emissions from asphalt milling machinery, landfill disposal and recycling of asphalt waste, transportation of asphalt waste to treatment facilities, and transformation of land. Field data were complemented with data from LCA databases and from scientific literature to create the LCI of inputs and outputs associated with each stage of the life cycle. Thermodynamic modeling was also performed to estimate the LCI of the production of any asphalt mix as a function of its composition and manufacturing temperature.

The ReCiPe method was used to assess the environmental impacts according to two sets of impact categories: midpoint categories and endpoint categories. Midpoint impact categories are climate change, fossil depletion, and another sixteen impact categories. Endpoint impact categories are damage to human health, damage to ecosystem diversity, and damage to resource availability. The cumulative energy demand was also assessed to ease energy comparisons between asphalt pavements.

As a case study, four different asphalt pavements were assessed and compared for a particular road using the LCA-based tool. The pavements evaluated include: HMA with 0% of RAP, HMA with 15% of RAP, zeolite-based WMA with 0% of RAP, and zeolite-based WMA with 15% of RAP. By comparing HMA and zeolite-based WMA throughout their entire life cycle, it was found that the impacts of WMA are almost equal to the impacts of HMA with the same RAP content. The reduction in the impacts of WMA due to lowering the manufacturing temperature is offset by the greater impacts of the materials used, especially the impacts of the synthetic zeolites. Moreover, by comparing the same type of asphalt mixes with different RAP contents, it was shown that the impacts of asphalt mixes are significantly reduced when RAP is added. The use of RAP as a raw material avoids the need to extract a portion of the virgin raw materials, the need to process a portion of the bitumen, and the need to dispose of the asphalt to landfill. Thus, both the impacts of the materials and the impacts of the end-of-life are decreased. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% of RAP. The uncertainty assessment through Monte Carlo simulations confirmed that these critical impacts could be reduced with a probability of about 99% by adding RAP to the asphalt mixes.

A key advantage of WMA is the potentially greater use of RAP. Thus, the decrease in the impacts achieved by adding large amounts of RAP in WMA could turn these asphalt mixes into a good alternative to HMA in environmental terms.

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3

The noise impact category in life cycle assessment

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3.1. Introduction

3.1.1. Life cycle assessment and impact categories

In recent decades, awareness of environmental issues has increased among the population, and this has led to the generation of strategies and methods for evaluating the impact on the environment so that levels of pollutants can be reduced. One of the tools most widely accepted by the scientific community for evaluating environmental impact is life cycle assessment (LCA), which is a methodology that assesses the entire life cycle of a process or product. According to standard ISO 14040:2006, "LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)" (ISO, 2006). A clear advantage of the methodology is that allow us to detect situations in which a particular system seems cleaner than another simply because it shifts the environmental burdens to other processes or geographic regions, with no real improvement from a global point of view (this phenomenon is known as 'problem shifting') (Iglesias, 2005).

The LCA methodology allows the composition and amounts of pollutants generated and resources consumed to be evaluated in terms of their impacts on the environment by grouping them into a small number of environmental impact categories. The impact categories most commonly considered in LCA of processes or products are climate change, ozone layer depletion, tropospheric ozone formation, acidification, eutrophication, human and environmental toxicity, and fossil fuel depletion. Unfortunately, to date, no reliable methods have been developed to analyse some categories, such as the impact on land use, the visual impact or impact on the landscape, or the impacts of odours and noise. These latter categories are not always taken into account in environmental impact assessments or are simply not well suited to such assessments. The application of indicators for these categories is still a time-consuming and complex task due to the scarcity of available data and the lack of agreement on the parameters to be considered and the methodology to be followed. However, bearing in mind that transportation is a cornerstone of the world production system, noise from road traffic is likely to become one of the most significant impact categories in the future, given its effects on human health.

3.1.2. Effects of noise on human beings

Environmental noise has become one of the major problems affecting the quality of life of people, especially in city centres and in suburban areas that lie close to major roads, where the noise generated by vehicles makes the problem even more important. In fact, it has been estimated that 80% of the noise produced in cities is attributable to motor vehicles. The problem is particularly serious in Spain; according to a 1986 report by the Organisation for Economic Cooperation and Development, Spain ranked second among the noisiest countries in the world (only surpassed by Japan).

According to the World Health Organization, noise can have negative effects on human health when the equivalent sound pressure levels exceed 65 dBA during the day and 55 dBA at night. High noise levels can have various adverse physical and mental effects on human beings, including hearing impairment, interference with speech communication, sleep disturbance, cardiovascular and physiological effects, mental health effects, and performance impairment. Noise can also have negative effects on relationships with family and neighbours, reduce the selling price of residential properties, and affect the fundamental right of people to their own privacy. This has led to the introduction of strict regulations in several European countries to limit the amount of noise to which the population is exposed.

3.2. Noise in life cycle assessment

Most studies on environmental noise conducted around the world have focused on quantifying or predicting noise levels, on estimating the percentage of population exposed to different levels, or on describing noise effects on people. Very few, however, have attempted to establish a relationship between the emission of a particular type of noise and its real measurable impact on human beings. Müller-Wenk (1999, 2002, 2004) stands out as a reference for his studies on the impact produced by noise from road traffic. He developed a method to quantify the effects of noise on health, using the DALY (disability-adjusted life year) as the unit of measurement, and to incorporate it into LCA. Doka (2003) and Nielsen and Laursen (2003) also developed methods for assessing the impact on health produced by noise from road traffic. The main features of these methods are outlined below.

3.2.1. The method of Müller-Wenk

The method of Müller-Wenk (1999, 2002, 2004) is based on the cause-effect chain. It consists in analysing any modification of a variable with a direct effect on a pollutant registered in the life cycle inventory (LCI) and estimating the damage to human health associated with such a modification. The procedure for building up this chain is made up of the following steps:

1. *Fate analysis*, which describes the increase in the concentration of the pollutant (in this case, the increase in noise level) caused by the modification of the variable affecting the pollutant registered in the LCI.
2. *Exposure analysis*, which shows how many people are affected by such a change in the concentration of the pollutant, and to what extent.
3. *Effect analysis*, which describes the incremental effect on health that is likely to occur if human beings are exposed to a certain increase in the concentration of the pollutant over a certain period of time.
4. *Damage analysis*, which describes the total extent of damage to human health that is represented by the above-mentioned effect on health.

The method of Müller-Wenk incorporates a road traffic noise model developed by the Swiss Agency for Environment, Forest and Landscape (SAEFL, 1991). This model computes the noise emission level of a road (LA_{eq}, in dBA) as a function of the car noise and the truck noise ($LE1$ and $LE2$, in dBA), which in turn depend on the traffic volume of cars and trucks ($N1$ and $N2$, in veh/h), their average speed ($V1$ and $V2$, in km/h), and the slope of the road (i, in %). The model includes the following equations:

$$LA_{eq} = 10 \cdot log(10^{0.1 \cdot LE1} + 10^{0.1 \cdot LE2}) \tag{2}$$

$$LE1 = E1 + 10 \cdot log(N1) \tag{3}$$

$$LE2 = E2 + 10 \cdot log(N2) \tag{4}$$

$$E1 = max[\{12.8 + 19.5 \cdot log(V1)\}, \{45 + 0.8 \cdot (0.5 \cdot i - 2)\}] \tag{5}$$

$$E2 = max[\{34 + 13.3 \cdot log(V2)\}, \{56 + 0.6 \cdot (0.5 \cdot i - 1.5)\}] \quad (6)$$

The first step of the method is to calculate the noise emission level, first with the actual traffic and then with an increase in traffic proportional to the actual traffic. The difference between the two values of the noise emission level is ΔLA_{eq}, which represents the noise increase caused by the increase in the number of vehicles. The transport to be assessed is not considered as a single isolated event, but rather as a small part of the annual increase in traffic density over the whole road network of a region or country. According to Müller-Wenk, statistics show that the annual increase in traffic on the different roads is, as a first approximation, proportional to the traffic level of the preceding year. If the traffic increase on every road is taken as proportional to the pre-existing traffic volume, calculations and theoretical considerations show that the value of ΔLA_{eq} is roughly constant over all segments of the road network, with small differences that are attributable to different vehicle speeds and road surface properties. In fact, the ΔLA_{eq} due to an increase of one vehicle per hour is roughly proportional to the first derivative of the logarithm of the hourly number of vehicles (N), which is inversely proportional to the hourly number of vehicles ($1/N$). But if the traffic increase on every road is proportional to N, instead of a constant additional vehicle, the corresponding ΔLA_{eq} is proportional to N multiplied by its reciprocal ($N \cdot 1/N$). Therefore, ΔLA_{eq} is independent of N and the same noise increase is considered for roads with high and low traffic volumes.

The second step is to quantify the number of people exposed to road traffic noise above threshold levels. Müller-Wenk used a computer-based model to obtain data on exposure to road traffic noise for the Swiss canton of Zurich (which accounts for approximately a sixth of the total Swiss population). The results for this area were then extrapolated to obtain exposure data for the whole Swiss population.

The third step is to determine the number of additional cases of health impairment due to a certain noise increase. Müller-Wenk relied on dose-response relationships between the disturbance and the level of road traffic noise. These relationships were based on a survey study in which interviewees were asked to what extent they experience communication disturbance and sleep disturbance (in order to measure daytime and night-time effects, respectively). Additionally, the noise level was calculated at the most exposed façade of dwellings, but it was not communicated to the interviewees. Müller-Wenk thus came to the conclusion that the approximate percentage of people who report that they suffer from communication disturbance increases linearly by 2.5% per dBA, starting at a daytime outdoor level of 55 dBA. He also deduced that the approximate percentage of people who report that they suffer from sleep disturbance increases linearly by 1.7% per dBA, starting at a night-time outdoor level of 46 dBA.

The last step is to calculate the damage to human health due to the noise increase caused by the additional number of vehicles on the road network. The data on noise increase, number of people exposed, and additional cases of disturbance per dBA are used together with the so-called 'disability weights' (DWs) to obtain values of health damage in DALY units (cf. Section 3.4).

3.2.2. The method of Doka

According to Doka (2003), no linear relationship exists between the value of noise in decibels and its effects on human health. The decibel is a logarithmic unit that measures the sound power and pressure. Due to the logarithmic nature of this unit, there is no single characterisation factor in LCA that can be readily multiplied by a value of noise in decibels to give a value in DALYs.

The method of Doka managed to adapt the approach of Müller-Wenk (1999, 2002, 2004) so as to be able to calculate the DALYs resulting from noise generated by different models of cars in Switzerland. Reasonable approximations were made to arrive at a simplified formula that calculates the damage to human health in DALYs per vehicle-kilometre (*Damage*, in DALY/vkm) as a function of the noise level produced by the car in decibels, as follows:

$$Damage = K \cdot 10^{a \cdot L_P + b} \tag{7}$$

where L_P is the noise level of a single car at a speed of 50 km/h (measured in dB at a distance of 7.5 m from the car), and a , b and K are parameters depending on the time of the day when the journey is undertaken (see Table 12).

Different values of noise levels can therefore be used to calculate the DALYs per vehicle-kilometre for various car models with different noise characteristics, resulting in graphs like the one in Fig. 5.

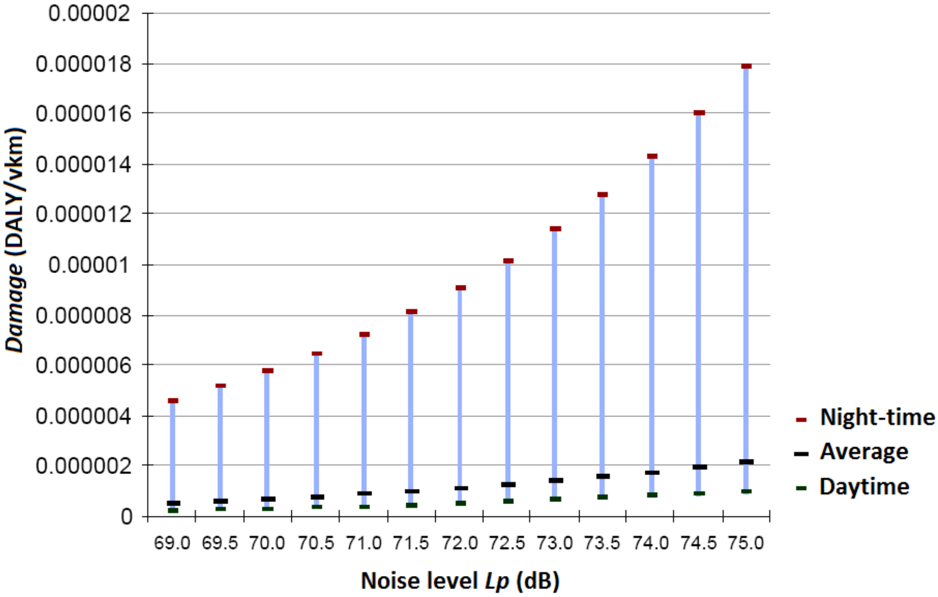

Fig. 5. Damage to human health per vehicle-kilometre depending on the noise level of the car and the time of the day when the journey is undertaken. *Source*: Doka (2003).

Table 12. Parameters of Eq. (7) for different times of the day.

Parameter	Unit	Average journey (93% daytime and 7% night-time)	Daytime journey	Night-time journey
a	1/dB	0.099962	0.09998766	0.0999043
b	Dimensionless	−6.243371	−6.3738654	−5.5943622
K	DALY	1.23406E-07	7.60872E-08	2.30486E-07

Source: Doka (2003).

3.2.3. The method of Nielsen and Laursen

Nielsen and Laursen (2003) focused their study exclusively on noise that disturbs human beings during transportation of products. The effects in areas that are potentially more sensitive to noise (such as natural parks and recreational areas) and the effects on animals were not taken into account to allow a clearer and simpler method. They also assumed other simplifications with regard to the distribution of noise and the quantification of the extent to which noise disturbs people.

The method of Nielsen and Laursen incorporates a noise model that can be represented graphically as in Fig. 6, which shows the isophones around a noise source as well as the number of people in each isophone. Noise level decreases as the distance from the source increases due to the attenuation caused by the divergence of the sound waves and the absorption of sound by the atmosphere. This noise reduction may also be influenced by several factors, such as topography and acoustic properties of the landscape around the source, presence of walls or buildings, speed and direction of the wind, temperature and relative humidity of the air, and directivity of the source.

