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# Development and application of a life-cycle assessment model for pavement management

João Santos[a], Adelino Ferreira[a], Gerardo Flintsch[b]

[a]*Department of Civil Engineering, University of Coimbra, Coimbra, Portugal*
[b]*Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute- VTTI, Blacksburg, VA, USA*

**Abstract**

The concept of sustainability has gained ground as a benchmark, both in the way we think and the way we act, and correct ethical and legal procedure requires it to be included the evaluation of highway pavement-related projects. Life Cycle Assessment (LCA) is a tool that provides some of the required metrics to add this new dimension to transportation infrastructure decision making. Despite the general consensus among the stakeholders on how useful it can be in helping to reduce the environmental burdens of a pavement system, less than a handful of pavement LCA models exist in published literature that consider entire life cycle; stages are omitted that could have the potential to, environmentally speaking, overwhelm those which are typically considered. This paper presents the development and application of a LCA model that considers the whole pavement life cycle, from the production of materials to construction, use and end-of-life.

*Keywords:* life cycle assessment; road pavement contruction and maintenance; environmental parameters; maintenance interventions; airborne emissions.

**Résumé**

Le concept de développement durable a gagné du terrain comme une référence, tant dans la manière de penser et d'agir, et ce n'est plus une procédure moralement ou juridiquement correc tde le laisser hors del'évaluation des projets liés à la chausséeroutière. L'Analyse du Cycle deVie (ACV) est un outil qui fournit une partie des mesures requises pour ajouter cette nouvelle dimension à l'infrastructure de transport pour la prise de décision. Malgré le consensus général parmi les parties prenantes de combien il peut être utile pour aider à réduire les pressions sur l'environnement d'un système de chaussées, moins d'une poignée de modèles de LCA de la chaussée existe dans la littérature qui ont considéré l'ensemble des phases du cycle de vie, en omettant les étapes que pourrait avoir le potentiel, écologiquement parlant, d'accabler ceux qui sont habituellement considérés. Cet article présente le développement et l'application d'un modèle ACV qui considère l'ensemble du cycle de la chaussée, de la production des matériaux de construction, utilisation et fin de vie.

*Mots-clé:* analyse du cycle de vie; construction et entretien des routes de chaussées; paramètres environnementaux; interventions de maintenance; émissions atmosphériques.

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**Nomenclature**

| | |
|---|---|
| AADT | Annual Average Daily Traffic |
| $AADT_h$ | Annual Average Daily Heavy - Traffic |
| AC | Acidification |
| ARD FF | Abiotic Resources Depletion of Fossil Fuels |
| ARD MR | Abiotic Resources Depletion of Mineral Resources |
| CC | Climate Change |
| CED F | Cumulative Fossil Energy Demand |
| CED Nuc | Cumulative Nuclear Energy Demand |
| CED PF | Cumulative Primary Forest Energy Demand |
| CED RR | Cumulative Renewable Energy Demand |
| CED Total | Cumulative Total Energy Demand |
| EOL | End-of-Life |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HDV | Heavy Duty Vehicle |
| HMA | Hot Mix Asphalt |
| HT | Human Toxicity |
| ILCD | International Reference Life Cycle Data System |
| IRI | International Roughness Index |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MPD | Mean Profile Depth |
| M&R | Maintenance & Rehabilitation |
| PAP | Project Analysis Period |
| PC | Passenger Car |
| PMS | Pavement Management System |
| POF | Photochemical Ozone Formation |
| PSI | Present Serviceability Index |
| RR | Rolling Resistance |
| TE | Terrestrial Eutrophication |
| WZ | Work Zone |

## 1. Introduction

Adverse environmental changes such as global warming, ozone depletion, soil acidification and humanity's growing awareness of health and safety issues have lead worldwide authorities to establish targets and adopt policies towards a reversal of the current paradigm of development. The transport sector, due to its contribution to the current emissions pattern, has a key role to play in achieving an efficient inversion of some of the current trends. Within the transport sector, the highway infrastructure, and in particular road pavements, have a set of specificities that can be addressed accordingly and managed to align the transport sector with the established milestones. However, improving the sustainability of road pavements requires road agencies and construction companies to identify, by means of appropriate methodologies and tools, the priority areas of action. Once the way in which the road pavement impacts the environment is known, new approaches and procedures can be developed and implemented, making sure they concur to bring about the greatest gains in all aspects and dimensions of the system. The LCA method has gradually become seen to be a versatile tool capable of informing decisions on resource and process selection to better understand, measure and reduce the environmental impacts of a system.

