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System Boundary Expansion in Road Pavement Life Cycle Assessment

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INDEX

Abstract

The application of Life Cycle Assessment to road pavements has been evolving over the last years, receiving a growing interest from the academic sector and from governmental and non-governmental institutions and organizations. However, the complete introduction of this approach in the asset management decision making process is not possible yet, due to an incomplete understanding of the impact of some relevant phases and components of a road pavement LCA, such as the work zone impact during maintenance events and the rolling resistance in the use phase. The first one refers to the additional congestion and traffic delay in an area of a trafficway interested by construction and maintenance activities. The road pavement rolling resistance is the energy loss due the pavement-vehicle interaction (PVI) and it is affected by the tire properties and by the pavement surface condition.

The introduction of the Carbon Footprint/LCA approach in highway asset management, as a decision making tool, requires a deep understanding of all the phases of the life cycle of a road and of the impact of the selected methods and assumed parameters to model them.

This thesis provides a review of the main models used to describe the influence on the vehicle fuel consumption - in terms of CO_2 emissions - of the work zone during maintenance activities and the rolling resistance during the use phase and investigates the potential impact of these models and of some input parameters on the LCA results. The study was applied on two different UK road sections, characterized by different traffic volume, maintenance activities and design.

The impact of the work zone during maintenance activities was explored, comparing the CO_2 emissions obtained from two generally applied models in Life Cycle Assessment studies (LCAs) with different level of sophistication: the microsimulation model Aimsun and the macroscopic analytical/deterministic method described in the Highway Capacity Manual (HCM), which is based on the Demand-Capacity (D-C) model and the queue theory. In these models, the traffic volume, the Traffic Management (TM) strategy, the Emission Factor (EF) model and the network boundary are input variables that potentially generate uncertainty in the results and their impact was investigated.

The impact of the rolling resistance, due to the pavement surface properties, was assessed with two different models provided in literature and a sensitivity test was performed on some significant input variables, namely the pavement deterioration, the traffic growth and the selected EF.

The results obtained in this research have shown that the models adopted to estimate the vehicle emissions for both the work zone impact and the rolling resistance components have a significant influence on the LCA results. Therefore, the selection of the model to assess the impact of these components need to be accurate and appropriate.

To assess the work zone impact during maintenance events, the selection of the traffic and emission models should be based on the study objectives and on the available resources.

The assessment of the impact of the rolling resistance on the vehicle emissions requires the development of models to estimate the deterioration rate of the pavement surface properties over time and models to link them to the rolling resistance energy loss and to the vehicle emissions. Although currently there are few models available in literature, they are affected by site specific elements and are not suitable for all geographical locations. In the UK, there is currently a lack of general pavement deterioration models able to predict the change of unevenness and texture depth over time and the relationship between them and the rolling resistance and the fuel consumption. This must be corrected before pavement LCA studies can be extended to the use phase.

The selected model is not the only source of uncertainty in the assessment of these components. In fact, the analysis of the work zone impact and of the rolling resistance requires several methodological assumptions that, as shown in this study, can have a relevant impact on the results, generating a high level of uncertainty.

The results obtained from the work zone impact analysis are sensitive to all the input variables taken into account in this study: the traffic growth, the TM strategy adopted, the EF model and the extent of the road network assumed to be impacted by the work zone.

For the rolling resistance, if the deterioration rate of the pavement surface properties is a significantly sensitive parameter, the traffic growth and the EF/fuel efficiency predictions, combined to predict future vehicle emissions, have a relatively small effect because they cancel out to a large extent. However, changes in predicted future traffic levels or EF could change this result and should be kept under review.

These research outcomes highlight the importance of incorporating uncertainty into pavement LCA. The reliability and accuracy of an LCA is affected by the reliability of the methodologies and models adopted. LCA results should not be presented as 'single figure' absolute values, but rather considering a range of values to reflect the uncertainties and variability that lie behind them.

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Declaration

The research reported in this thesis was conducted at the University of Nottingham, Department of Civil Engineering, Nottingham Transportation Engineering Centre (NTEC), between December 2013 and September 2017.

I declare that the work is my own and has not been submitted for a degree at another university.