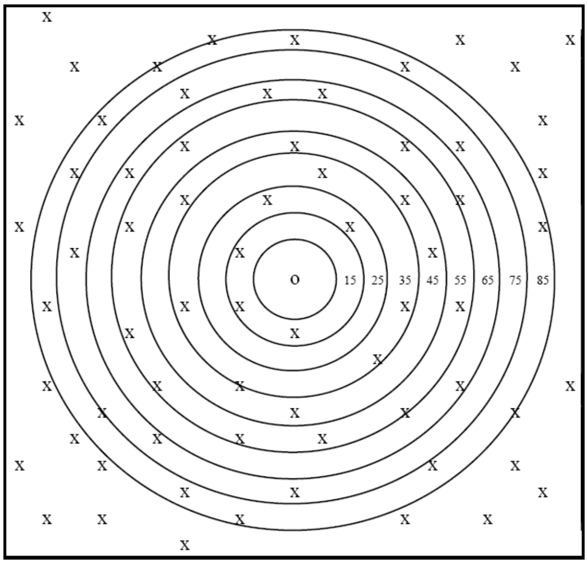

Fig. 6. Model of the distribution of population (x) within circular isophones at a distance *d* (0–85 m) around a noise source (o). *Source*: Nielsen and Laursen (2003).

The circular isophones in Fig. 6 appear only in flat open landscapes when the atmosphere is still and homogeneous. However, in many situations the isophones are not circular as they are shaped according to the environmental conditions of the moment. For the sake of simplicity, Nielsen and Laursen assumed circular isophones with noise levels given by simple mathematical formulas.

The noise nuisance (NN_d) at a specific distance d from a point source can be quantified in terms of person-hours as follows:

$$NN_d = P_d \cdot T_{proc} \cdot NNF_{L_P} \tag{8}$$

where P_d is the number of persons within a distance d from the source (which can be determined by counting or by average estimation), T_{proc} is the duration of the noisy process (i.e., the time required to produce one unit of the product or service according to the functional unit; this time in hours can be determined by measurement or by average calculation), and NNF_{Lp} is a noise nuisance factor specific for the actual noise level L_p relative to the background noise level (dimensionless).

The noise nuisance factor represents the inconvenience caused by noise to human beings. This is a subjective parameter that is determined by aspects such as noise level, frequency composition of the noise, background noise level, and certain characteristics of each person. The relationship between the noise nuisance factor and the noise level is defined by the following equation:

$$NNF_{L_P} = 0.01 \cdot 4.22^{0.1 \cdot (L_P - K)} \tag{9}$$

where L_P is the noise level (in dBA), K is the background noise level (in dBA), and the exponential factor ($L_p - K$) expresses the part of the noise that exceeds the background noise.

The total noise nuisance caused by a specific process (NN_{proc}, in person-hours) can be determined by the sum of the nuisances on all the persons within each isophone as follows:

$$NN_{proc} = \sum_d NN_d = T_{proc} \cdot \sum_d P_d \cdot 0.01 \cdot 4.22^{0.1 \cdot (L_P(d) - K)} \tag{10}$$

where $L_P(d)$ is the noise level at the distance d from the noise source.

Finally, the total nuisance from a product or service (NN_{prod}, in person-hours) can be determined by the sum of the nuisances from all processes as follows:

$$NN_{prod} = \sum NN_{proc} \tag{11}$$

This method can be used to calculate the noise nuisance due to transportation of products by road and rail. With certain modifications, it can also be used to calculate the nuisance caused by noise from other sources such as air transport, industry and building works.

3.2.4. Discussion of the methods

The method of Müller-Wenk (1999, 2002, 2004) is the most commonly cited among the methods described above. Despite being apparently difficult to use at first, it greatly simplifies the task of determining the additional cases of health impairment due to an increase in traffic and the task of calculating the corresponding damage to human health in DALYs. This method is very useful to obtain generic overall impacts of road traffic noise regardless of the route followed, which are applicable to large areas such as an entire country. However, the method has several aspects that need to be improved, such as the noise emission model, which is quite obsolete, and it should also take into account other effects on human health.

The method of Doka (2003) is quite practical because, by obtaining adjustment parameters, it establishes a direct relationship between the noise produced by road traffic and the damage to human health in DALYs. Since the adjustment parameters were based on previous work by Müller-Wenk (1999, 2002, 2004), this method has the same aspects that are in need of improvement in that of Müller-Wenk and is only applicable to the Swiss road network.

The method of Nielsen and Laursen (2003) is also simple to apply because it requires only the population density, distance to the noise source, noise levels and time of the process to calculate the noise nuisance in terms of person-hours affected by road traffic noise. However, this method has the drawback that it does not convert the noise nuisance into the corresponding damage to human health in DALYs.

3.3. Guidelines for incorporating the effects of noise into life cycle assessment

The purpose of studies aimed at incorporating the category 'noise' into LCA must be to analyse the damage to human health caused by noise from a product-oriented point of view. This will allow the noise to be assessed and considered on the same level as any other impact category. The noise will thus be included as an environmental aspect in the development of products.

We believe it is wise to use the cause-effect chain as the basis for the integration of the noise impact category into LCA. It is therefore necessary to start by modelling the noise emission level of a traffic flow on a virtual road network with a virtual population distributed around the roads. The road traffic noise model must be up-to-date and able to calculate the noise emission level of a traffic flow composed of various classes of vehicles (cars, vans, trucks, mopeds, motorcycles, and so forth) as a function of the flows and speeds of such vehicle classes. Furthermore, other parameters must also be considered, such as air temperature, acceleration and deceleration, road slope, road surface type, engine type, tyre type and width, fraction of illegal exhaust systems, and so forth. These parameters make it possible to model the virtual road network and its vehicles with the same characteristics as the roads and vehicle fleets under study. One of the most widely accepted models in Europe for this purpose is that developed within the IMAGINE project (Peeters and van Blokland, 2007).

Once the initial traffic flow on the road network has been modelled, a new traffic flow has to be modelled with a small increase in vehicle flow with respect to initial flow, and the noise emission level must then be recalculated without varying any other initial condition. The difference in noise emission level between the initial and final traffic situations represents the noise increase attributable to the increase in traffic flow. Since this incremental approach assumes the same conditions of noise propagation for the initial and final situations, the noise increase perceived by the receivers is the same as the increase in noise emission level.

In order to determine the amount of population affected by the noise increase, it is necessary to collect data on frequency distributions of people exposed to road traffic noise by different intervals of noise levels. These frequency distributions can be obtained through a combination of strategic noise maps for roads and data on population density within the areas under study.

Once the amount of population exposed to different noise levels has been quantified, the additional cases of health impairment due to the noise increase must be calculated. This can be achieved through social survey studies that establish relationships between the percentage of persons who report that they experience 'high disturbance' due to road traffic noise and the particular noise level to which they are exposed. These relations between disturbance and noise level allow psychological aspects of noise to be introduced. Moreover, these relations are represented through curves that can be treated as straight lines within the different intervals of noise levels, thus simplifying the calculation of the additional cases of disturbance due to a noise increase.

Finally, the above-mentioned disability weights have to be used to quantify the damage to human health in DALYs. The DALY is an internationally recognised unit of measurement and is recommended by the World Health Organization to measure health damages. The main characteristics of the DALY unit are defined in the next section.

3.4. The DALY unit

The concept of the unit of measurement known as the DALY (disability-adjusted life year) started to be developed in the early 1990s as an alternative to the QALY (quality-adjusted life year). After extensive review and international discussion, and based on the findings of a study aimed at quantifying the overall burden of disease on the population, the foundations for the definition and calculation of DALYs were published in 'The global burden of disease' (Murray and López, 1996).

The DALY unit expresses in a single measure both the years of life lost due to premature death and the years lived with a disability of specified severity and duration. One DALY is thus one lost year of healthy life (Murray and López, 1996). This unit of measurement is recommended by the World Health Organization to quantify the burden of diseases and their sequelae in human beings.

The years of life lost due to premature death are calculated from the standard life expectancy at the age at which death occurs. The years lived with a disability are calculated from the average duration of disability multiplied by a severity factor known as disability weight (DW). These DWs are developed by the World Health Organization for each disease based on the severity of the associated health impairment, and they act as factors that weigh the relative importance of each health condition (attributed to each disease) with respect to death. DWs are thus expressed on a scale from zero to one, where zero indicates a perfect health condition and one is death. Table 13 shows some examples of diseases and their corresponding DWs.

Table 13. Disability weights for some diseases.

DW range	Diseases (as indicators of health conditions)
0.00–0.02	Vitiligo on face, mild obesity
0.02–0.12	Watery diarrhoea, severe sore throat, severe anaemia
0.12–0.24	Radius fracture in a stiff cast, infertility, erectile dysfunction, rheumatoid arthritis, angina
0.24–0.36	Below-the-knee amputation, deafness
0.36–0.50	Rectovaginal fistula, mild mental retardation, Down syndrome
0.50–0.70	Unipolar major depression, blindness, paraplegia
0.70–1.00	Active psychosis, dementia, severe migraine, quadriplegia

Source: Murray and López, 1996.

The World Health Organization database does not include DWs for the harmful effects of noise exposure. Nevertheless, some authors have conducted studies and surveys to obtain consistent data for the quantification of damage to human health caused by noise:

- Müller-Wenk (2002, 2004) carried out a survey involving 41 physicians who were experienced in evaluating and comparing the severity of various disabilities. His findings provided DWs for two types of health impairment due to noise, namely communication disturbance (in the daytime) and sleep disturbance (at night-time), which obtained DW values of 0.033 and 0.055, respectively.
- Meijer (2006) conducted an LCA study on the improvement of the environmental performance of buildings. In order to assess the environmental benefit of using materials with improved soundproofing properties, he applied the DWs provided by Müller-Wenk (2002, 2004).
- Westerberg and Glaumann (2002) performed an analysis of health risks in buildings and outdoors. They applied DWs for different diseases and confort problems, including disturbance due to road traffic noise. The DW for noise disturbance was estimated to be 0.01.

3.5. Conclusions

A critical review of existing methods for the assessment of the impact of road traffic noise on human health has been conducted. As a result of this review, the following conclusions can be drawn:

- Because transportation now plays a key role in the global system of production and is continually expanding, the category of noise must be included when assessing the environmental impact of vehicles and their effects on population health.
- The environmental cause-effect chain is the ideal procedure to incorporate the effects of noise on health into environmental impact assessments with methods like LCA.
- The DALY is the unit of measurement best suited for quantifying the effects of noise on health, not only because it is recommended by the World Health Organization but also because it is simple to be calculated and interpreted. Furthermore, this unit is typically used in LCA to quantify the effects on health from other pollutants. The DWs related to the effects of noise, however, have not yet been published by the World Health Organization, but these can be obtained from previous studies or derived from expert surveys.

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4

A method to assess the impact of road transport noise within the framework of life cycle assessment

DYNA (accepted for publication 16 September 2013)

4.1. Introduction

Road transport is an essential element for the development of industrial activity, but it also contributes heavily to air pollution, climate change and environmental noise. The impact assessment of air pollutant emissions from road vehicles has a solid methodological basis, both in environmental impact assessments and within the framework of life cycle assessment (LCA). By contrast, noise has special characteristics (dependence on local factors, lack of linear additivity of emissions, and so forth) which complicate the assessment of its impact upon health. The lack of data on noise has been an additional problem for the assessment.

In order to tackle the problem of environmental noise, the Directive 2002/49/EC (European Commission, 2002a) –also known as the Environmental Noise Directive– provide a common basis for the assessment and management of noise across the EU. In this respect, the use of harmonised indicators and methods for assessing environmental noise has a key role. According to the Environmental Noise Directive, the determination of exposure to noise must be conducted through noise mapping by using the common indicators of noise levels: day-evening-night noise indicator (L_{den}) to assess annoyance, and night-time noise indicator (L_{night}) to assess sleep disturbance. The EU Member States have published strategic noise maps for their major roads. Although the Environmental Noise Directive refers to annoyance and sleep disturbance as indicators of the harmful effects of noise exposure, it does not provide specific methods to assess such effects.

A number of valuable contributions towards the methodological development of the impact assessment of noise from road transport have been made in the past decade, especially in the context of LCA (Müller-Wenk, 2002, 2004; Doka, 2003; Nielsen and Laursen, 2005; Althaus et al., 2009; Franco et al., 2010). Müller-Wenk (2002, 2004) was first to devise a comprehensive methodology to estimate the health impact of noise attributable to an additional transport unit. This methodology helped raise awareness about the relevance of noise as a major source of global health impairment. However, it showed limited applicability in the context of everyday practice, and it assumed some simplifications that lead to an overestimation of the overall health impacts caused by transport noise (Franco et al., 2010). Bearing in mind these shortcomings, Franco et al. (2010) developed an alternative calculation method that incorporates an advanced noise emission model for road traffic, thus allowing for better accuracy in the computation of health impacts. This method was devised to be consistent with the Environmental Noise Directive (European Commission, 2002a), since it uses data from strategic noise maps to calculate the effects of noise upon health in terms of annoyed persons. The method of Franco et al. (2010), however, has two drawbacks: it does not consider the effects of noise associated with sleep disturbance, and it does not convert the effects of noise into their corresponding damages to human health.

The method of Franco et al. (2010) is complemented here with the calculation of the effects of noise upon health in terms of sleep disturbed persons. Additionally, the method is extended to quantify not only the effects of noise but also the damages to human health associated with such effects. To this end, the calculation of the environmental burden of disease associated with annoyance and sleep disturbance is also included, thus quantifying the health impact of noise in DALYs (disability-adjusted life years). The DALY indicator allows the impact of noise to be compared and aggregated with other health impacts that are usually assessed in LCA.

In order to illustrate the application of the extended method, we present a case study that deals with the calculation of the noise impact caused by a heavy vehicle that travels one kilometre on three different roads. The extended method is used to calculate the health impact caused by the noise from the heavy vehicle on each of the roads. Moreover, the impact assessment method ReCiPe (Goedkoop et al., 2009) is used to calculate the health impacts due to fuel consumption and air pollutant emissions from the heavy vehicle. Finally, the noise impact is compared and aggregated with the health impacts from the other pollutants emitted by the vehicle.

4.2. Materials and methods

A comprehensive method is provided herein for the assessment of the impact of road transport noise upon human health. This method uses data from strategic noise maps for calculations. It was also devised to be applicable at different geographical scales and to integrate easily within the framework of LCA. A schematic representation of the complete method is shown in Fig. 7, which includes both the elements of the original method (Franco et al., 2010) and the elements incorporated herein.