In order to facilitate the integration of the LCA methodology into the pavement infrastructure decision-making process, this paper presents the development of a fully integrated and highly customizable project-level pavement LCA model capable of including all six pavement life cycle phases. The ability of such a model to assess the environmental performance of the life cycle of a road pavement is illustrated by its application to a case study based on the Portuguese practice of pavement construction and management.

## 2. Pavement LCA model description

### *2.1. Model structure*

The model described in this paper was written in Visual Basic .NET (VB.NET) and SQL programming languages, the latter is used for managing the data introduced and held in the system. It encompasses three types of VB.NET Classes: Pavement Life Cycle Phase Class, Database Class, and Other Classes, those not covered by the two classes previously mentioned. Each Pavement Life Cycle Phase Class is linked to several classes, including a Main Class that is the hub of the model. Apart from other functions, the hub is responsible for the interaction between all classes, so that the system is automatically updated whenever the user makes a decision that affects the remaining system components. The majority of the data required to run the model is inputted through windows, either by scrolling through the classes representing the pavement life cycle phases or directly accessing the classes existing in the database. Once the data is put in the Database Class, it becomes available for all future analysis, unless it is deleted by the user. Moreover, given the open nature of the database, project-specific data can be added and pre-existing data can be edited to fit the characteristics and particularities of the analysis being performed.

### *2.2. Goal and scope definition*

The model presented in this paper is intended to give highway agencies a highly customizable tool to assist them in quantitatively assessing, at project level, the total environmental footprint of their procedures, strategies, and decisions regarding the construction and maintenance of flexible pavements used for a rural/interurban highway. The target audience for using the methods, data, and results made available by the model includes LCA practitioners, pavement engineers, and other technical experts. The model enables the user to assess the environmental impacts and resource consumption (energy resources and materials) of alternative solutions for pavement design and maintenance throughout the different phases of the PAP. The user can track where in the life cycle of the pavement's PAP environmental impacts are greatest and which materials, energy sources, equipment and processes contribute to the environmental impacts. After acknowledging the environmental consequences of their potential decisions, they will be more likely to adopt more sustainable pavement design and management practices.

### *2.3. System boundaries and system processes*

The system boundaries of the proposed pavement LCA model entail six pavement life cycle phases, modeled through individual but interconnected modules hosted in VB.NET Classes. They are the following: (1) extraction of materials and production; (2) construction and maintenance; (3) transportation; (4) WZ traffic management; (5) usage; and (6) EOL. Various supplementary sub-models that are attached to the corresponding modules, as well as some of the data required to run those models, are introduced and discussed in the following sections.

#### *2.3.1. Extraction and production of materials phase*

Pavement-related environmental burdens assigned to the extraction and production of materials phase are due to material acquisition and processing. This includes all manufacturing processes of the materials, from the extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), up to the final mixture production at a mixing plant (material production sub-phase).

#### *2.3.2. Transportation phase*

The transportation phase accounts for the transportation of materials to and from the construction site and between intermediate facilities (e.g., transportation of aggregates from the quarries to HMA mixing plants). All materials were assumed to be hauled by HDVs that run at their maximum legal capacity when loaded and empty on return journeys. Emissions data associated with the operation of these vehicles was obtained from the EMEP/EEA Emission Inventory Guidebook 2009 (EEA, 2009). The pavement LCA model user is asked to assign a set of data for each material and mixture being transported: type of movement; type of HDV and engine technology; hauling distance (km), and average speed (km/h).

#### *2.3.3. Construction and maintenance phase*

In the construction and maintenance phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The construction and M&R related environmental burdens associated with the operation of construction equipment were obtained by applying a methodology based on the Tier 3 approach described in the EMEP/EEA Emission Inventory Guidebook 2009 (EEA, 2009) for non-road mobile sources and machinery.

### *2.3.4. WZ traffic management phase*

In the proposed model, the environmental impacts associated with the on-road vehicles when subject to a WZ traffic management plan implemented during the M&R activities were treated as an individual phase and designated as WZ traffic management phase. The WZ traffic management phase was kept separate in order to highlight the influence of the WZ on the environmental performance when compared to normal traffic flow. The marginal fuel consumption and airborne emissions released by vehicles either going through or detouring a WZ were determined by adopting a two-step method. In the first step, changes in driving patterns were modeled using the capacity and delay models proposed by the Highway Capacity Manual 2000 (TRB, 2000). In the second step, the traffic outputs were fed into two hot exhaust emissions models. The fuel consumption resulting from acceleration and deceleration movements associated with speed changes between homogeneous driving patterns were estimated by using the macroscopic four-mode "elemental model" as described by Akçelik et al. (2012) **and combined with** the Tier 1 fuel consumption-dependent emission factors (minimum values) defined in the EMEP/EEA Emission Inventory Guidebook 2009 (EEA, 2009). The Tier 3 approach presented in the EMEP/EEA Emission Inventory Guidebook 2009 (EEA, 2009) was adopted to estimate the emissions released by on-road vehicles during driving patterns characterized by a constant average speed.