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List of Acronyms and Abbreviations

AADT: Annual Average Daily Traffic

asPECT: Asphalt Pavement Embodied Carbon Tool

ALCA: Attributional Life Cycle Assessment

BFS: Blast Furnace Slag

BS: British Standard

BSI: British Standard Institution

BS EN: British Standard European Norm

CBM 3: Cement Bound Material

CO_2: Carbone Dioxide

CO_2-e: Equivalent Carbon Dioxide

CLCA: Consequential Life Cycle Assessment

COPERT 4: COmputer Programme to calculate Emissions from Road Transport

CRS: Composite asphalt Reinforcement System

DBC: Dense Binder Course

D-C model: Demand-Capacity Model

Defra: Department of Environment, Food and Rural Affairs

DfT: (UK) Department for Transport

ECRPD: Energy Conservation in Road Pavement Design, Maintenance and Utilisation

EEA: European Environmental Agency

EF: Emission Factors

ELCD: European Reference Life Cycle Database

EOL: End of Life

EnvPro: Environmental Program

EPA (U.S.) Environmental Protection Agency

EPD: Environmental Product Declaration

FHWA: Federal Highway Administration

GHG: Greenhouse Gases

GWP: Global Warming Potential

HBEFA: Handbook Emission Factors for Road Transport

HDM-4: Highway Development and Management Model – version 4

HCM: Highway Capacity Manual

HGV: Heavy Good Vehicles

HRA: Hot Rolled Asphalt

IERD: Integration of Energy Usage into Road Design

IPCC: Intergovernmental Panel on Climate Change

IRI: International Roughness Index

ISO: International Organisation for Standardisation

KyUCP: Kentucky User Cost Program

LCA: Life Cycle Assessment

LCAs: Life Cycle Assessment studies

LCCA: Life Cycle Cost Analysis

LCI: Life Cycle Cost Inventory

LCIA: Life Cycle Impact Assessment

M&R: Maintenance and Rehabilitation

MEET: Methodologies for estimating air pollutant emissions from transport

Miriam: Models for rolling resistance In Road Infrastructure Asset Management systems

MPD: Mean Profile Depth

MTD: Mean Texture Depth

MOVES: MOtor Vehicle Emission Simulator

MSOD: Mobile Source Observation Database

NOx: Oxides of nitrogen

NREL: National Renewable Energy Laboratory)

PAS: Public Available Specification

PCR: Product Category Rules

PVI: Pavement Vehicle Interaction

PTV: Planung Transport Verkehr

TM: Traffic Management

TORG: Transport Operations Research Group

TRL: Transport Research Laboratory

TRLHP: Track Road Load Horse Power

TSS: Transport Simulation System

SETAC: Society of Environmental Toxicology and Chemistry

VPS: Vehicle Specific Power

VISSIM: Traffic in Town Simulation

VTI: Swedish National Road and Transport Research Institute

WBCSD: World Business Council for Sustainable Development

VKT: Vehicle Kilometres Travelled

WMA: Warm – mix asphalt

WRI: World Resources Institute

UCPRC: University of California Pavement Research C

List of Publication

- Trupia L, Parry T, Neves L, Lo Presti D (2016) Rolling resistance Contribution To A Road Pavement Life Cycle Carbon Footprint Analysis. The International Journal of Life Cycle Assessment doi:10.1007/s11367-016-1203-9.

- Trupia L, Parry T, Neves L, Lo Presti D. (2017) "Rolling resistance and traffic delay impact on a road pavement life cycle carbon footprint analysis." Pavement Life-Cycle Assessment. CRC Press, 79-88.

- Trupia, L., Parry, T., Neves, L., & Presti, D. L. (2017). Rolling resistance impact on a road pavement life cycle carbon footprint analysis. *Aiit International Congress on Transport Infrastructure and Systems (Tis 2017), Rome, Italy, 10-12 April 2017.*

- Perrotta, F., Trupia, L., Parry, T., Neves, L.."Route level analysis of road pavement surface condition and truck fleet fuel consumption." *Pavement Life-Cycle Assessment*. CRC Press, 2017. 51-57.

List of Figures

List of Tables

1 Introduction

1.1 Background

The road network represents the most valuable asset owned by the public sector in the UK (UK Roads Liaison Group (UKRLG) 2013) and is a key component in the transportation infrastructure, contributing to economic and social development of a country. At the same time, the road transport sector represents a critical component requiring big investments for its maintenance and management and produces a significant environmental impact. In 2014, the UK total Greenhouse Gases (GHG) emissions from transport were 116.9 Mt carbon dioxide equivalent (CO_2e) , accounting for 23% of the total UK GHG and road transport was the major source of emissions in this sector (UK Department of Energy & Climate Change 2015).