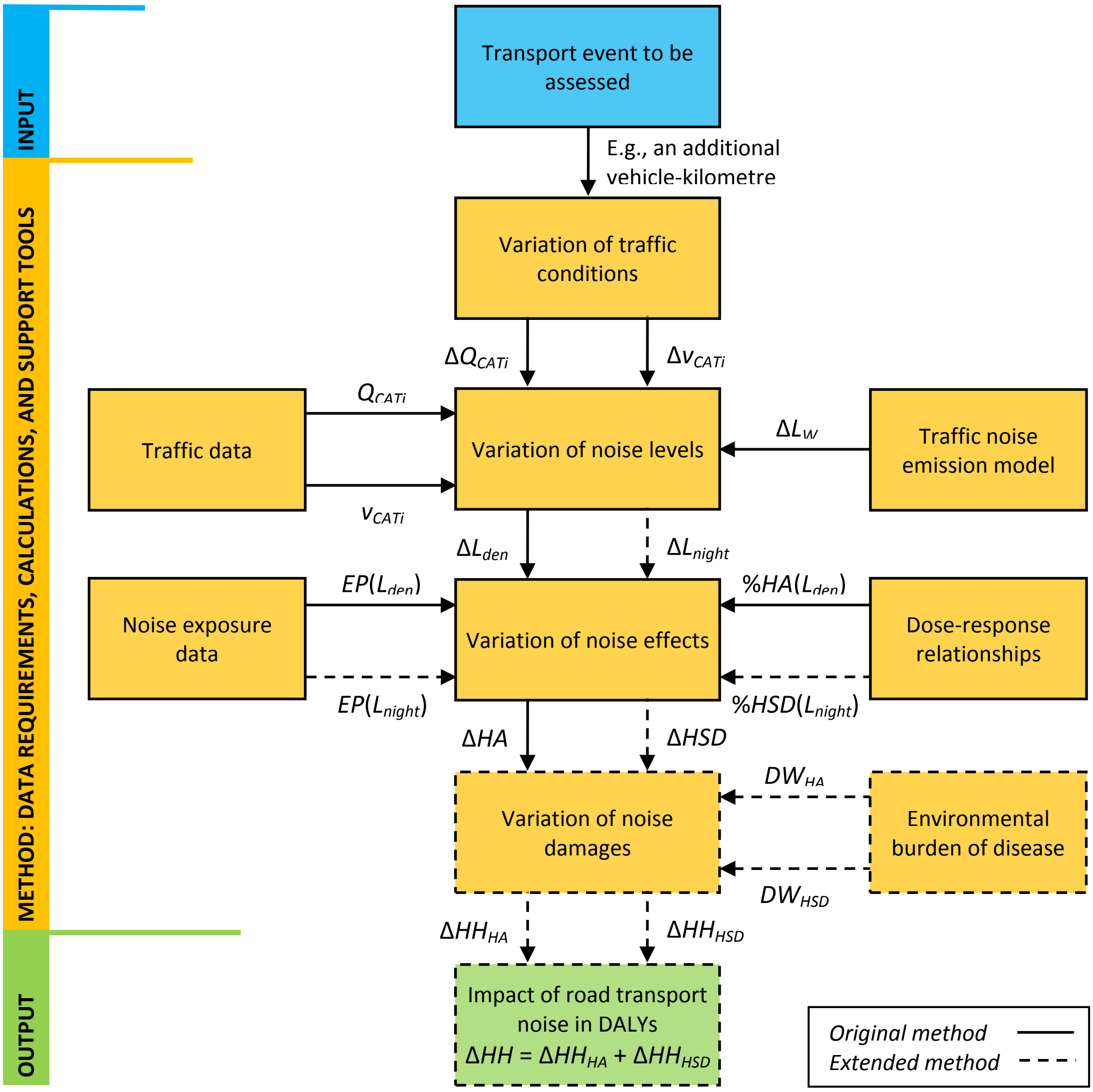

Fig. 7. Method overview.

4.2.1. Variation of traffic conditions

Müller-Wenk (2002, 2004) devised an incremental approach to assess the health impact of noise caused by an additional transport unit. The incremental approach calculates the impact of two scenarios: a baseline scenario, which reflects the current traffic situation (flow, composition and speed); and a modified scenario, which is based on the baseline scenario but includes one additional vehicle that travels a given distance. The difference between the impacts of both scenarios represents the noise impact of that additional number of vehicle-kilometres. This approach has been considered by several authors as the most suitable for the inclusion of the impact assessment of road transport noise in LCA (Doka, 2003; Althaus et al., 2009; Franco et al., 2010). The method of Franco et al. (2010) incorporates a traffic noise emission model that allows the assessment of traffic variations other than the typical increases in the number of vehicle-kilometres travelled (e.g., variations in traffic flow, composition, speed, or combinations of these).

4.2.2. Variation of noise levels

The method uses the noise level indicators L_{den} and L_{night} to assess respectively annoyance and sleep disturbance. L_{den} is the day-evening-night noise indicator and represents the A-weighted long-term average sound level determined over all the day-evening-night periods (24 h) of a year. L_{den} (in A-weighted decibels, dBA) is defined by the following equation (European Commission, 2002a):

$$L_{den} = 10 \cdot log\left(\frac{12}{24} \cdot 10^{\frac{L_{day}}{10}} + \frac{4}{24} \cdot 10^{\frac{L_{evening}+5}{10}} + \frac{8}{24} \cdot 10^{\frac{L_{night}+10}{10}}\right) \tag{12}$$

where L_{day}, $L_{evening}$ and L_{night} are the day, evening and night noise indicators, which represent the A-weighted long-term average sound levels determined respectively over all the day (12 h), evening (4 h) and night (8 h) periods of a year.

Exposure to noise levels L_{den} and L_{night} can be determined either by calculation or by measurement. Traffic noise prediction models are a valuable alternative to traditional techniques for in situ measurement, since they save time and costs and are suitable to simulate changes in traffic conditions (Steele, 2001). These models need detailed modelling of the noise emission sources and the propagation environment to calculate the sound power level emitted by the noise sources and the sound pressure level at the position of the receivers. The incremental approach can, however, save modelling efforts: since sound pressure level variations are fully transmitted along every noise propagation path (Müller-Wenk, 2002, 2004), all receivers in the noise propagation environment will experience the same increase or decrease in equivalent noise levels after a given variation of traffic conditions takes place (see Fig. 8). Furthermore, sound power level variations are directly translated into sound pressure level variations, so no distinction is made between the two. Thus, assessments based on an incremental approach can be performed without modelling the sound propagation in most situations, requiring only a suitable traffic noise emission model to calculate the variation of noise levels (Franco et al., 2010).

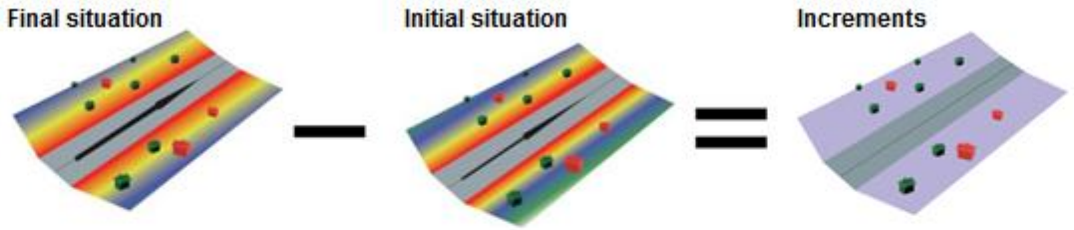

Fig. 8. Illustration of the incremental approach: for a given increment in noise emission levels, increments in noise exposure levels are equal for all receivers.

The traffic noise emission model used herein is an advanced model developed within the CNOSSOS-EU project (Kephalopoulos et al., 2012). This model provides the instantaneous sound power level of a single vehicle at a specific point as a function of speed for different vehicle classes: light motor vehicles (CAT1), medium heavy vehicles (CAT2), heavy vehicles (CAT3), and powered two-wheelers (CAT4). This model also includes several correction factors to account for variations in noise emissions due to regional variations in vehicle fleet characteristics, meteorological conditions, road properties or driving behaviour.

To calculate the noise emission level of a given vehicle flow, the single-vehicle sound power level provided by the model can be combined with traffic data (vehicle flow and speed) to obtain an equivalent line source emitting the sound power of the vehicle flow. The equivalent sound power level per unit length as emitted by a flow of vehicles of the same class during a time period T ($L_{W,T,CATi}$, in dBA/m) is computed by applying the following equation (Kephalopoulos et al., 2012):

$$L_{W,T,CATi} = L_{W,0,CATi} + 10 \cdot log\left(\frac{Q_{CATi}}{1000 \cdot v_{CATi}}\right) \tag{13}$$

where $L_{W,0,CATi}$ is the instantaneous sound power level emitted by a single vehicle of the class i (in dBA, as provided by the model), Q_{CATi} is the number of vehicles of the class i passing per unit time (in veh/h), and v_{CATi} is the average speed of the vehicle flow of the class i (in km/h).

The overall noise emission level caused by a given traffic situation ($L_{W,T}$, in dBA/m) can then be calculated through the logarithmic sum of the noise emission levels associated with the flows of the different vehicle classes composing the whole traffic. The sum of equivalent sound power levels is computed as follows (Kephalopoulos et al., 2012):

$$L_{W,T} = 10 \cdot log\left(\sum_i 10^{\frac{L_{W,T,CATi}}{10}}\right) \tag{14}$$

Finally, the variation of noise levels (both emission and exposure levels) due to a variation of traffic conditions is calculated as the difference in overall noise emission levels between the initial and final traffic situations.

4.2.3. Variation of noise effects

In order to determine the effects of noise upon the health of people exposed, the method incorporates additional indicators that are obtained from dose-response relationships. The Environmental Noise Directive (European Commission, 2002a) refers to relationships between annoyance and L_{den} and relationships between sleep disturbance and L_{night}, but it does not specify the mathematical expressions to be used. EU-position papers on dose-response relationships for noise (European Commission, 2002b, 2004) indicate the mathematical expressions to be used for assessing each noise effect. Specifically, the relationships of Miedema and Oudshoorn (2001) are applied to assess the percentage of highly annoyed persons (%*HA*), whilst the relationships of Miedema et al. (2003) are applied to assess the percentage of highly sleep disturbed persons (%*HSD*). Both dose-response relationships are defined on the basis of noise exposure at the façade of dwellings. Their polynomial approximations are shown in Table 14.

Table 14. Dose-response relationships for annoyance and sleep disturbance due to road traffic noise.

Descriptor	Polynomial approximation	Range
Percentage of highly annoyed persons	$\%HA = 9.868 \cdot 10^{-4} \cdot (L_{den} - 42)^3 - 1.436 \cdot 10^{-2} \cdot (L_{den} - 42)^2 + 0.5118 \cdot (L_{den} - 42)$	45–75 dBA
Percentage of highly sleep disturbed persons	$\%HSD = 0.01486 \cdot L_{night}^2 - 1.05 \cdot L_{night} + 20.8$	40–70 dBA

The method of Franco et al. (2010) uses the polynomial approximations of the dose-response relationships in combination with noise exposure data to determine the variation of the number of highly annoyed persons (Δ*HA*) attributable to a given variation of traffic conditions. The variation of this noise effect is calculated using the following equation:

$$\Delta HA \cong \Delta L_{den} \cdot \sum_{L_{den}} \left(\frac{d\%HA(L_{den})}{dL_{den}} \cdot EP(L_{den}) \right) \tag{15}$$

where ΔL_{den} is the variation of day-evening-night noise level attributable to the variation of traffic conditions, $EP(L_{den})$ is the number of persons exposed to a 5 dBA interval of L_{den} (55–60, 60–65, 65–70, 70–75, >75) in the initial situation, and the differential term accounts for the approximated increment in the percentage of highly annoyed persons with respect to the L_{den} increment in that 5 dBA interval (calculated at the midpoint of the interval; e.g., for the 55–60 dBA interval, the differential increment is calculated at 57.5 dBA).

Likewise, the method is extended here to also assess the variation of the number of highly sleep disturbed persons (Δ*HSD*). The variation of this noise effect is calculated using the following equation:

$$\Delta HSD \cong \Delta L_{night} \cdot \sum_{L_{night}} \left(\frac{d\%HSD(L_{night})}{dL_{night}} \cdot EP(L_{night}) \right) \tag{16}$$

where ΔL_{night} is the variation of night noise level attributable to the variation of traffic conditions, $EP(L_{night})$ is the number of persons exposed to a 5 dBA interval of L_{night} (50–55, 55–60, 60–65, 65–70, >70) in the initial situation, and the differential term accounts for the approximated increment in the percentage of highly sleep disturbed persons with respect to the L_{night} increment in that 5 dBA interval (calculated at the midpoint of the interval).

Note that the polynomial approximations for *%HA* and *%HSD* do not apply to the ranges over 75 and over 70 dBA, respectively (see Table 14). Thus, the values where the differentiation is applied for the noise bands L_{den} > 75 dBA and L_{night} > 70 dBA are conservatively set to 75 and 70 dBA.

4.2.4. Variation of noise damages

The method of Franco et al. (2010) expresses the noise impact as the number of persons affected by noise effects, but it does not convert such effects into their damages to human health. The calculation of the environmental burden of disease associated with noise effects is included here to also assess the noise impact in terms of damages to human health. The World Health Organization (2011) proposes to quantify the burden of disease using the DALY indicator, which combines the years of life lost due to premature mortality (*YLL*) and the years lived with disability (*YLD*) in a single measure:

$$DALY = YLL + YLD \tag{17}$$

DALY values for a wide range of diseases have been derived from human health statistics on life years both lost and disabled. There are several harmful effects caused by road traffic noise, but only annoyance and sleep disturbance are considered herein because they comprise the vast majority of the disease burden from environmental noise (World Health Organization, 2011). Neither annoyance nor sleep disturbance causes mortality, thus the estimation of *YLL* is omitted. With regards to disability, *YLD* can be estimated as follows (World Health Organization, 2011):

$$YLD = I \cdot DW \cdot D \tag{18}$$

where *I* is the number of incident cases, *DW* is a disability weight that reflects the severity of the disease on a scale from zero (indicating a health condition equivalent to full health) to one (indicating a health condition equivalent to death), and *D* is the average duration of disability in years.

Variations of traffic conditions are translated by using the method into variations of L_{den} and L_{night} and variations of the number of annoyed persons and sleep disturbed persons. Since L_{den} and L_{night} are annual average levels by definition and annoyance and sleep disturbance usually disappear when the noise stops, the duration of disability is assumed to be one year (World Health Organization, 2011). Based on the above assumptions, the basic formula for calculating DALYs (which results from substituting Eq. (18) into Eq. (17)) can be adapted to calculate the impact of noise as the variation of noise damages to human health (ΔHH, in DALYs) as follows:

$$\Delta HH = \Delta HH_{HA} + \Delta HH_{HSD} = \Delta HA \cdot DW_{HA} + \Delta HSD \cdot DW_{HSD} \tag{19}$$

where ΔHH_{HA} and ΔHH_{HSD} are the variations of noise damages to human health related to high annoyance and high sleep disturbance, ΔHA is the variation of the number of highly annoyed persons (as results from Eq. (15)), ΔHSD is the variation of the number of highly sleep disturbed persons (as results from Eq. (16)), and DW_{HA} and DW_{HSD} are the disability weights associated with high annoyance and high sleep disturbance.

The disability weights used in the method are extracted from a study by the World Health Organization (2011) on burden of disease from environmental noise. These disability weights are shown in Table 15.

Table 15. Disability weights for annoyance and sleep disturbance due to environmental noise.