Data on Portuguese vehicle stocks, consisting of the distribution of the Portuguese fleet by vehicle category, type, and Euro legislation classes, from 2010 to 2030, were gathered from the EMISIA SA website (EMISIA SA, 2009) and inserted into the "On-Road Vehicle Fleet Distribution" Database Class. For years beyond the period 2010 to 2030, the tendency observed in the aforementioned period of time was extrapolated. The AADT was proportionally distributed into different vehicle classes and technologies, according to the vehicle population observed in each year of the "On-Road Vehicle Fleet Distribution" Database Class. The fuel consumed and vehicle emissions from detoured vehicles were added to those going through the WZ after the on-road vehicles emissions model had been run for the detour conditions. Finally, the marginal fuel consumption and airborne emissions due to the WZ traffic management phase were calculated by subtracting fuel consumption and emissions released during a WZ period from the results of an equivalent non-WZ period.

### *2.3.5. Usage phase*

The usage phase addresses the contribution to the pavement's environmental burden resulting from the interaction of the road pavement with vehicles and environment throughout its PAP. The following factors have been identified as worthy of consideration during the usage phase of the pavement: Tyre - Pavement Interaction, Traffic Flow, Albedo, Leachate and Runoff, Carbonation, and Lighting. However, many of these factors (e.g. Albedo, Carbonation and Lighting) do not directly apply to the scope of the pavement LCA model. Thus, only the Tyre - Pavement Interaction factor, expressed in terms of RR, was considered in the proposed pavement LCA model, through the MIRIAM models (Hammarström et al., 2012). According to those models the influence of the pavement condition on RR comes partially from changes in the pavement's roughness and macrotexture, measured by IRI and MPD, respectively. In Portugal, the PMS of the Portuguese Road Administration (Ferreira et al., 2011) and other municipal PMSs use the pavement performance model of the flexible pavement design method developed by the American Association of State Highway and Transportation Officials (AASHTO, 1993) to predict the future quality of pavements. Integrating this new pavement LCA model with the Portuguese current practice on pavement management requires transforming the PSI to the IRI. Several equations relating those indicators were included in the usage module and made available for choice according the model user's preference. Once the additional fuel consumption due to rolling resistance is calculated, those values are coupled with the Tier 1 fuel consumption-dependent emission factors (minimum values) defined in the EMEP/EEA Emission Inventory Guidebook 2009 (EEA, 2009).

### *2.3.6. End-of-life phase*

At the end of its service life, a pavement can be either allowed to remain in place, serving as part of the underlying structure for another pavement layer, or removed. If the pavement is removed, the debris can be landfilled or recycled in a central plant. For pavements that are removed and entirely rebuilt, the EOL environmental impacts result from the demolition, transportation, and landfilling or recycling processes. EOL consists of a set processes accounted for in other phases of the pavement LCA, namely in the construction and transportation phases. However, for the purpose of assessing the contribution of the EOL to the pavement LCA, the environmental burdens of those processes were allocated to the EOL phase.

*2.3.7. Energy sources production*

Although it is not considered a pavement life cycle phase, like those introduced previously, the energy sources production and transportation is an unavoidable process that is common to all pavement life cycle phases. To account for the upstream energy consumption, and respective airborne emissions, eight CED indicators (fossil, nuclear, primary forest, biomass, wind, solar, geothermal, and water) were considered. In doing so, the pre-combustion-related life cycle impacts are considered and displayed separately from the impacts due to the process energy consumption. Presenting the impacts from the production of energy sources facilitates the understanding of where in the pavement life cycle the use of less environmentally burdensome energy sources may help reduce the environmental load of a road pavement.

*2.4. Life cycle impact assessment*

The purpose of the LCIA is to assign the LCI results to different impact categories based on the expected types of impacts on the environment. According to the LCI results and the impact categories commonly recognized as the most representative of the three protection areas (human health, natural environment, and natural resources), the following impact categories were selected: CC, AC, TE, POF, HT, ARD FF and ARD MR. The characterization models and associated characterization factors proposed to quantify the contribution of each LCI element to the aforementioned impact categories were selected according to the recommendations of the ILCD handbook (Hauschild et al., 2013), taking into account the compatibility between the LCI level of detail promoted by the pavement LCA model and those required by the methods suggested in the ILCD handbook, as well as the recent publications addressing emissions timing in LCA. For this reason, the time-adjusted characterization model proposed by Kendall (2012), was selected, as opposed to the traditional time-steady International Panel on Climate Change model. Energy-related issues were evaluated through CED indicators.