Traditionally, to reduce the environmental impact of road transport infrastructure, the focus of governmental policy was on vehicle operation impacts, as vehicle fuel consumption and tailpipe emissions, are considered much more relevant than the roadway infrastructure. More recent research has proved that the potential benefits coming from an appropriate and optimized management of the roadway infrastructure (construction, operation and maintenance) on energy use and emissions are not negligible, when compared with vehicle operation impacts (Chester and Horvath 2009). Therefore, the pavement network itself represents an opportunity for governmental policy and strategies to achieve a significant reduction of the environmental impact due to the road transport (Santero et al. 2011c).

This is the reason why sustainable pavement management is a growing area of research, nowadays. Consideration of the environmental impacts of pavements has been introduced into pavement management decision making processes, through the use of the systematic and standardized approach of Life Cycle Assessment (LCA) (Wayman et al. 2014).

The main aim of this approach is to assess a product or service throughout its entire life, “from cradle to grave”, valuing direct and indirect impacts. For pavements, a typical life cycle includes material production, construction, use, maintenance and rehabilitation (M&R), and end of life (EOL) phases (Wang et al. 2014a).

In the road transport sector this approach is promising because it offers a comprehensive methodology to estimate the impacts of infrastructure and operations on the environment and then assist highway authorities, companies and government institutions in evidence-based decision ‑ making (Muench et al. 2014). Over the last years, the LCA approach has begun to permeate into the planning, construction, operation, and maintenance processes in highway asset management (Matute et al. 2014).

However, the complete introduction of this approach in the asset management decision making process is not possible yet, due to an incomplete understanding and uncertainty regarding the impact of some relevant phases and components of a road pavement LCA.

Among them, the traffic delay due to the work zone - during construction or maintenance activities - and the rolling resistance impact – during the use phase - are areas where the supporting science is incomplete or is ineffectively incorporated into a globally accepted pavement LCA framework (Santero et al. 2011b).

This lack of information does not allow currently to compare different structures adequately, but above all, to understand the actual environmental impact of a pavement and possible ways to reduce it. In addition, several studies have shown that these generally omitted phases and components can have a significant environmental impact and the magnitude of an individual component varies based on its contextual details, such as pavement location, structure, and traffic volumes (Santero and Horvath 2009).

Despite some more recent efforts to implement these components into pavement LCA framework and improve the approaches to model the correlation between them and the road pavement, there is still a high level of uncertainty related to methodological choices.

Specifically, for the rolling resistance, the main concern is about the lack of validated and accurate models to correlate the pavement surface properties with the rolling resistance and the fuel consumption. Moreover, some input parameters, such as the traffic growth during the use phase, the vehicle EF/fuel efficiency improvement and the pavement deterioration rate, required to run the models, are a source of high uncertainty.

Rolling resistance is one of the forces resisting vehicle movement partly due to the energy loss associated with the pavement-vehicle interaction (PVI), due to the physical interaction between pavement and tyre. Much of the rolling resistance can be tracked to tyre properties, but it is also affected by other parameters related to the characteristics of the pavement, such as the pavement surface properties. The impact of these on rolling resistance has been an area of study for many years because of its effect on vehicle fuel consumption and emissions and the opportunity to reduce them with conventional maintenance strategies.

The pavement surface properties that affect rolling resistance include roughness and macrotexture, usually represented by parameters International Roughness Index (IRI) and mean profile depth (MPD) or mean texture depth (MTD) (Sandberg et al. 2011a). Calculating the impact of pavement surface properties on the rolling resistance and then on vehicle fuel consumption is complex, although over the last years, some studies have been performed to estimate the emissions related to these components (Hammarström et al. 2012; Wang et al. 2014a; Wang et al. 2012a). However, the different rolling resistance models and the incomplete knowledge related to the influence of specific variables and assumptions on the results, generates a high level of uncertainty in their interpretation.

In the UK, not only are there no significant studies involving national case studies on the impact of the rolling resistance on the LCA of a pavement, but there are is also a lack of general pavement deterioration models able to predict the change of unevenness and texture depth over time (deterioration rate of IRI and MPD). The change in these parameters may be different for each lane, since it depends on the traffic volume and type, on the surfacing type and on the regional climate. While some empirical models to describe the deterioration rate of IRI and MPD have been developed (Lu et al. 2009; Tseng 2012), these models are calibrated for specific areas and maintenance treatments and are not applicable to each case study (in these models, the value of MPD tends to increase over time, which is not typical in the UK, where MPD may decrease over time). The impact of this input parameter on the results, along with the others, need to be understood before using any model.