Health condition	Disability weight (*DW*)
High annoyance	0.02
High sleep disturbance	0.07

4.2.5. Data requirements

The data required by the method can be classified into traffic data and noise exposure data. Traffic data are needed to calculate the variation of noise levels (cf. Section 4.2.2) and include traffic composition (i.e., a breakdown by vehicle class), vehicle flows and vehicle speeds. Noise exposure data are needed to calculate the variation of noise effects (c.f. Section 4.2.3) and consist of frequency distributions of people exposed to road traffic noise by 5 dBA intervals of L_{den} and L_{night} on the most exposed façade of dwellings. All these data are publicly available through the strategic noise maps drafted by the EU Member States for their major roads in compliance with the Environmental Noise Directive (European Commission, 2002a). The data published so far by the European Commission are available on the web-based public information systems ReportNet–EIONET[1] and NOISE.[2]

4.3. Case study and results

A case study is presented to illustrate the application of the extended method to perform impact assessments of noise from road transport based on data from strategic noise maps. To this end, data from the strategic noise maps for three Spanish motorways were used (Fig. 9). The noise maps for these major roads refer to the year 2006 (Spanish Ministry of Agriculture, Food and Environment, 2007) and were obtained from SICA.[3] Traffic and noise exposure data (Tables 16 and 17) were used to assess the noise impact caused by a heavy vehicle that travels one kilometre on each of these motorways. Thus, the impact of noise upon health caused by an additional vehicle-kilometre per year was calculated in DALYs.

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[1] European Environment Information and Observation Network (http://cdr.eionet.europa.eu).

[2] Noise Observation and Information Service for Europe (http://noise.eionet.europa.eu).

[3] Spanish Information System on Noise Pollution (http://sicaweb.cedex.es).

The case study also compares the health impact caused by the noise from the additional heavy vehicle with the health impacts caused by other pollutants from the same vehicle. To this end, an average heavy vehicle was modelled according to the vehicle fleet average on Spanish highways for the year 2005 (Ntziachristos et al., 2008). Fuel consumption and emissions to air for this heavy vehicle were inventoried based on data from the 'EMEP/EEA air pollutant emission inventory guidebook' (European Environment Agency, 2009). The impact assessment method ReCiPe (Goedkoop et al., 2009) was then used to translate the inventory of fuel consumption and air emissions into the corresponding health impacts in DALYs. Finally, the noise impact was compared and aggregated with the health impacts from the other pollutants emitted by the vehicle.

Fig. 9. Geographic locations of the roads.

Table 16. Traffic data: traffic flows and speeds by vehicle class and time of the day.

Road name	Length (km)	Time of the day	Light vehicles (CAT1)		Heavy vehicles (CAT3)	
			Flow (veh/h)	Speed (km/h)	Flow (veh/h)	Speed (km/h)
AP-7 North	221.5	Day	1079	120	362	100
		Evening	799	120	477	100
		Night	179	120	156	100
AP-7 South	147.6	Day	1295	120	434	100
		Evening	959	120	572	100
		Night	150	120	131	100
AP-4	93.4	Day	1266	120	157	100
		Evening	1203	120	134	100
		Night	159	120	68	100

Source: Spanish Ministry of Agriculture, Food and Environment (2007).

Table 17. Noise exposure data: number of persons exposed to noise per kilometre of road.

Road name	Noise levels L_{den} by 5 dBA intervals					Noise levels L_{night} by 5 dBA intervals				
	55–60	60–65	65–70	70–75	>75	50–55	55–60	60–65	65–70	>70
AP-7 North	90.29	26.19	4.06	0.45	0.00	54.18	11.74	1.35	0.00	0.00
AP-7 South	226.96	54.88	10.16	1.36	0.00	88.75	18.29	2.71	0.00	0.00
AP-4	61.03	13.92	2.14	0.00	0.00	25.70	6.42	0.00	0.00	0.00

Source: Spanish Ministry of Agriculture, Food and Environment (2007).

4.3.1. Noise impact assessment

The data from the strategic noise maps were used to assess the noise impact caused by adding a heavy vehicle to the existing annual traffic on each of the roads investigated. The addition of the heavy vehicle was allocated among the different periods of the day in proportion to the initial flow of heavy vehicles on each road for each period. The variations of noise levels attributable to an additional heavy vehicle were calculated using the CNOSSOS-EU model (Kephalopoulos et al., 2012). Fig. 10 shows the variations of noise levels L_{den} and L_{night} caused by an additional vehicle-kilometre per year, together with the total number of persons that are initially exposed to each of these noise levels.

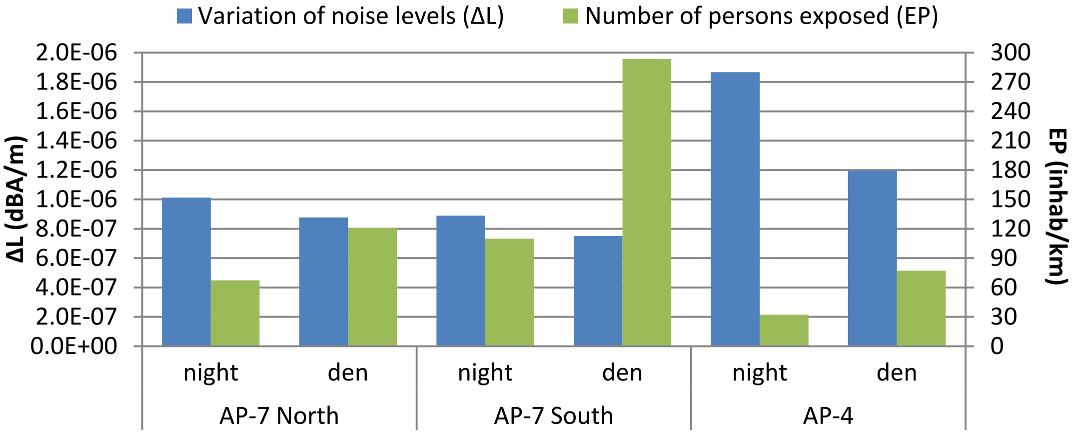

Fig. 10. Variations of noise levels L_{den} and L_{night} and number of persons initially exposed to L_{den} > 55 dBA and L_{night} > 50 dBA.

Fig. 11 shows the variations of noise damages to human health derived from the variations of noise levels. These results distinguish between damages related to high annoyance (day-evening-night period), damages related to high sleep disturbance (night period), and total damages (as the sum of the two above damages). The variations of the total noise damages represent the total impact of noise caused by an additional vehicle-kilometre.

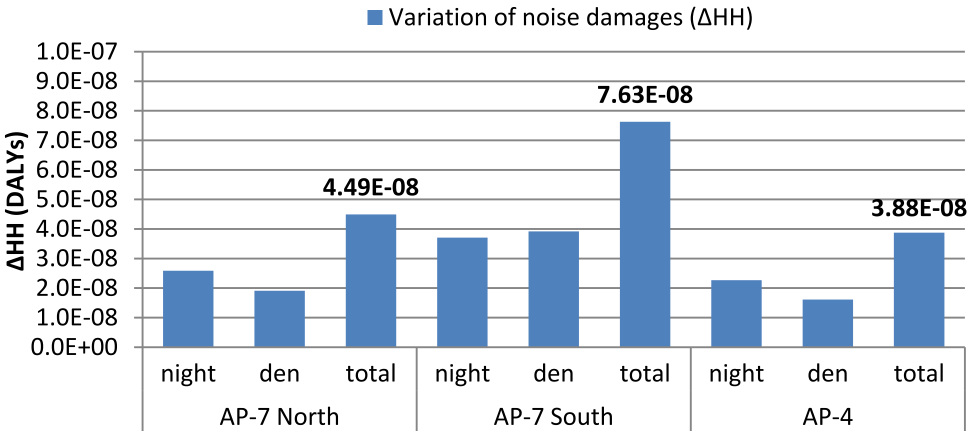

Fig. 11. Variations of noise damages to human health.

4.3.2. Assessment of other health impacts

Table 18 shows the inventory of fuel consumption and emissions to air for an average heavy vehicle travelling on Spanish highways at a speed of 100 km/h. The average heavy vehicle is a mix of heavy duty trucks and buses with different technologies (diesel engines including various emission standards, such as conventional and Euro I to Euro IV). Fuel consumption and air emissions for heavy vehicles also depend on road gradient and vehicle load (European Environment Agency, 2009); a road gradient of 0% and a load factor of 50% were assumed.

Table 18. Inventory of environmental loads for an average heavy vehicle on Spanish highways.

Environmental load	Amount
Diesel consumption (g/km)	180.23
CO_2 (kg/km)	0.60
CO (g/km)	1.17
NO_X (g/km)	5.90
$PM_{2.5}$ (g/km)	0.18
NMVOC (g/km)	0.22
CH_4 (mg/km)	45.16
N_2O (mg/km)	13.13
NH_3 (mg/km)	3.00
Cd (mg/km)	0.01
Cu (mg/km)	1.70
Cr (mg/km)	0.05
Ni (mg/km)	0.07
Se (mg/km)	0.01
Zn (mg/km)	1.00
Total PAH (µg/km)	241.86
Total dioxins (pg/km)	3.00
Total furans (pg/km)	7.90

The inventory data were used as input to the impact assessment method ReCiPe (Goedkoop et al., 2009) in order to calculate the health impacts associated with fuel consumption and air emissions due to the operation of one vehicle-kilometre. These impacts are shown in Table 19, which also includes the noise impact calculated above for each road.

Table 19. Health impacts caused by an additional vehicle-kilometre.

Impact category	Damage to human health (DALYs)
Climate change	9.76E–07
Ozone depletion	2.21E–10
Human toxicity	1.58E–08
Photochemical oxidant formation	2.66E–10
Particulate matter formation	4.54E–07
Ionising radiation	2.08E–10
Noise	
AP-7 North	4.49E–08 (3.01%)
AP-7 South	7.63E–08 (5.01%)
AP-4	3.88E–08 (2.61%)
Damage to human health (total impact)	
AP-7 North	1.49E–06
AP-7 South	1.52E–06
AP-4	1.49E–06

4.3.3. Integration of noise impact with other health impacts

Finally, the health impact due to the noise caused by an additional heavy vehicle was integrated with the other health impacts caused by the same vehicle. The health impacts caused by an additional vehicle-kilometre are shown in Table 19, which distinguishes several impact categories among which the noise is included. All the impacts for the different impact categories are expressed in DALYs, thus being possible to compare the impacts with each other and aggregate them to determine the total impact. The percentages in Table 19 indicate the share of noise impact in total impact for each of the roads assessed.

4.4. Discussion

The impact of noise from road transport depends on local factors such as traffic conditions and population density close to the road. As a result, the noise impact caused by an additional heavy vehicle was different for each of the roads assessed in the case study (see Fig. 11). The total impact of noise caused by an additional vehicle-kilometre ranged from 3.88E–08 to 7.63E–08 DALYs depending on the road. These differences are attributable to both the variations of the initial noise levels and the number of persons exposed to noise, which are specific to each road (see Figs. 10 and 11). The highest variations of noise levels (which take place in the AP-4) are in this case offset by low levels of population exposed, leading to the lowest noise impact among the roads assessed. Conversely, the lowest variations of noise levels (which take place in the AP-7 South) are linked to high levels of population exposed, resulting in the highest noise impact. The differences in impact between roads could have been even greater if roads with very dissimilar levels of traffic and population exposed had been compared, since offsetting effects do not arise (e.g., roads with high traffic levels located in sparsely populated areas versus roads with low traffic levels located close to populated areas). The extrapolation of the results obtained for a particular road to other roads may therefore lead to substantial under- or overestimation of noise impacts, the error involved being difficult to predict. For this reason, noise impact assessments differentiated for each particular case are recommended herein, provided that traffic and noise exposure data are available. The method provided here allows performing such assessments in a simple yet effective manner based on publicly available data from strategic noise maps.

The health impact due to noise was quantified in DALYs, thus allowing the comparison and aggregation of noise impact with other health impacts from road transport, such as those due to fuel consumption and air pollutant emissions (see Table 19). The noise impact accounted for between 2.61% and 5.01% of the total impact caused by an additional heavy vehicle. Noise was the third most significant impact category in terms of damage to human health, being surpassed only by climate change and particulate matter formation.

4.5. Conclusions

A further development of the method of Franco et al. (2010) for the assessment of the impact of road transport noise has been presented here. The original method assesses the health impact of noise attributable to a given variation of traffic conditions, which is quantified as the number of highly annoyed persons. The method developed here also assesses the harmful effects of noise, but it quantifies not only the number of highly annoyed persons but also the number of highly sleep disturbed persons. The new method is more consistent with the Environmental Noise Directive (European Commission, 2002a), which requires the assessment of both annoyance and sleep disturbance due to road traffic noise. In addition, the new method converts both harmful effects of noise into their damages to human health in DALYs.

On the basis of a case study, the dependence of noise impact on certain local factors has been discussed, and the need for specific impact assessments for each road has been highlighted. The validity of the new method to perform such assessments in an effective manner based on data from strategic noise maps has also been demonstrated. In the case study, the health impact of noise caused by an additional vehicle-kilometre has been assessed, as this is the most common practice in LCA to assess the impact of road transport noise. The DALY indicator has allowed us to compare and aggregate the heath impact of noise with other health impacts from road transport. The results have shown that noise has significant relevance in comparison with other impact categories typically assessed in LCA, which justifies its consideration as a usual impact category.

The method provided here is able to assess traffic variations other than mere increases in the number of vehicle-kilometres travelled; e.g., variations in traffic flow, composition, speed, or combinations of these. Thus, various scenarios representative of potential measures for noise abatement can be analysed (e.g., reduce traffic flow and/or speed on a particular road) to provide valuable results to support decision making in noise management.

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5

A fair method for the calculation of the external costs of road traffic noise according to the Eurovignette Directive

Transportation Research Part D: Transport and Environment 24 (2013) 52–61

5.1. Introduction

Pricing instruments for the internalisation of external costs of transport have been implemented through a number of EU Directives. The Eurovignette Directive (European Commission, 1999) was initially adopted to allow EU Member States to charge heavy goods vehicles (HGVs) for the use of motorways to cover construction, maintenance and operation costs. It was later amended (European Commission, 2006) to extend the charges to all roads in the trans-European road network and to allow a limited differentiation of charges according to the amount of congestion and certain environmental effects. It also mandated the development of a reliable model for the assessment of all external costs to serve as the basis for future calculations of infrastructure charges. To this end, the European Commission commissioned the IMPACT project (Maibach et al., 2008), which provided an overview of the state of the art and best practice in the estimation of external costs. Based on this overview, the Eurovignette Directive was amended (European Union, 2011) to allow Member States to charge HGVs for the costs of air pollution and noise, providing methods for calculating these costs; e.g., the average noise costs per vehicle-kilometre differentiated according to type of road, vehicle class and time of the day. Two types of road are distinguished: suburban roads are subject to higher noise costs because of their close proximity to populated areas, whereas interurban roads are subject to lower noise costs. Calculations use weighting factors for vehicle classes and times of the day to allow for differentiation in noise costs.