## 3. Case study

*3.1. Introduction*

The potential life cycle environmental impacts of four functional units were estimated by applying the pavement LCA model presented in this paper. Each functional unit is mean to represent the construction, maintenance, usage and EOL of a flexible pavement structure of a straight and flat inter-urban motorway segment, with two lanes per direction, which would provide safe, comfortable, economical and durable driving conditions over a 40-year PAP. The pavement structures evaluated are those recommended by the Portuguese manual of pavement designed, called MACOPAV, for the pavement foundations F2 and F4 when subject to the traffic classes T5 and T1. Details on pavement foundation and traffic class characteristics are presented in Table 1. Table 2 presents the pavement structure dimensions.

**Table 1. Pavement foundation and traffic class characteristics**

| Pavement foundation | CBR (%) | E (MPa) | $\upsilon$ | Traffic class | $AADT_h$ | $\alpha$ | g (%) | Pavement structure recommended |
|---|---|---|---|---|---|---|---|---|
| F2 | 10 | 60 | 0.35 | T5 | 300 | 3 | 3 | P7 |
| | | | | T1 | 2000 | 5.5 | 3 | P16 |
| F4 | 30 | 150 | 0.35 | T5 | 300 | 3 | 3 | P3 |
| | | | | T1 | 2000 | 5.5 | 3 | P12 |

Key: CBR - Californian Bearing Ratio; E - Stiffness Modulus; $\upsilon$ - Poisson's Ratio; $AADT_h$ - Annual Average Daily Heavy - Traffic; $\alpha$ - Average Heavy-Traffic Damage Factor; g - Annual Average Growth Rate of Traffic.

**Table 2. Pavement structure dimensions**

| Layer | Mixture name | Thickness (cm) | | | | Width (m) | | | | Length (km) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P3 | P7 | P12 | P16 | P3 | P7 | P12 | P16 | P3 | P7 | P12 | P16 |
| Surface | AC 14 surf | 4 | 4 | 6 | 6 | 22.5 | 22.5 | 22.5 | 22.5 | 1 | 1 | 1 | 1 |
| Binder | AC 14 bin | 5 | - | - | - | 22.5 | 22.5 | 22.5 | 22.5 | 1 | 1 | 1 | 1 |
| | AC 20 bin | - | 7 | 8 | 11 | | | | | | | | |
| Base | AC 20 base | 7 | - | - | - | 22.5 | 22.5 | 22.5 | 22.5 | 1 | 1 | 1 | 1 |
| | AC 32 base | - | 11 | 12 | 15 | | | | | | | | |
| Sub-Base | CA | 20 | 20 | 20 | 20 | 22.5 | 22.5 | 22.5 | 22.5 | 1 | 1 | 1 | 1 |

Key: AC - Asphalt Concrete; CA - Crushed Aggregates.

For traffic composition, HDV are assumed to represent 10% of the total AADT, handling the outer lanes 45% of the total $AADT_h$ (in each direction). The remaining percentage of the total AADT (90%) refers to PCs. In each year of the PAP, the two main vehicle classes (PC and HDV) were broken down into several engine capacity categories and each one of those engine capacity categories was further split into several levels of Euro stages compliance. This desegregation of the traffic categories was done for each year of the PAP, proportionally to the Portuguese traffic fleet distribution, defined in “On-Road Vehicle Fleet Distribution” Database Class.