The presence of work zone, resulting from lane and road closures and detour during construction and maintenance events, affects traffic flow by producing a delayed traffic, a congestion impact on the road network and an overall increase of the vehicle fuel consumption. To analyse the impact of this component during the life cycle of a pavement, it is necessary to resort to traffic modelling principles. If the introduction of the work zone traffic delay in pavement LCA research is quite recent, traffic modelling is a developed science that uses known mathematical principles. In order to introduce this component in the system boundary of pavement LCAs with confidence, it is necessary to assess how it has been implemented so far in these studies. Methods of modelling of traffic in the work zone and input variables may raise some concerns about the reliability and the accuracy of the results obtained. There are, indeed, a number of traffic models with specific features and level of sophistication, requiring different levels of detail in input data, working with diverse mathematical models and providing different types of results. The selection of the most appropriate model to obtain reliable and accurate results, based on the resources available and on the aim of the study, is a basic requirement for each traffic modeller. Moreover, these models require the estimation of input parameters and methodological choices, such as - the traffic volume assigned, the vehicle emission model selected, the TM layout and the network boundary expansion assessed – that may impact the results significantly.

All these issues produce a high level of uncertainty concerning the introduction of rolling resistance and work zone traffic delay components into the LCA approach. In order to introduce pavement LCA results into the decision making process of highway authorities, governmental institutions and companies, it is necessary that methods of modelling and methodological assumptions in LCA and carbon footprint studies are transparent and lead to consistent results.

1.2 Problem statement

Despite some recent efforts to introduce the impact of the work zone traffic delay and the rolling resistance in the system boundary of pavement LCAs, their implementation is still at an early stage, so there remain knowledge gaps and outstanding questions that need to be answered, before introducing this approach in the highway asset management decision making process:

- Under which circumstances are the work zone traffic delay and the rolling resistance impacts relevant in a pavement LCA?
- Which are the “sensitive” input parameters for these two components that may affect the LCA results?
- Does the level of sophistication of a traffic model to evaluate the traffic delay affect the LCA results? How do the choices made by the modeller, in terms of TM layout and network boundary expansions, impact the results? Are traffic volume and EF sensitive parameters?
- Are the rolling resistance models ready for implementation in pavement LCA? Can they be applied in the UK? How do pavement deterioration, traffic growth, fuel efficiency improvement influence the results?
- How can we reduce the uncertainty and increase the accuracy of the outcomes of LCAs, including these two components?

1.2.1 Research methodology, aims and objectives

In this PhD thesis, the influence of the model and the methodological assumptions made to estimate the impact of the work zone during a construction/maintenance event and the PVI rolling resistance in the use phase of a pavement were assessed on two different case studies (see figure 1.1). For both components, different models and approaches available in literature have been used to estimate the GHG related to them and a sensitivity test was performed on specific input parameters and methodological choices.

Specifically, the GHG impact of the traffic delay due to the work zone during maintenance activities was calculated through the use of a macroscopic-analytical approach and a microsimulation model. Finally, the influence of the traffic volume, the EF model, the selected TM strategy and the road network boundary was tested.

To estimate the effect of the pavement surface properties on rolling resistance and on vehicle fuel consumption, two models available in literature have been used: the model developed at the University of California Pavement Research Center (UCPRC, Davis) (Wang et al. 2014a) and the model developed by the Swedish National Road and Transport Research Institute (VTI), within the European Commission project Miriam (Models for rolling resistance In Road Infrastructure Asset Management systems),(Hammarström et al. 2012). Details related to the models are provided in the methodology chapter. Moreover the impact of traffic growth, EF/fuel efficiency improvement and pavement deterioration rate were investigated.

The comparison of the model used and the results of the sensitivity test were used to understand if the current level of knowledge is sufficient to implement these components in a standard pavement LCA framework in the UK. In particular, the sensitivity test provided information about which are the most sensitive input data and how to manage them in order to reduce the level of uncertainty that they generate.

Although this study is focused on the impact of the work zone traffic delay and the rolling resistance, in order to assess the relative environmental impact and the magnitude of these components in the life cycle of a pavement, the other components (material production, transportation, onsite equipment) of the construction and maintenance phase were also taken into account, even if not in detail.