The 2011 revision of the Directive, however, does not provide guidelines for the calculation of the weighting factors. Moreover, each Member State can only determine a specific charge for each combination of type of road, vehicle class and time of the day. The Directive applies a top-down approach to calculate the noise costs for each road type, meaning that it uses aggregated data from a large set of roads of the same type to compute the total costs, which are then divided by the traffic on the roads to obtain the average costs for each road type. Here we consider a bottom-up approach allowing more detailed differentiation by vehicle class, speed and time of day.

5.2. Materials and methods

Under the Eurovignette Directive, noise costs for HGVs are calculated by applying the following equations:

$$NCV_{j,daily} = e \cdot \frac{\sum_k NC_{jk} \cdot POP_k}{WADT} \tag{20}$$

$$NCV_{j,day} = f_{day} \cdot NCV_{j,daily} \tag{21}$$

$$NCV_{j,night} = f_{night} \cdot NCV_{j,daily} \tag{22}$$

where NCV_j is the noise cost per HGV on road type j (€/vehicle-km), NC_{jk} is the noise cost per day per person exposed to noise level k from road type j (€/person), POP_k is the population exposed to daily noise level k per kilometre of road (person/km), $WADT$ is the weighted average daily traffic (passenger car equivalent), e is an equivalence factor between HGVs and passenger cars, and f_{day} and f_{night} are weighting factors for day and night.

The Directive also defines maximum chargeable noise costs per vehicle-kilometre: 1.1 €ct for suburban roads during day, 2.0 €ct for suburban roads during night, 0.2 €ct for interurban roads during day, and 0.3 €ct for interurban roads during night. If the noise costs calculated from Eqs. (20)–(22) exceed the maximum charges, the latter are used instead.

The Directive focuses on the charging of HGVs for day and night, while we use more disaggregated weighting factors to extend the calculation of noise costs to other vehicle classes and time periods (see Fig. 12).

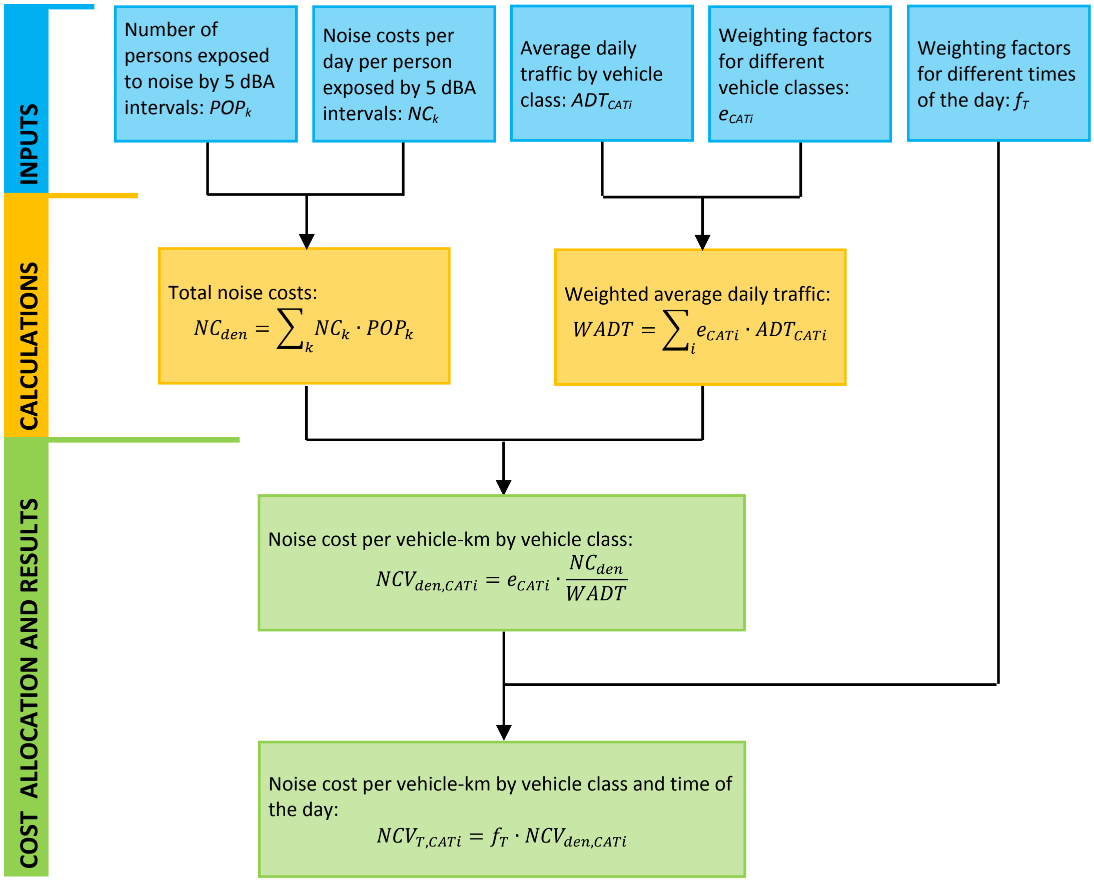

Fig. 12. The extended method: inputs, calculations, cost allocation and results.

Daily noise levels are measured using the day-evening-night noise indicator (L_{den}), which represents the A-weighted long-term average sound level determined over all 24-h periods of a year. L_{den} in A-weighted decibels (dBA) is defined in the Environmental Noise Directive (European Commission, 2002) by:

$$L_{den} = 10 \cdot log\left(\frac{12}{24} \cdot 10^{\frac{L_{day}}{10}} + \frac{4}{24} \cdot 10^{\frac{L_{evening}+5}{10}} + \frac{8}{24} \cdot 10^{\frac{L_{night}+10}{10}}\right) \tag{23}$$

where L_{day}, $L_{evening}$ and L_{night} are the A-weighted long-term average sound levels determined over all the day (12 h), evening (4 h) and night (8 h) periods of a year. These levels are measured at the most exposed façade of dwellings. The number of persons exposed to L_{den} by 5 dBA intervals is multiplied by the costs per person exposed to calculate the total noise costs. Data on traffic volume and speed (by vehicle class) are then used to allocate the costs to individual vehicles of different classes. The traffic and noise exposure data required are publicly available through strategic noise maps drafted under the

Environmental Noise Directive.[4] The noise costs per person exposed per dBA are provided in the HEATCO project (Bickel et al., 2006). These costs represent the willingness to pay for reducing annoyance and the quantifiable costs of adverse health effects.

Since different vehicle classes are responsible for variable noise levels, weighting factors must be applied to correct for differences in noise emissions between classes. The Eurovignette Directive refers to a weighting factor of no more than four between HGVs and passenger cars, but does not provide specific values or guidelines to calculate it. Moreover, there is no agreed set of weighting factors: e.g., the European Conference of Ministers of Transport (1998) used a weighting of 10:10:1 for the relative noise nuisance from HGVs, buses and cars, while the Organisation for Economic Cooperation and Development (OECD/INFRAS/Herry, 2003) used 3:2.5:1. The example weighting factors in Table 20 were calculated by van Essen et al. (2004) from noise reference values for light, medium heavy and heavy vehicles in the Netherlands, with the values for mopeds and motorcycles being based on expert assumptions. Although these factors are provided for a wide range of vehicle classes, they only differentiate between urban roads with speeds of 50 km/h and other roads with speeds of 80 km/h or greater. The ratios between the noise emission levels of different vehicle classes can, however, vary significantly depending on speed, which may not be the same for all classes, even on the same road.

Table 20. Example weighting factors for vehicle classes.

Vehicle class	Urban roads (50 km/h)	Other roads (80 km/h or higher)
Passenger car, petrol	1.0	1.0
Passenger car, diesel	1.2	1.0
Passenger car, LPG	1.0	1.0
Moped	9.8	3.0
Motorcycle	13.2	4.2
Bus	9.8	3.3
Van	1.5	1.2
HGV solo < 12 tons GVW	9.8	3.0
HGV solo > 12 tons GVW	13.2	4.2
HGV with trailer	16.6	5.5

Source: van Essen et al. (2004).

To take into account the variations in the effects of noise exposure throughout the day, the Eurovignette Directive establishes the use of weighting factors for day and night periods. However, it does not provide specific values or guidelines to calculate these factors. Time of the day is only considered in a few studies of marginal noise costs, such as Nash and partners (2003), Schreyer et al. (2004) and Müller-Wenk and Hofstetter (2003). Due to the logarithmic nature of the unit typically used for noise (i.e., the decibel), marginal noise costs are sensitive to existing traffic volumes; if the existing traffic volume is high, adding one extra vehicle will result in a small increase in the existing noise levels, and vice versa (Franco et al., 2010). Since studies estimating marginal noise costs are based on specific

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[4] The data reported by EU Member States are available on the web-based public information systems Reportnet–EIONET (http://cdr.eionet.europa.eu) and NOISE (http://noise.eionet.europa.eu).

case studies and marginal noise costs depend on the traffic situation, substantial differences are found between the results of the different studies (Maibach et al., 2008). Consequently, the ratios between the marginal noise costs for different times of the day, which can be obtained from marginal cost studies based on specific traffic situations, are hardly transferable to other European roads.

5.3. Theoretical basis for noise cost allocation

The noise costs are calculated as a function of the population exposed to daily noise levels, which are measured by the noise indicator L_{den} (Eq. (23)). This indicator uses a weighted noise measure to take the impact of time of the day into account; evening noise carries a penalty of 5 dBA and night noise carries a penalty of 10 dBA. These noise levels relate to sound pressure levels measured at the position of the receivers. Because noise exposure levels are directly caused by noise emissions from traffic, the noise costs should be allocated to individual vehicles of different classes in each time period based on their shares in total noise emissions, but also considering the weighted noise measure. To this end, a day-evening-night noise emission level ($L_{W,den}$) is assumed. $L_{W,den}$ can be defined by the same formula as L_{den} but using sound power levels emitted by the traffic during each period instead of sound pressure levels at the position of receivers. The equivalent sound power level per unit length as emitted by a flow of vehicles of the same class i during a time period T ($L_{W,T,CATi}$, in dBA/m) can be computed as (Kephalopoulos et al., 2012):

$$L_{W,T,CATi} = L_{W,0,CATi} + 10 \cdot log\left(\frac{Q_{T,CATi}}{1000 \cdot v_{T,CATi}}\right) \tag{24}$$

where $L_{W,0,CATi}$ is the instantaneous sound power level emitted by a single vehicle of the class i (dBA), $Q_{T,CATi}$ is the number of vehicles of the class i passing per unit time during the time period T (veh/h), and $v_{T,CATi}$ is the average speed of the vehicle flow of the class i during the time period T (km/h). $L_{W,0,CATi}$ values can be calculated with a traffic noise emission model according to a set of input variables, like vehicle class and speed.

The equivalent sound power level caused by the traffic during a time period T ($L_{W,T}$, in dBA/m) can then be calculated through the logarithmic sum of the sound power levels associated with the flows of the vehicle classes. The sum of equivalent sound power levels is computed as:

$$L_{W,T} = 10 \cdot log\left(\sum\nolimits_i 10^{\frac{L_{W,T,CATi}}{10}}\right) \tag{25}$$

The definition of noise emission level $L_{W,den}$ forms the basis for the noise cost allocation to individual vehicles of different classes in each time period. However, even though sound is usually measured in decibels, the sound power level is not the correct measure for noise cost allocation; the sound power level must be translated from the logarithmic unit decibel into an energy unit that can be linearly disaggregated. The relationship between the sound power level in decibels and the sound power in watts is given by:

$$L_W = 10 \cdot log\left(\frac{W}{W_{ref}}\right) \tag{26}$$

where L_W is the sound power level in decibels, W is the sound power in watts produced by the source, and W_{ref} is a reference sound power of 10^{-12} W.

The sound power level $L_{W,den}$ can be converted to sound power through the relationship in Eq. (26). The day-evening-night sound power (W_{den}, in W/m) is thus:

$$W_{den} = \frac{12}{24} \cdot W_{day} + \frac{4}{24} \cdot 10^{\frac{5}{10}} \cdot W_{evening} + \frac{8}{24} \cdot 10^{\frac{10}{10}} \cdot W_{night} \tag{27}$$

where W_{day}, $W_{evening}$ and W_{night} are the sound powers for the day, evening and night periods (W/m). The sound power W_T for each time period T (day, evening and night) can be obtained by substituting Eq. (26) into Eqs. (25) and (24), which results in:

$$W_T = \sum\nolimits_i W_{T,CATi} = \sum\nolimits_i W_{0,CATi} \cdot \frac{Q_{T,CATi}}{1000 \cdot v_{T,CATi}} \tag{28}$$

where $W_{T,CATi}$ is the sound power per unit length emitted by a flow of vehicles of the class i for the time period T (W/m) and $W_{0,CATi}$ is the instantaneous sound power emitted by a single vehicle of the class i (W).

Noise cost allocation can be conducted on the basis of the shares of the individual vehicles for each time period in total noise emissions, which are expressed through the day-evening-night sound power W_{den}. The noise costs can initially be allocated to time periods:

$$NC_{den} = NC_{day} + NC_{evening} + NC_{night} \tag{29}$$

$$NC_{day} = \frac{\frac{12}{24} \cdot W_{day}}{W_{den}} \cdot NC_{den} \tag{30}$$

$$NC_{evening} = \frac{\frac{4}{24} \cdot 10^{\frac{5}{10}} \cdot W_{evening}}{W_{den}} \cdot NC_{den} \tag{31}$$

$$NC_{night} = \frac{\frac{8}{24} \cdot 10^{\frac{10}{10}} \cdot W_{night}}{W_{den}} \cdot NC_{den} \tag{32}$$

where NC_{den}, NC_{day}, $NC_{evening}$ and NC_{night} are the noise costs per day and kilometre of road during the day-evening-night, day, evening and night periods.

The noise costs for each time period can then be allocated to vehicle flows by class:

$$NC_{day,CATi} = \frac{W_{day,CATi}}{W_{day}} \cdot NC_{day} = \frac{\frac{12}{24} \cdot W_{day,CATi}}{W_{den}} \cdot NC_{den} \tag{33}$$

$$NC_{evening,CATi} = \frac{W_{evening,CATi}}{W_{evening}} \cdot NC_{evening} = \frac{\frac{4}{24} \cdot 10^{\frac{5}{10}} \cdot W_{evening,CATi}}{W_{den}} \cdot NC_{den} \tag{34}$$

$$NC_{night,CATi} = \frac{W_{night,CATi}}{W_{night}} \cdot NC_{night} = \frac{\frac{8}{24} \cdot 10^{\frac{10}{10}} \cdot W_{night,CATi}}{W_{den}} \cdot NC_{den} \tag{35}$$

where $NC_{day,CATi}$, $NC_{evening,CATi}$ and $NC_{night,CATi}$ are the noise costs per day and kilometre of road for the vehicle flow of the class *i* during the day, evening and night.