The functional units were assessed under the perspective of the total pavement life cycle phases covered by the model: extraction and production of materials, transportation, construction and maintenance, WZ traffic management, usage and EOL. The system boundaries were set at the sub-base and at the finished road surface. Then, production and construction of all layers covered by the limits stated above and subsequent M&R activities was taken into account. The environmental impacts related to the earthworks required to build the pavement foundation were excluded from the systems boundaries. This decision is based on the fact that those works are specific to a particular project and different initial conditions (e.g. geotechnical characteristics) may result in equal pavement foundation classes by undertaking a set of soil improvement activities. The environmental loads assigned to the extraction and production of materials phase were determined by combining data provided by Portuguese companies (e.g., asphalt mixtures composition, batch mix plant performance, in terms of production and fuel consumption rates) with LCI database (US EPA, 2004; Eurobitume, 2011) and scientific papers (Jullien et al., 2012). In modeling the transportation phase three HDV classes were considered: a rigid 26 - 28 tonne truck with a Euro IV diesel engine; a 34 - 40 tonne articulated truck trailer with a Euro IV engine and a rigid > 32 tonne truck with a Euro IV engine. Different hauling distances and speeds were considered depending on the type of materials being hauled. During the construction sub-phase, which was carried out in the year before the beginning of the PAP, it was assumed that there was no traffic demand, as the road did not exist. Such an assumption means that there are no traffic delays and consequently no environmental impacts arise from it. The procedures required to construct the several pavement layers and to undertake the M&R activities were modeled according to the data gathered from Portuguese construction companies. The data includes information on type, features (brand, model, engine horsepower, etc), and respective production rate of each piece of construction equipment used. Technical specifications made available by the manufactures of construction equipment were used to complement the onsite data when needed. The M&R plans determined by Santos & Ferreira (2013) were adopted to determine the timing, materials type and quantities involved in the maintenance sub-phase. It consists of applying a rehabilitation activity when the PSI value is lower than 2.0. Accordingly, it was assumed that PSI is restored to its initial value (4.5) when rehabilitation activity is performed, which corresponds to an IRI value of 0.41 m/km. All the rehabilitation activities were assumed to be performed at night, from 10 p.m. to 6 a.m., with one lane closed. The operation speed of the PCs and HDV is reduced from 120 km/h and 90 km/h to 80 km/h, respectively. Moreover, it is assumed that 10% of drivers will self-detour 10 km on a no-highway road at an average speed of 60 km/h. The M&R actions involved in the activity are shown in Table 3. Table 4 presents the M&R plans to be followed throughout the PAP.

As regards the usage phase, a macrotexture value of 1 mm, as measured by MPD, was considered for all pavement structures. The equation proposed by Al-Omari & Darter (1994) was used to convert the PSI into IRI. The IRI degradation effect on vehicle operation speed was taken into account by means of the model proposed by Yu & Lu (2013), according to which every 1 m/km increase of the IRI leads to a 0.84 km/h decrease of the free flow average speed. When accounting for the EOL phase, it was assumed that all bounded and unbounded pavement layers would be removed and transported to the asphalt plant, so that they could be upgraded to a usable recycled material. These operations were assumed to be performed one year after the end of the PAP (41$^{st}$ year). Emissions due to this process arise from the equipment operation and materials transportation.

**Table 3. M&R activity description**

| M&R activity | M&R actions involved | Mixtures applied | Thickness (cm) or area ($m^2$) | | Duration |
|---|---|---|---|---|---|
| | | | Value | Units | (per direction) |
| Structural rehabilitation | Wearing layer | AC 14 surf | 5 | cm | 6 days |
| | Tack coat application | Bitumen Emulsion 65% | 3750 [a] | $m^2$ | |
| | Base layer | AC 20 base | 10 | cm | |
| | Tack coat application | Bitumen Emulsion 65% | 3750 [a] | $m^2$ | |
| | Surface leveling | AC 20 base | 2 | cm | |
| | Tack coat application | Bitumen Emulsion 65% | 3750 [a] | $m^2$ | |

[a] Value per lane.

**Table 4. M&R plans**

| Pavement foundation | Traffic class | Pavement structure | M&R plan (years) | | PSI final |
|---|---|---|---|---|---|
| F2 | T5 | P7 | 20 | - | 3.50 |
| | T1 | P16 | 15 | 35 | 4.04 |
| F4 | T5 | P3 | - | - | 3.25 |
| | T1 | P12 | 27 | - | 3.72 |

### *3.2. Results of the application of the pavement LCA model*

The LCIA results for each functional unit are given in Table 5. According to the results, the contribution of the several pavement life cycle phases across all of the impact categories considered depends on the traffic class. For low traffic volumes, such as those characterized by the traffic class T5, the contribution of the materials phase is dominant for all the impact categories. Its share of contribution ranges between 42% (impact category ARD MR corresponding to the pavement structure laid on a pavement foundation F4) and 60% (impact categories TE corresponding to the pavement structure laid on a pavement foundation F4). The transportation and usage phases were found to be the second main contributors to the overall environmental impacts associated with the pavement structures recommended for the foundation classes F2 and F4, respectively. On the other hand, the WZ traffic management phase denotes a residual contribution to the overall spectrum of impact categories, with a percentage lower than 1%. This result, although seemingly anomalous due to the reduced value, follows the trend observed in studies that have considered similar traffic volumes and WZ traffic closure scenarios (Chan et al. 2008 and Yu and Lu, 2013). It happens because, due to the very low traffic volume going through the WZ, a traffic queue never develops during the night time M&R events. Therefore, the traffic delay emissions only occur due to the speed change inherent to going through the WZ and detouring. For both traffic classes, the construction, M&R and EOL phases showed limited relevance when compared with the contribution given by the remaining phases. When considering a traffic class representing high traffic volumes, a different relative and absolute contribution to the overall environmental impact categories was found to be given by the various pavement life cycle phases. It can be seen in Table 5 that in the case of the traffic class T1, the usage phase relegates the materials phase to second place in the ranking of the largest contributor in the majority of the impact categories. The usage phase was found to be responsible for 24%-53% of the values of each impact category indicator, whereas the materials phase was found to be responsible for a share of 11%-33%.

Table 5 also presents the feedstock energy and the CED Total (calculated with higher heating values) corresponding to each functional unit, split up into the following categories: CED F, CED Nuc, CED PF and CED RR. By definition, CED should account for the usage of any sort of energy. That means that the feedstock energy of bitumen should also be included when accounting for CED. However, since the feedstock energy inherent to bitumen remains unexploited while used as a binder in a pavement, it was presented separately from the primary energy as recommended by the UCPRC Pavement LCA guideline (Harvey et al., 2010). For all functional units whose environmental performance was analysed in detail, Table 5 shows an identical relationship between the values of the different impact category indicators and the CED values, particularly those referring to CC and CED F.

**Table 5. LCIA per pavement life cycle phase for each functional unit**

| Foundation class | Traffic class | Pavement structure | Life cycle phase | CC (tonnes $CO_2$-eq.) | AC (mol $H^+$-eq.) | TE (mol N-eq.) | POF (Kg NMVOC-eq.) | HT (kg 1,4-DCB eq.) | ARD MR (Kg Sb-eq.) | ARD FF (MJ-eq.) | Feedstock Energy (MJ) | CED F (MJ-eq.) | CED Nuc (MJ-eq.) | CED PF (MJ-eq.) | CED RR (MJ-eq.) | CED Total (MJ-eq.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F2 | T5 | P7 | Materials | 6.25E+02 | 1.15E+03 | 7.80E+03 | 3.87E+03 | 5.15E+03 | 5.21E-02 | 1.17E+07 | 4.58E+07 | 1.28E+07 | 4.40E+04 | 8.35E+00 | 4.20E+05 | 1.32E+07 |
| | | | Const. and M&R | 7.21E+01 | 1.33E+02 | 1.15E+03 | 5.71E+02 | 5.38E+02 | 8.12E-03 | 1.12E+06 | 0.00E+00 | 1.19E+06 | 1.56E+04 | 1.59E+00 | 2.73E+03 | 1.21E+06 |
| | | | Transportation | 1.60E+02 | 3.08E+02 | 2.72E+03 | 1.13E+03 | 1.27E+03 | 1.83E-02 | 2.52E+06 | 0.00E+00 | 2.67E+06 | 3.50E+04 | 3.58E+00 | 6.14E+03 | 2.71E+06 |
| | | | WZ traffic manag. | 3.03E+00 | 4.87E+00 | 3.87E+01 | 2.62E+01 | 1.83E+01 | 3.31E-04 | 5.13E+04 | 0.00E+00 | 5.36E+04 | 7.50E+02 | 4.36E-02 | 1.44E+02 | 5.45E+04 |
| | | | Usage | 1.27E+02 | 2.54E+02 | 2.21E+03 | 1.09E+03 | 1.01E+03 | 1.46E-02 | 2.23E+06 | 0.00E+00 | 2.37E+06 | 2.54E+04 | 2.07E+00 | 4.77E+03 | 2.40E+06 |
| | | | EOL | 6.29E+01 | 1.68E+02 | 1.45E+03 | 6.21E+02 | 6.75E+02 | 1.02E-02 | 1.40E+06 | 0.00E+00 | 1.49E+06 | 1.95E+04 | 2.00E+00 | 3.42E+03 | 1.51E+06 |
| | | | Total | 1.05E+03 | 2.01E+03 | 1.54E+04 | 7.31E+03 | 8.67E+03 | 1.04E-01 | 1.90E+07 | 4.58E+07 | 2.05E+07 | 1.40E+05 | 1.76E+01 | 4.37E+05 | 2.11E+07 |
| | T1 | P16 | Materials | 9.79E+02 | 1.77E+03 | 1.16E+04 | 5.83E+03 | 6.94E+03 | 8.45E-02 | 1.94E+07 | 7.67E+07 | 2.12E+07 | 7.09E+04 | 1.38E+01 | 6.76E+05 | 2.20E+07 |
| | | | Const. and M&R | 9.73E+01 | 1.85E+02 | 1.60E+03 | 7.92E+02 | 7.47E+02 | 1.15E-02 | 1.59E+06 | 0.00E+00 | 1.69E+06 | 2.21E+04 | 2.26E+00 | 3.88E+03 | 1.72E+06 |
| | | | Transportation | 2.33E+02 | 4.67E+02 | 4.12E+03 | 1.71E+03 | 1.92E+03 | 2.77E-02 | 3.82E+06 | 0.00E+00 | 4.06E+06 | 5.31E+04 | 5.44E+00 | 9.31E+03 | 4.12E+06 |