Finally, the average noise costs per vehicle-kilometre by vehicle class and time of day can be expressed as a function of the total noise costs:

$$NCV_{day,CATi} = \frac{NC_{day,CATi}}{12 \cdot Q_{day,CATi}} = \frac{\frac{1}{24} \cdot W_{day,CATi}}{Q_{day,CATi} \cdot W_{den}} \cdot NC_{den} \tag{36}$$

$$NCV_{evening,CATi} = \frac{NC_{evening,CATi}}{4 \cdot Q_{evening,CATi}} = \frac{\frac{1}{24} \cdot 10^{\frac{5}{10}} \cdot W_{evening,CATi}}{Q_{evening,CATi} \cdot W_{den}} \cdot NC_{den} \tag{37}$$

$$NCV_{night,CATi} = \frac{NC_{night,CATi}}{8 \cdot Q_{night,CATi}} = \frac{\frac{1}{24} \cdot 10^{\frac{10}{10}} \cdot W_{night,CATi}}{Q_{night,CATi} \cdot W_{den}} \cdot NC_{den} \tag{38}$$

where $NCV_{day,CATi}$, $NCV_{evening,CATi}$ and $NCV_{night,CATi}$ are the average noise costs per vehicle-kilometre for a vehicle of the class *i* during the day, evening and night.

5.4. Improved weighting factors

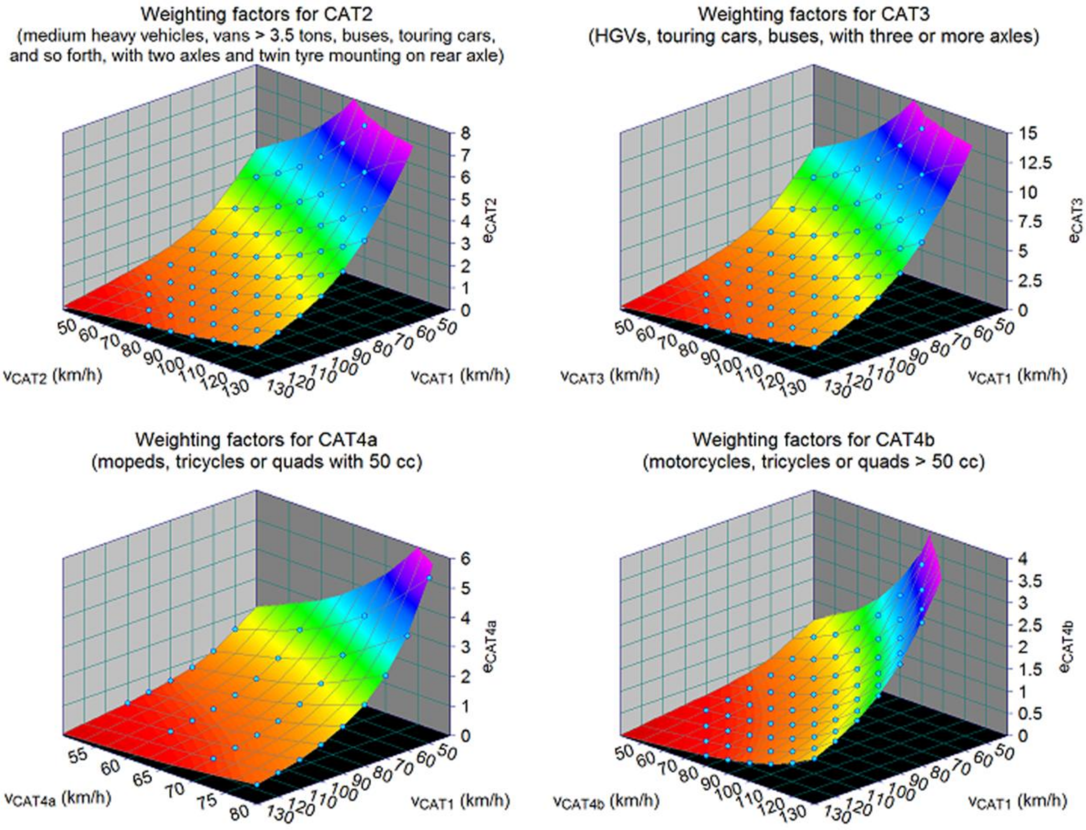
Traffic volumes by vehicle class can be used to allocate the noise costs to individual vehicles of different classes. Weighting factors for vehicle classes must be applied to the corresponding traffic volumes to correct for differences in noise emissions between vehicle classes. Each weighting factor describes the relationship between the costs per vehicle-kilometre for a given vehicle class and the costs per vehicle-kilometre for a vehicle class taken as a reference (usually passenger car). Based on this relationship and using the equations in Section 5.3, the weighting factor for a vehicle class *i* and a time period *T* ($e_{T,CATi}$) can be expressed as:

$$e_{T,CATi} = \frac{NCV_{T,CATi}}{NCV_{T,CATref}} = \frac{W_{T,CATi} \cdot Q_{T,CATref}}{W_{T,CATref} \cdot Q_{T,CATi}} = \frac{W_{0,CATi} \cdot v_{T,CATref}}{W_{0,CATref} \cdot v_{T,CATi}} \tag{39}$$

Weighting factors for vehicle classes depend only on the instantaneous sound power emitted by single vehicles of each class and their average speeds. The instantaneous sound power does not depend on the time of the day and the average speed can be assumed to be the same for all time periods; only a few cases are found in strategic noise maps where the speed at night is slightly higher (about 5 km/h) than for other time periods. As a result, the weighting factors can be considered independent of the time of the day:

$$e_{CATi} = \frac{NCV_{T,CATi}}{NCV_{T,CATref}} = \frac{W_{0,CATi} \cdot v_{CATref}}{W_{0,CATref} \cdot v_{CATi}} \tag{40}$$

The noise emission model from the CNOSSOS-EU project (Kephalopoulos et al., 2012) was used to calculate W_0 values. This model provides the instantaneous sound power level of an average European road vehicle under a set of reference conditions as a function of speed for light motor vehicles (CAT1), medium heavy vehicles (CAT2), heavy vehicles (CAT3), mopeds (CAT4a), and motorcycles (CAT4b). The W_0 values derived from the model were inserted in Eq. (40) to calculate a set of weighting factors for vehicle classes according to their speeds. These factors were calculated for multiple combinations of vehicle speeds from 50 to 130 km/h in intervals of 10 km/h and assuming that the speeds of the vehicle classes differ by no more than 50 km/h from that of the reference vehicle class (see Fig. 13). The weighting factors for CAT1 (which includes passenger cars, vans ≤ 3.5 tons, sport utility vehicles, and multi-purpose vehicles including trailers and caravans) are always unity because CAT1 is taken as the reference vehicle class.


Weighting factors for CAT2
(medium heavy vehicles, vans > 3.5 tons, buses, touring cars, and so forth, with two axles and twin tyre mounting on rear axle)

Weighting factors for CAT3
(HGVs, touring cars, buses, with three or more axles)

Weighting factors for CAT4a
(mopeds, tricycles or quads with 50 cc)

Weighting factors for CAT4b
(motorcycles, tricycles or quads > 50 cc)

Fig. 13. Weighting factors for vehicle classes according to the speeds of the vehicles.

The surface fitting software TableCurve 3D® was used to convert the series of data points shown in Fig. 13 for each vehicle class into simplified surface equations. The weighting factors for each vehicle class were thus defined by rational functions:

$$e_{CATi} = \frac{p_{0,0} + p_{0,1} \cdot v_{CATi} + p_{1,0} \cdot v_{CATref} + p_{1,1} \cdot v_{CATi} \cdot v_{CATref} + p_{0,2} \cdot v_{CATi}^2 + p_{2,0} \cdot v_{CATref}^2}{1 + q_{0,1} \cdot v_{CATi} + q_{1,0} \cdot v_{CATref} + q_{1,1} \cdot v_{CATi} \cdot v_{CATref} + q_{0,2} \cdot v_{CATi}^2 + q_{2,0} \cdot v_{CATref}^2} \quad (41)$$

The equation coefficients were computed for each vehicle class using the surface fitting software (see Table 21).

Table 21. Coefficients and fit statistics of Eq. (41) for vehicle classes.

Coefficient	CAT2	CAT3	CAT4a	CAT4b
$p_{0,0}$	1.088E+01	9.247E+00	2.819E+00	1.571E+00
$p_{0,1}$	–5.349E–02	–1.107E–01	–3.888E–03	–9.645E–03
$p_{1,0}$	–1.161E–02	7.633E–02	–3.127E–02	–1.459E–02
$p_{1,1}$	–3.686E–04	–8.047E–04	–2.035E–05	1.444E–04
$p_{0,2}$	1.918E–03	3.457E–03	2.639E–04	–2.750E–05
$p_{2,0}$	2.135E–05	–2.091E–04	1.033E–04	1.082E–05
$q_{0,1}$	5.674E–03	1.077E–02	–3.718E–02	–2.245E–02
$q_{1,0}$	–2.580E–02	–5.621E–02	4.984E–02	1.479E–02
$q_{1,1}$	–2.150E–04	7.427E–05	–5.864E–04	–2.540E–04
$q_{0,2}$	–2.886E–06	–6.369E–05	3.164E–04	1.548E–04
$q_{2,0}$	1.504E–03	1.312E–03	1.222E–04	1.319E–04
r^2	1.000E+00	1.000E+00	1.000E+00	9.980E–01
SE	5.225E–03	1.194E–02	6.796E–03	4.075E–02

The weighting factors and their mathematical expressions were calculated under a set of reference conditions: constant vehicle speed; a flat road; an air temperature of 20 °C; a virtual reference road surface, consisting of an average of dense asphalt concrete 0/11 and stone mastic asphalt 0/11, between two and seven years old and in a representative maintenance condition; a dry road surface; a vehicle fleet with characteristics corresponding to the European average (Peeters and van Blokland, 2007); and no studded tyres. The CNOSSOS-EU model includes several correction factors to account for variations in noise emissions due to regional variations in vehicle fleet characteristics, meteorological conditions, road properties or driving behaviour. The effects of regional variations were also investigated by performing a sensitivity analysis of regional parameters to estimate their influence on the weighting factors (see Table 22).

Regional variations were considered a second-order effect. The acceleration and deceleration of vehicles may have a significant effect, but it is restricted to the vicinity of crossings with traffic lights and roundabouts. Moreover, the uncertainty in the estimation of acceleration and deceleration of the traffic can be higher than the effect on noise emissions. Most of the attention was therefore focused on developing weighting factors that account for the vehicle classes and speeds in European roads under the reference conditions.

Table 22. Sensitivity analysis of regional parameters influencing weighting factors.

Correction factor	Reference value	Variability in inputs	Variability in outputs
Acceleration and deceleration	$\lvert x \rvert \geq 100$ m (distance to the nearest crossing with traffic lights or roundabout)	$\lvert x \rvert = 100$ to 50 m	e_{CAT2} = 0.0% to 215.3% e_{CAT3} = 0.0% to 202.8% e_{CAT4a} = 0.0% to 42.1% e_{CAT4b} = 0.0% to 42.1%
Road slope	s = 0% (average slope along the road segment)	s = –1 to 1%	e_{CAT2} = 0.0% to 16.3% e_{CAT3} = 0.0% to 13.6% e_{CAT4a} = 0.0% e_{CAT4b} = 0.0%
Air temperature	T_{air} = 20 °C (yearly average air temperature)	T_{air} = 15 to 25 °C	e_{CAT2} = –6.9% to 7.4% e_{CAT3} = –6.8% to 7.2% e_{CAT4a} = –8.1% to 8.8% e_{CAT4b} = –8.1% to 8.8%
Studded tyres	p_s = 0% (yearly average proportion of light vehicles equipped with studded tyres)	p_s = 0 to 10% (30% of light vehicles equipped with studded tyres from December 1st to March 31st)	e_{CAT2} = 0.0% to –9.7% e_{CAT3} = 0.0% to –9.7% e_{CAT4a} = 0.0% to –9.7% e_{CAT4b} = 0.0% to –9.7%

The noise costs per day and kilometre of road can be allocated to individual vehicles of different classes using the weighting factors for each class. The daily noise costs per vehicle-kilometre thus obtained for each vehicle class can then be converted to noise costs per vehicle-kilometre by vehicle class and time of the day. To this end, weighting factors for times of the day must be applied to account for differences in impacts of noise emissions between times of the day. Each weighting factor describes the relationship between the costs per vehicle-kilometre for a given time of the day and the daily costs per vehicle-kilometre (i.e., the costs for the day-evening-night period). Thus, the weighting factor for a vehicle class i and a time period T ($f_{T,CATi}$) can be expressed as:

$$f_{T,CATi} = \frac{NCV_{T,CATi}}{NCV_{den,CATi}} \tag{42}$$

Based on this relationship and using the equations in Section 5.3, the ratios between the weighting factors for times of the day are expressed as:

$$\frac{f_{night,CATi}}{f_{day,CATi}} = \frac{NCV_{night,CATi}}{NCV_{day,CATi}} = \frac{10^{\frac{10}{10}} \cdot W_{night,CATi} \cdot Q_{day,CATi}}{W_{day,CATi} \cdot Q_{night,CATi}} = \frac{10^{\frac{10}{10}} \cdot v_{day,CATi}}{v_{night,CATi}} \tag{43}$$

$$\frac{f_{evening,CATi}}{f_{day,CATi}} = \frac{NCV_{evening,CATi}}{NCV_{day,CATi}} = \frac{10^{\frac{5}{10}} \cdot W_{evening,CATi} \cdot Q_{day,CATi}}{W_{day,CATi} \cdot Q_{evening,CATi}} = \frac{10^{\frac{5}{10}} \cdot v_{day,CATi}}{v_{evening,CATi}} \tag{44}$$

The ratios between the weighting factors for times of the day depend on the average speed of the vehicles for each time period. As mentioned above, the average speed can be assumed to be the same for all time periods, thus resulting in constant ratios between the weighting factors for the same vehicle class:

$$f_{night,CATi} = 10^{\frac{10}{10}} \cdot f_{day,CATi} \tag{45}$$

$$f_{evening,CATi} = 10^{\frac{5}{10}} \cdot f_{day,CATi} \tag{46}$$

The constants in Eqs. (45) and (46) arise from the formula that defines the noise indicator L_{den} (Eq. (23)), which was devised to take into account the impact of time of the day. This indicator uses a weighted noise measure that increases evening noise by 5 dBA and night noise by 10 dBA. These penalties for times of the day, when expressed in terms of sound power (Eq. (27)), lead to the aforementioned constants.