| | | | WZ traffic manag. | 8.92E+02 | 2.60E+03 | 1.20E+04 | 3.07E+04 | 5.63E+03 | 1.20E-01 | 1.84E+07 | 0.00E+00 | 1.95E+07 | 2.17E+05 | 1.66E+01 | 4.06E+04 | 1.97E+07 |
| | | | Usage | 1.43E+03 | 3.02E+03 | 2.66E+04 | 1.25E+04 | 1.22E+04 | 1.68E-01 | 2.57E+07 | 0.00E+00 | 2.74E+07 | 2.92E+05 | 2.36E+01 | 5.49E+04 | 2.77E+07 |
| | | | EOL | 9.46E+01 | 2.43E+02 | 2.06E+03 | 9.04E+02 | 9.60E+02 | 1.53E-02 | 2.10E+06 | 0.00E+00 | 2.23E+06 | 2.92E+04 | 3.00E+00 | 5.13E+03 | 2.27E+06 |
| | | | Total | 3.73E+03 | 8.28E+03 | 5.80E+04 | 5.24E+04 | 2.84E+04 | 4.28E-01 | 7.11E+07 | 7.67E+07 | 7.61E+07 | 6.84E+05 | 6.47E+01 | 7.90E+05 | 7.75E+07 |
| F4 | T5 | P3 | Materials | 3.17E+02 | 6.46E+02 | 4.68E+03 | 2.27E+03 | 3.66E+03 | 2.69E-02 | 5.29E+06 | 1.23E+06 | 5.78E+06 | 2.29E+04 | 3.78E+00 | 2.31E+05 | 6.03E+06 |
| | | | Const. and M&R | 4.92E+01 | 8.65E+01 | 7.55E+02 | 3.78E+02 | 3.52E+02 | 5.26E-03 | 7.25E+05 | 0.00E+00 | 7.70E+05 | 1.01E+04 | 1.03E+00 | 1.77E+03 | 7.82E+05 |
| | | | Transportation | 9.53E+01 | 1.74E+02 | 1.53E+03 | 6.35E+02 | 7.15E+02 | 1.03E-02 | 1.42E+06 | 0.00E+00 | 1.51E+06 | 1.97E+04 | 2.02E+00 | 3.46E+03 | 1.53E+06 |
| | | | WZ traffic manag. | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | | | Usage | 1.00E+02 | 2.11E+02 | 1.82E+03 | 9.10E+02 | 8.36E+02 | 1.23E-02 | 1.88E+06 | 0.00E+00 | 2.00E+06 | 2.12E+04 | 1.70E+00 | 4.00E+03 | 2.03E+06 |
| | | | EOL | 5.27E+01 | 1.42E+02 | 1.23E+03 | 5.24E+02 | 5.73E+02 | 8.54E-03 | 1.18E+06 | 0.00E+00 | 1.25E+06 | 1.64E+04 | 1.68E+00 | 2.87E+03 | 1.27E+06 |
| | | | Total | 6.15E+02 | 1.26E+03 | 1.00E+04 | 4.71E+03 | 6.14E+03 | 6.32E-02 | 1.05E+07 | 1.23E+06 | 1.13E+07 | 9.02E+04 | 1.02E+01 | 2.44E+05 | 1.16E+07 |
| | T1 | P12 | Materials | 6.74E+02 | 1.24E+03 | 8.37E+03 | 4.17E+03 | 5.42E+03 | 5.71E-02 | 1.29E+07 | 5.05E+07 | 1.40E+07 | 4.82E+04 | 9.18E+00 | 4.60E+05 | 1.46E+07 |
| | | | Const. and M&R | 7.36E+01 | 1.38E+02 | 1.20E+03 | 5.93E+02 | 5.60E+02 | 8.45E-03 | 1.16E+06 | 0.00E+00 | 1.24E+06 | 1.62E+04 | 1.66E+00 | 2.84E+03 | 1.26E+06 |
| | | | Transportation | 1.69E+02 | 3.33E+02 | 2.94E+03 | 1.22E+03 | 1.37E+03 | 1.97E-02 | 2.72E+06 | 0.00E+00 | 2.89E+06 | 3.78E+04 | 3.87E+00 | 6.63E+03 | 2.93E+06 |
| | | | WZ traffic manag. | 1.42E+02 | 2.53E+02 | 2.00E+03 | 1.45E+03 | 9.39E+02 | 1.75E-02 | 2.68E+06 | 0.00E+00 | 2.83E+06 | 3.38E+04 | 2.44E+00 | 6.68E+03 | 2.87E+06 |
| | | | Usage | 9.99E+02 | 2.04E+03 | 1.80E+04 | 8.54E+03 | 8.24E+03 | 1.15E-01 | 1.75E+07 | 0.00E+00 | 1.86E+07 | 1.99E+05 | 1.61E+01 | 3.74E+04 | 1.88E+07 |
| | | | EOL | 7.11E+01 | 1.88E+02 | 1.61E+03 | 6.96E+02 | 7.54E+02 | 1.15E-02 | 1.58E+06 | 0.00E+00 | 1.73E+06 | 2.65E+04 | 2.71E+00 | 4.64E+03 | 1.77E+06 |
| | | | Total | 2.13E+03 | 4.19E+03 | 3.41E+04 | 1.67E+04 | 1.73E+04 | 2.29E-01 | 3.85E+07 | 5.05E+07 | 4.13E+07 | 3.61E+05 | 3.60E+01 | 5.18E+05 | 4.22E+07 |

Key: CC- Climate Change; AC - Acidification; TE - Terrestrial Eutrophication; POF - Photochemical Ozone Formation; HT - Human Toxicity; ARD MR - Abiotic Resources Depletion of Mineral Resources; ARD FF - Abiotic Resources Depletion of Fossil Fuels; CED F - Cumulative Fossil Energy Demand; CED Nuc - Cumulative Nuclear Energy Demand; CED PF - Cumulative Primary Forest Energy Demand; CED RR - Cumulative Renewable Resources Energy Demand.

For a traffic class T5, the materials phase was the most energy-consuming phase, comprising 62% and 51% of the 20.539 TJ and 11.305 TJ CED F corresponding to the life cycle of the pavement structures recommended for the foundation classes F2 and F4, respectively. An identical relationship had already been acknowledged with regard to CC, for which the aforementioned pavement structures were found to contribute 59% and 52% of the 1050 tonnes of $CO_2$-eq and 615 tonnes of $CO_2$-eq, respectively. In the case of the pavement structures recommended for a traffic class T1, the usage phase overtakes the materials phase as the highest energy intensive phase in both foundation classes. It was found to be responsible for 36% and 45% of the 56.468 TJ and 30.235 TJ CED F consumed during the life cycle of the pavement structures recommended for the foundation classes F2 and F4, respectively.

When analysing the relevance of each type of energy (fossil energy, nuclear energy, primary forest energy and renewable energy resources), it can be seen that the nuclear, primary forest and renewable energy sources have a residual share of the CED Total. The main purpose of the latter three types of energy is the production and delivery of other energy sources, mainly electricity, to their point of consumption, as opposed to the fossil energy (provided by diesel, gasoline, etc.) that has been used, amongst other things, to power the processes directly linked to the construction, maintenance and usage phases of the pavement systems. Moreover, the majority of the airborne emissions released during the diverse pavement life cycle phases stem from the combustion of fossil fuels, as the production of the materials consumed to construct and maintain the pavement structures does not cause the occurrence of chemical reactions from which additional airborne emissions would result (e.g. limestone calcination during cement production). Therefore, the results described above can be seen as a mirror of a road transport mode, and particularly a road pavement construction and management sector, which are still excessively dependent on the consumption of fossil fuels for energy sources. It is expected that the results would differ slightly if the introduction of alternative automotive fuels was taken into account in modeling the usage phase. However, there are both considerable uncertainties on how the rolling resistance effect would change the fuel consumption pattern of the vehicles propelled by alternative fuels, and the assumptions about the proliferation of alternative fuels in the long-term market.

Finally, when comparing feedstock energy and CED F, Table 5 shows the feedstock energy of the bituminous materials to be, on average, approximately four times the CED F corresponding to the materials phase of the various functional units and twice the CED F corresponding to the whole pavement life cycle.

## 4. Conclusions

This paper has presented the development of an integrated VB.NET-based pavement LCA model capable of considering the whole pavement life cycle, from material extraction and production to construction, to usage and EOL. The developed model expands the LCIA to categories other than CC and upgrades the impact assessment techniques typically incorporated in the majority of pavement LCA tools by the inclusion of dynamic characterization factors. In addition, thanks to the open and customizable database that comes with the pavement LCA model, the approach can be applied to a variety of case studies and projects while providing trust and credibility to the geographical and temporal context of the results. The application of the pavement LCA model to the case study showed that, for less demanding traffic classes, the materials phase is the main contributor to the overall life cycle environmental impacts of the road pavement. On the other hand, if the road pavement is expected to carry a significant volume of traffic over its PAP, the usage phase would assume a highlighted position in driving the overall environmental performance of the road pavement.

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