It can also be demonstrated that weighting factors for different times of the day are the same for all vehicle classes:

$$\frac{f_{T,CATi}}{f_{T,CATref}} = \frac{NCV_{T,CATi}}{NCV_{T,CATref}} \cdot \frac{NCV_{den,CATref}}{NCV_{den,CATi}} = e_{CATi} \cdot \frac{1}{e_{CATi}} = 1 \tag{47}$$

Moreover, to cover the noise costs, the following equation must be satisfied:

$$\sum_i ADT_{CATi} \cdot NCV_{den,CATi} = \sum_i \sum_T ADT_{T,CATi} \cdot NCV_{T,CATi} \tag{48}$$

where ADT_{CATi} is the average daily traffic for the vehicle class i during the day-evening-night period (veh/day) and $ADT_{T,CATi}$ is the average daily traffic for the vehicle class i during the time period T (veh/day). Eq. (48) can be developed to obtain an additional relationship between the weighting factors for times of the day:

$$\sum_i e_{CATi} \cdot ADT_{CATi} = \sum_i \sum_T e_{CATi} \cdot f_T \cdot ADT_{T,CATi} \tag{49}$$

The weighting factors for times of the day can be derived by combining Eq. (49) with Eqs. (45) and (46). The weighting factors thus obtained are expressed as:

$$f_{day} = \frac{\sum_i e_{CATi} \cdot \left(12 \cdot Q_{day,CATi} + 4 \cdot Q_{evening,CATi} + 8 \cdot Q_{night,CATi}\right)}{\sum_i e_{CATi} \cdot \left(12 \cdot Q_{day,CATi} + 4 \cdot 10^{\frac{5}{10}} \cdot Q_{evening,CATi} + 8 \cdot 10^{\frac{10}{10}} \cdot Q_{night,CATi}\right)} \tag{50}$$

$$f_{evening} = \frac{\sum_i e_{CATi} \cdot \left(12 \cdot Q_{day,CATi} + 4 \cdot Q_{evening,CATi} + 8 \cdot Q_{night,CATi}\right)}{\sum_i e_{CATi} \cdot \left(12 \cdot 10^{-\frac{5}{10}} \cdot Q_{day,CATi} + 4 \cdot Q_{evening,CATi} + 8 \cdot 10^{\frac{5}{10}} \cdot Q_{night,CATi}\right)} \tag{51}$$

$$f_{night} = \frac{\sum_i e_{CATi} \cdot \left(12 \cdot Q_{day,CATi} + 4 \cdot Q_{evening,CATi} + 8 \cdot Q_{night,CATi}\right)}{\sum_i e_{CATi} \cdot \left(12 \cdot 10^{-\frac{10}{10}} \cdot Q_{day,CATi} + 4 \cdot 10^{-\frac{5}{10}} \cdot Q_{evening,CATi} + 8 \cdot Q_{night,CATi}\right)} \tag{52}$$

5.5. Case study

A case study was conducted to illustrate the application of the improved weighting factors to calculate the external costs of road traffic noise. The calculation method used in the case study is more complete than the method of the Eurovignette Directive because it allows calculating the noise costs of various vehicle classes (passenger cars and HGVs) for three time periods (day, evening and night). The average noise costs per vehicle-kilometre by vehicle class and time of the day were thus calculated for three Spanish motorways (see Fig. 14).

Fig. 14. Geographic locations of the roads.

Table 23. Traffic flows and speeds by vehicle class and time of the day.

Road name	Length (km)	Time of the day	Light vehicles (CAT1)		Heavy vehicles (CAT3)	
			Flow (veh/h)	Speed (km/h)	Flow (veh/h)	Speed (km/h)
AP-7 North	221.5	Day	1079	120	362	100
		Evening	799	120	477	100
		Night	179	120	156	100
AP-7 South	147.6	Day	1295	120	434	100
		Evening	959	120	572	100
		Night	150	120	131	100
AP-4	93.4	Day	1266	120	157	100
		Evening	1203	120	134	100
		Night	159	120	68	100

Source: Spanish Ministry of Agriculture, Food and Environment (2007).

Table 24. Persons exposed to noise per kilometre of road.

Road name	Noise levels L_{den} by 5 dBA intervals				
	55–60	60–65	65–70	70–75	>75
AP-7 North	90.29	26.19	4.06	0.45	0.00
AP-7 South	226.96	54.88	10.16	1.36	0.00
AP-4	61.03	13.92	2.14	0.00	0.00

Source: Spanish Ministry of Agriculture, Food and Environment (2007).

Data from strategic noise maps for these roads for the year 2006 were used as inputs for the calculations. The strategic noise maps were obtained from the Spanish Information System on Noise Pollution (Spanish Ministry of Agriculture, Food and Environment, 2007). Traffic and noise exposure data used for the calculations are shown in Tables 23 and 24.

In addition to traffic and noise exposure data, the calculation method requires the following inputs: noise costs per day per person exposed to road traffic noise, weighting factors for vehicle classes and weighting factors for times of the day. The noise costs for Spain per day per person exposed were based on the HEATCO project (Bickel et al., 2006). The HEATCO values were adjusted to year 2006 for purchasing power parity (i.e., values were expressed as €$_{2006}$ PPP) and were bundled in 5 dBA intervals as shown in Table 25.

Table 25. Noise costs for Spain per year per person exposed to road traffic noise.

Noise levels L_{den} by 5 dBA intervals	Noise costs per year per person exposed (€$_{2006}$ PPP/person/year)
55–60	58
60–65	99
65–70	141
70–75	226
75–80	303

The weighting factors for light vehicles (CAT1) are always unity because they correspond to the reference vehicle class. The weighting factors for heavy vehicles (CAT3) were calculated according to the vehicle speeds using Eq. (41). The weighting factors for times of the day were calculated according to the traffic flows by vehicle class and time of the day using Eqs. (50)–(52). The weighting factors both for vehicle classes and for times of the day are shown in Table 26.

Table 26. Weighting factors for vehicle classes and times of the day.

Road name	Weighting factors for different vehicle classes: e_{CATi}		Weighting factors for different times of the day: f_T		
	Light vehicles (CAT1)	Heavy vehicles (CAT3)	Day	Evening	Night
AP-7 North	1.00	2.02	0.39	1.24	3.92
AP-7 South	1.00	2.02	0.44	1.39	4.40
AP-4	1.00	2.02	0.44	1.41	4.44

Noise exposure data were combined with noise costs per day per person exposed to calculate the total noise costs. Data on traffic flows by vehicle class and weighting factors for vehicle classes were used to translate these noise costs into the average noise costs per vehicle-kilometre by vehicle class. Weighting factors for times of the day were applied to determine the average noise costs per vehicle-kilometre by vehicle class and time of the day. The total and average noise costs determined for each of the roads studied are shown in Table 27.

Table 27. Total and average costs of road traffic noise.

Road name	Total noise costs: NC_{den} (€$_{2006}$ PPP/km/day)	Average noise costs: $NCV_{T,CATi}$ (€ct$_{2006}$ PPP/vehicle-km)					
		Light vehicles (CAT1)			Heavy vehicles (CAT3)		
		Day	Evening	Night	Day	Evening	Night
AP-7 North	23.30	0.028	0.088	0.279	0.056	0.178	0.563
AP-7 South	55.72	0.065	0.205	0.648	0.131	0.414	1.309
AP-4	14.30	0.023	0.074	0.233	0.047	0.149	0.471

What we find, therefore, is that the lack of differentiation by vehicle speed in the weighting factors can lead to a misjudgement of the noise costs attributable to vehicles of different classes. If the weighting factors given by van Essen et al. (2004) had been used in the case study instead the improved factors, the error involved would have ranged from −37.4% to −24.3% for one passenger car and from 30.2% to 57.5% for one HGV, depending on the road. The charges to be borne by HGVs would have thus been highly overestimated, which is inconsistent with the 'polluter pays' principle. Moreover, the bottom-up approach applied in the case study produced significant differences in average noise costs between roads (see Table 27); the costs for AP-7 South were more than double the costs for AP-7 North and almost triple the costs for AP-4. These differences could have been even greater if the vehicle speeds had been different for each road. If the top-down approach favoured by the Eurovignette Directive had been applied, the average noise costs would have been the same for all roads, which is also inconsistent with the polluter pays principle.

5.6. Conclusions

The Eurovignette Directive provides a method to calculate the external costs of road traffic noise. This method requires the use of weighting factors to account for differences in noise costs according to vehicle class and time of the day. However, the Eurovignette Directive does not provide specific values or guidelines to calculate these weighting factors, and research findings are scarce and do not seem to be clearly substantiated. For this reason, improved weighting factors both for vehicle classes and for times of the day have been developed. These factors are more reliable than those found in previous studies, because they are more disaggregated, taking better account of the influence of vehicle class, speed and time of the day. The method of the Eurovignette Directive has thus been extended to vehicle classes other than HGVs and to the consideration of not only the day and night, but also the evening.

5.7. References

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6

Conclusions

6.1. Summary

The aim of this thesis is to provide more insight into certain environmental issues of road transport that have not been investigated in depth to date. To this end, the following lines of research were addressed: LCA of road pavements, LCA of noise from road transport, and valuation of external costs of noise from road transport. Below are summarized the contributions made and the main conclusions reached in each research line.

6.1.1. Life cycle assessment of road pavements

A comprehensive LCA of road pavements was conducted including HMA, zeolite-based WMA, and asphalt mixes with RAP. An LCA-based tool was developed in parallel to automatically calculate the environmental impacts of various pavements. The impacts associated with energy consumption and air emissions were assessed, as well as other impacts resulting from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic on the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. Monte Carlo simulations were also conducted to take into account the variability of critical input parameters.

Taking into account the entire life cycle of the pavements, it was found that the impacts of zeolite-based WMA pavements are almost equal to the impacts of HMA pavements with the same RAP content. The reduction in the impacts of WMA resulting from the lowering of the manufacturing temperature is offset by the greater impacts of the materials used, especially the impacts of the zeolites.

Moreover, by comparing asphalt mixes with different RAP contents, it was shown that the impacts of asphalt mixes are significantly reduced when RAP is added. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% of RAP. A key advantage of WMA is the potentially greater use of RAP. Thus, the decrease in the impacts achieved by adding large amounts of RAP to WMA could turn these asphalt mixes into a good alternative to HMA in environmental terms.

6.1.2. Life cycle assessment of noise from road transport

A critical review of existing methods for the assessment of the impact of noise from road transport was conducted. As a result of this review, the guidelines for incorporating the noise impact into LCA were provided, and the DALY was supported as the best-suited unit for measuring the impacts of noise on human health. Based on these findings, an improved method was developed to assess the impact of noise from road transport and to incorporate it into LCA. This method overcomes the drawbacks found in earlier methods and uses data from strategic noise maps to perform the assessments. The impacts on health due to noise are quantified in DALYs, which allows noise to be compared and aggregated with other pollutants harmful to health.

A case study was conducted where the method was applied to calculate the noise impact caused by an additional heavy vehicle that travel one kilometre on three different roads. The noise impact caused by the heavy vehicle differed significantly (up to twofold) between roads due to the dependence of noise impact on local factors, such as traffic conditions and population density close to the roads. The extrapolation of the results obtained for a particular road to other roads may therefore lead to substantial under- or overestimation of noise impacts, the error involved being difficult to predict. For this reason, noise impact assessments differentiated for each particular case are recommended, provided that traffic and noise exposure data are available. The method provided here allows such assessments to be performed in a simple yet effective way based on publicly available models and datasets.

Furthermore, the noise impact caused by the heavy vehicle was compared and aggregated with the health impacts due to fuel consumption and air pollutant emissions from the same vehicle. The noise impact accounted for between 2.58% and 4.96% of the total impact caused by the additional heavy vehicle. Noise was the third most significant impact category in terms of damage to human health, being surpassed only by climate change and particulate matter formation. Noise from road transport may therefore have a significant impact in comparison with other impact categories typically assessed in LCA, which justifies its inclusion as a usual impact category in LCA studies of road transport.

6.1.3. Valuation of external costs of noise from road transport

The latest revision of the Eurovignette Directive allows EU Member States to charge HGVs for the external costs of noise pollution they generate, and it provides a method for calculating such costs. This method requires the use of weighting factors for vehicle classes and times of the day to allow for differentiation in noise costs. However, the Eurovignette Directive does not provide specific values or guidelines to calculate the weighting factors, while the factors found in previous studies do not seem to be clearly substantiated. Moreover, the Eurovignette Directive applies a top-down approach that leads to a single specific charge for each combination of type of road, vehicle class and time of the day.

A method for the calculation of the external costs of road traffic noise was developed here as an alternative to the method of the Eurovignette Directive. Improved weighting factors were also developed to be used in the method. These factors are more detailed than those in earlier studies, as they are highly differentiated to better account for the influence of key cost drivers, namely vehicle class, speed and time of the day. They are also more reliable because they were computed from an advanced traffic noise model (CNOSSOS-EU). The alternative method allows distance-based charges to be calculated for any vehicle class (passenger cars, vans, HGVs, mopeds and motorcycles) and time of the day (day, evening and night), whereas the method of the Eurovignette Directive only applies to HGVs for day and night. All data required by the alternative method are publicly available from strategic noise maps.

A case study was conducted where the alternative method was applied to calculate the average noise costs per vehicle-kilometre by vehicle class and time of the day for three different roads. The noise costs differed significantly (up to almost threefold) between roads due to the dependence of noise costs on local factors. If the top-down approach favoured by the Eurovignette Directive had been applied, the noise costs would have been equal for all roads, which is inconsistent with the polluter pays principle that should guide the charging for the use of road infrastructure. Moreover, it was found that the lack of differentiation by vehicle speed in the weighting factors given in previous studies may lead to a misjudgement of the noise costs attributable to vehicles of different classes. If weighting factors from another study had been used in the case study instead the improved factors, the error involved would have ranged from −37.36% to −24.27% for one passenger car and from 30.24% to 57.46% for one HGV, depending on the road. The charges to be borne by HGVs would have thus been highly overestimated, which is also inconsistent with the polluter pays principle.

6.2. Fulfilment of research objectives

All research objectives set in this thesis were achieved. Below is described the way in which each specific objective was fulfilled.

Research objective 1: to provide an LCA-based tool for road pavements. This tool is aimed at quantifying and comparing the environmental impacts of various asphalt pavements (including HMA, WMA, and asphalt mixes with RAP) to determine the best alternatives in environmental terms.

An LCA-based tool was developed and implemented in a spreadsheet software application (Microsoft® Excel®). It allows users to automatically calculate the environmental impacts of road pavements throughout their entire life cycle. Only the functional unit and other input variables must be specified by the users (e.g., road length and width, pavement thickness, road service life, average daily traffic, composition of asphalt mixes, manufacturing temperature, transport distances for materials, maintenance and end-of-life scenarios). The tool uses these inputs to quantify the amount of each life cycle sub-component (e.g., the amount of a specified material extracted or processed). Each sub-component, and its associated amount, is linked to its corresponding LCI to compute the total environmental burdens due to such a sub-component. The environmental burdens are then automatically assessed by applying the impact assessment method ReCiPe. Finally, the environmental impacts thus obtained for the different sub-components are aggregated into the various life cycle stages of road pavements.

The LCA-based tool was used here to quantify and compare the environmental impacts of four different asphalt pavements. The pavements evaluated included HMA and zeolite-based WMA, both with and without RAP content.

Research objective 2: to provide an LCA method for the assessment of the health impact of noise from road transport. This method is aimed at comparing and adding the impact of noise with other health impacts from road transport to determine the importance of noise with respect to other impact categories typically assessed in LCA.

A method was developed to assess the impact of road transport noise and to incorporate it into LCA. The method was devised to be consistent with the Environmental Noise Directive, since it uses data from strategic noise maps to calculate the effects of noise on health in terms of annoyance and sleep disturbance. In addition, the method converts both effects of noise into their corresponding damage to human health. To this end, it includes the calculation of the environmental burden of disease associated with annoyance and sleep disturbance, thus quantifying the health impact of noise in DALYs. Several methods for life cycle impact assessment (e.g., Eco-indicator 99, ReCiPe, and IMPACT 2002+) use the DALY indicator to measure the impacts on human health. Hence, the DALY indicator makes it possible to compare and aggregate the impact of noise with the health impacts from other pollutants that are usually assessed in LCA of road transport.

The method was used here to calculate the impact of noise caused by an additional heavy vehicle on three different roads. The impact of noise caused by the heavy vehicle was compared and aggregated with the health impacts due to fuel consumption and air emissions from the same vehicle, which were calculated using the impact assessment method ReCiPe.

Research objective 3: to provide a method for the valuation of the external costs of noise from road transport. This method is aimed at calculating distance-based charges to be applied to road users according to the road, vehicle class and time of the day.

A method was developed to calculate the external costs of noise from road transport. The method relies on weighting factors for vehicle classes and times of the day to allow for differentiation in noise costs. Improved weighting factors were developed, which are highly differentiated to account for the influence of key cost drivers, namely vehicle class, speed and time of the day. Thus, the method allows distance-based charges to be calculated for any road, vehicle class and time of the day. All data required for the calculation are publicly available from strategic noise maps.

The method was used here to calculate the external noise costs per vehicle-kilometre by vehicle class and time of the day for three different roads. Different charges were thus determined for each combination of road, vehicle class (passenger car and HGV) and time of the day (day, evening and night).

6.3. Validation of hypotheses

The development and subsequent application of the tool and methods provided in this thesis allowed to confirm the hypotheses set in advance. Below is described the way in which each hypothesis was validated.

Hypothesis 1: if the entire life cycle of road pavements is considered, the environmental benefit of WMA pavements compared to HMA pavements may not be as great as shown in many studies, due to the high impact of producing the chemical additives used in WMA.

The LCA-based tool developed here was used to calculate and compare the environmental impacts of HMA pavements and zeolite-based WMA pavements with the same RAP content. The impacts of these pavements were assessed both at the midpoint level and at the endpoint level.

The results obtained from the endpoint impact assessment shown that the overall impacts of WMA are almost equal to those of HMA. There were no significant differences between the endpoint impacts of HMA and WMA in the transportation, construction and end-of-life stages. By contrast, the impacts of WMA in the asphalt production stage were 14–15% lower than those of HMA, due to the reduction of the manufacturing temperature, which is 165 °C for HMA and 135 °C for WMA. However, the impacts of WMA in the materials stage were higher: damage to HH was increased by 6–7%, damage to ED was increased by 4–5%, and damage to RA was increased by 2–3%. As a result, the decrease in the overall impacts of WMA compared to HMA was less than 1% for every endpoint impact category. An uncertainty assessment was conducted to determine the variability of the results due to uncertainties in LCI data, and also due to the potential variability of some input variables. The coefficient of variation was 6–7% for damage to HH, 11% for damage to ED, and 5% for damage to RA. The results from the midpoint impact assessment were similar to those from the endpoint impact assessment; the overall impacts on CC and FD are almost equal in HMA and WMA, the coefficient of variation being 4–6% for impact on CC and 4–5% for impact on FD.

Since the most significant differences in impacts between HMA and WMA are attributable to the materials and asphalt production stages, these stages were analysed in more detail. As previously noted, the impacts of WMA were lower than those of HMA in the asphalt production stage. The temperature reduction of 30 °C in WMA led to a fuel saving of 15–16%, which resulted in a twofold environmental benefit: the impact on CC due to air emissions from the asphalt production process was decreased in the same proportion, whilst the impacts on CC and FD associated with the life cycle of fuel were both decreased. Conversely, the impacts of WMA were higher than those of HMA in the materials stage due to the differences in composition between HMA and WMA. The composition of both asphalt mixes is very similar, except that synthetic zeolites and hydrated lime are added to the WMA at a rate of 0.24% and 1.5%, respectively, replacing the same amounts of cement. Hydrated lime has slightly greater impacts than cement, but the impacts of synthetic zeolites are much greater than those of cement because their production is highly intensive in energy and resources. Hence, despite being added in tiny proportions, zeolites caused the greatest part of the increase in the impacts of WMA with respect to HMA in the materials stage. The increase in the impacts of WMA due to the addition of zeolites offset the decrease in the impacts resulting from the reduction in manufacturing temperature. To give more certainty to the results, comparisons were made using Monte Carlo simulations. The probability that the impacts of HMA were higher than those of WMA was 54.1% for CC and 50.9% for FD.

Therefore, WMA pavements are hardly environmentally beneficial over HMA pavements when the entire life cycle of road pavements is considered. The reduction in manufacturing temperature of WMA causes an environmental benefit, but this is counteracted by the greater impacts of the materials used in WMA, especially the impacts of synthetic zeolites.

Hypothesis 2: the environmental benefit of pavements containing RAP may be significant if the entire life cycle of road pavements is considered, because the use of RAP avoids the extraction and processing of virgin raw materials and the disposal of asphalt to landfill, but it does not significantly affect the asphalt manufacturing process.

The LCA-based tool was also used to calculate and compare the environmental impacts of asphalt pavements with and without RAP content. The impacts of the pavements were assessed both at the midpoint level and at the endpoint level.

The results obtained from the endpoint impact assessment shown that the overall impacts of asphalt pavements are significantly reduced when RAP is added. The endpoint impacts of the materials stage were reduced about 15–16% by adding 15% of RAP. Likewise, the endpoint impacts of the end-of-life stage were reduced as follows: damage to HH was decreased by 42%, damage to ED was decreased by 41%, and damage to RA was decreased by 45%. There were no significant differences between the impacts of pavements with different RAP contents in the transportation, asphalt production and construction stages.

As a result, the decrease in the overall impacts by adding 15% of RAP was as follows: 13% both for damage to HH and for damage to ED, and 14% for damage to RA. The results from the midpoint impact assessment were similar to those from the endpoint impact assessment; the overall impacts on CC and FD were decreased by 13% and 14%, respectively, when a 15% of RAP was added. To give more certainty to the results, comparisons were made using Monte Carlo simulations. The probability that the impacts of road pavements were reduced by adding 15% of RAP was 99.7% for CC and 98.8% for FD.

The reduction in the impacts is mainly attributable to the materials and end-of-life stages. The use of RAP as a raw material avoids the need to extract a portion of the virgin raw materials, such as sand and gravel, and also made the processing of a portion of the bitumen unnecessary. The use of RAP also avoids disposal of asphalt to landfill.

It is worth noting that one of the main advantages of WMA is the potentially greater use of RAP. As previously demonstrated, WMA pavements are hardly environmentally beneficial over HMA pavements with the same RAP content. However, the decrease in the impacts that can be achieved by adding amounts of RAP to WMA could turn WMA pavements into a good alternative to HMA pavements in environmental terms.

Hypothesis 3: noise from road transport may have a significant impact in comparison with other impact categories typically assessed in LCA, and therefore it must be included as a usual impact category in LCA studies of road transport.

An LCA method for the assessment of noise from road transport was developed here on the basis of recent advances in the field of environmental noise (strategic noise maps, health statistics for harmful effects of noise, and an advanced noise prediction model). This method was used to calculate the health impact of noise caused by an additional heavy vehicle travels one kilometre on three different roads. The impact of noise caused by an additional vehicle-kilometre ranged from 3.82E–08 to 7.54E–08 DALYs depending on the road. The noise impact caused by the heavy vehicle was then compared and aggregated with the health impacts due to fuel consumption and air emissions from the same vehicle, which were calculated using the impact assessment method ReCiPe. The noise impact accounted for between 2.58% and 4.96% of the total impact caused by an additional heavy vehicle. Noise was the third most significant impact category in terms of damage to human health, being surpassed only by climate change and particulate matter formation. Therefore, noise from road transport may have significant relevance compared to other impact categories that are typically assessed in LCA, which justifies its consideration as a usual impact category in LCA studies for road transport.

Hypothesis 4: the method provided by the Eurovignette Directive to calculate the external costs of noise from road transport has some drawbacks that may lead to significant inaccuracies, but it can be improved on the basis of publicly available models and datasets.

The method provided by the Eurovignette Directive has two major drawbacks. Most notably, it refers to the use of weighting factors for vehicle classes and times of the day in order to allow for differentiation in noise costs, but it does not provide specific values or guidelines to calculate these factors. Moreover, each EU Member State can only determine a single specific charge for each combination of vehicle class, type of road and time period. The method of the Eurovignette Directive applies a top-down approach to calculate the noise costs for two different types of road (suburban and interurban). This approach uses aggregated data from a large set of roads of the same type to compute the total noise costs, which are then divided by the total amount of traffic on these roads to obtain the average noise costs to be applied to all such roads. A bottom-up approach might be preferable to assess the noise costs of each particular road, or at least more detailed differentiation should be made between roads to take into account other key drivers influencing noise costs (e.g., speed on the roads).

A method for the calculation of the external costs of road traffic noise was developed here as an alternative to the method of the Eurovignette Directive. Improved weighting factors to be used in the method were also developed from an advanced traffic noise model (CNOSSOS-EU). These factors are highly differentiated in order to account for the influence of key cost drivers, namely vehicle class, speed and time of the day. The method of the Eurovignette Directive only focuses on the charging of HGVs for day and night, while the alternative method was devised to extend the calculation of noise costs to other vehicle classes and times of the day.

The alternative method was used to calculate the average noise costs by vehicle class and time of the day for three different roads. A bottom-up approach was used instead of the top-down approach favoured by the Eurovignette Directive. As a result, the average noise costs differed significantly between roads; e.g., the noise costs for a HGV during the day period varied from 0.047 to 0.131 €ct/vehicle-km. If a top-down had been applied, the average noise costs would have been the same for all roads assessed, which is inconsistent with the polluter pays principle that should guide the charging for the use of road infrastructure.

The bottom-up approach is better from a theoretical point of view, since it takes into account local factors that directly influence the size of noise costs (e.g., traffic conditions and population density close to the road). Despite this, the bottom-up approach has not been widely applied because it has usually required more data and time. However, the lack of data has been resolved by the publication of the strategic noise maps required by the Environmental Noise Directive. A bottom-up approach could thus be applied to calculate the noise costs for each major road based on data from strategic noise maps and applying the method provided here. In fact, the calculation of external cost of road traffic noise could become part of the action plans that the Environmental Noise Directive requires EU Member States to adopt.

6.4. Suggestions for further research

The contributions of this thesis may lead to new research. Below are provided a number of suggestions for further research.

Suggestion 1: to assess the environmental impacts of other types of road pavements.

The road pavements investigated in this thesis include HMA and WMA with the addition of synthetic zeolites. This thesis was focused on zeolite-based WMA because these asphalt mixes are widely used in road pavements as an alternative to conventional HMA. However, other types of WMA can also be investigated, such as those that involve the use of organic additives, chemical additives, or water-based foaming processes. Moreover, other types of asphalt mixes with lower manufacturing temperature are likely to become more important in the future; e.g., half-warm mix asphalt or cold mixes. The above asphalt mixes may be valuable alternatives to HMA in environmental terms, but these are the result of recent technologies that have rarely been assessed within the framework of LCA. Once more field data are available, the environmental impacts of road pavements with alternative asphalt mixes should be quantified and compared using the LCA methodology in order to determine the best alternatives in environmental terms.

Suggestion 2: to incorporate the occupational exposure into the LCA of road pavements.

The environmental impacts due to air emissions from the production and placement of different asphalt pavements were assessed in this thesis using the LCA methodology. However, the impacts related to occupational exposure were not considered due to the inconclusiveness on the effects upon the health of the workers exposed to asphalt fumes. Some studies have shown that exposure to asphalt fumes causes acute health effects including irritation to the eyes, nose and throat. There is also evidence of acute lower respiratory tract symptoms, but the relationship is not well understood. The chronic and more serious health effects are associated with the potential carcinogenicity of asphalt fumes, but the existing data are inconclusive and a direct relationship between asphalt fumes and cancer has not yet been verified. The carcinogenicity of asphalt fumes is currently being investigated by the World Health Organization. Once conclusive data on the health effects of asphalt fumes are available, the health impacts due to occupational exposure should be considered within the LCA of road pavements, since these may be significant given the direct exposure of asphalt workers to fumes.

Suggestion 3: to assess the impact of other health effects from road transport noise within the framework of LCA.

The LCA method developed in this thesis calculates the levels of annoyance and sleep disturbance caused by road transport noise, and it subsequently converts these noise effects into the corresponding health impact in DALYs. There are several harmful effects from road transport noise, but only annoyance and sleep disturbance were considered herein. This was due to two reasons: (1) these effects are established by the Environmental Noise Directive as the indicators of the harmful effects of noise exposure, and (2) both together comprise the vast majority of the disease burden from environmental noise. The impact of other health effects of noise (e.g., cardiovascular disease, cognitive impairment in children, or tinnitus) may be incorporated in future developments of the LCA method.

Suggestion 4: to incorporate the monetary valuation of health impact into the LCA of road transport noise.

The LCA method developed in this thesis assesses the health impact of noise attributable to a given variation of traffic conditions, which is quantified in DALYs. However, it does not express the health impact in monetary terms. The monetary valuation of health impact has not yet been integrated into the method because there is not a straightforward way for expressing DALYs in monetary terms. The DALY concept is partly inconsistent with the welfare economics theory, and the available evidence does not provide a single monetary value per DALY. The monetization of the noise impact attributable to traffic variations could be useful to assess in economic terms the socio-environmental benefit of different noise abatement measures (e.g., reduce traffic flow and/or speed on a particular road). Once consensus on the monetary valuation of DALYs is achieved and a single monetary value per DALY is assigned, monetization of the health impact from road transport noise will be incorporated into the LCA method. Thus, the method will be suitable to conduct an objective cost-benefit analysis, providing a more valuable support to decision making and action planning for noise management.