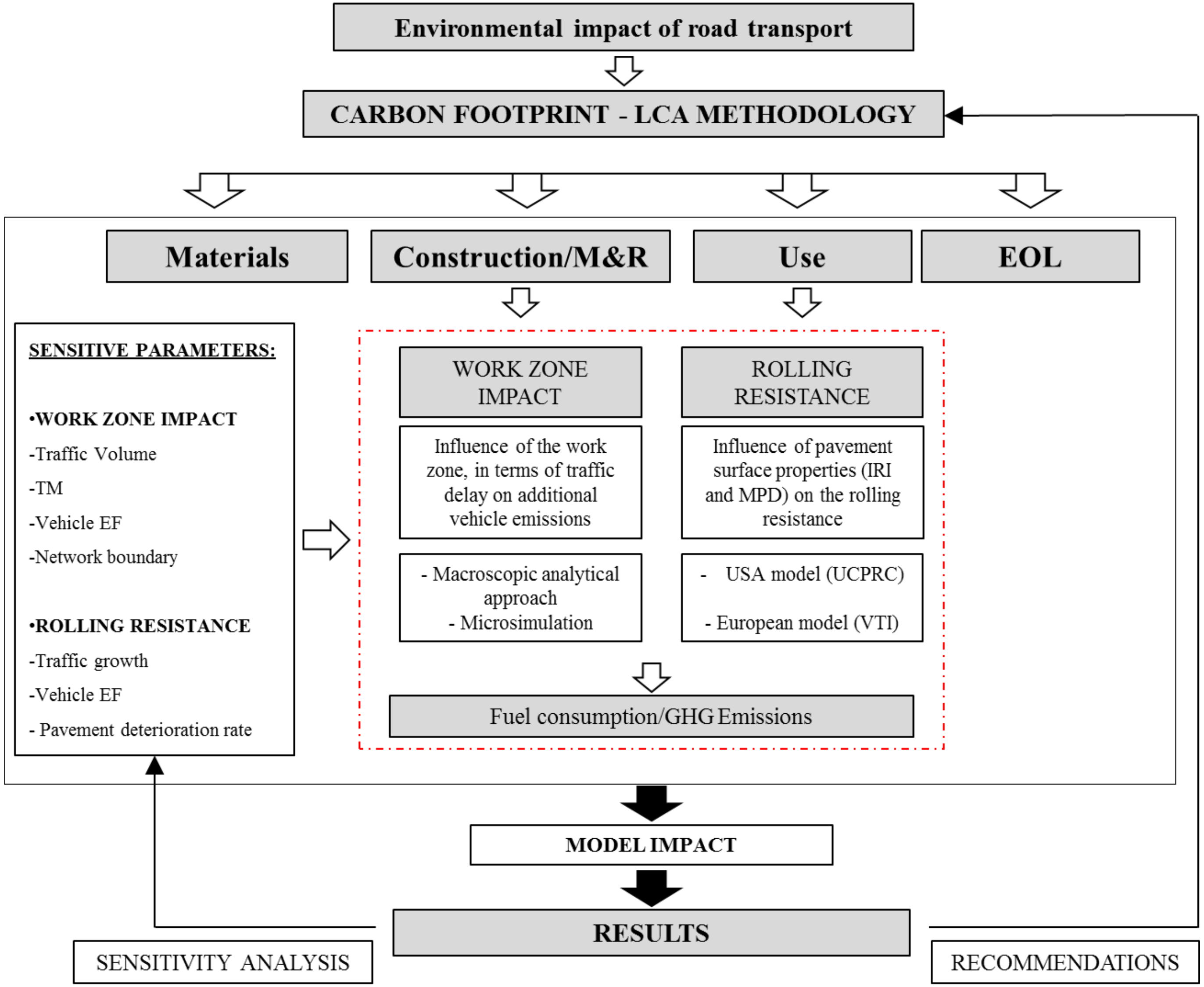


Figure 1.1: Approach used in this research

The main objectives of this work are:

- To add further knowledge in the carbon footprint and LCA fields, investigating the limitations of this approach when applied to a complex system as road pavement engineering.
- To add understanding of construction/maintenance phases - in terms of work zone traffic delay impact - and road pavement use phase - in terms of rolling resistance - by assessing their overall relevance during the life cycle, identifying the range of potential impact and their magnitude, in terms of CO_2-e emissions.
- To investigate the impact of the models used to estimate these components and the level of maturity when implemented in a pavement LCA framework.
- To assess the variables and conditions that make the rolling resistance and the work zone traffic delay components more significant.
- Make recommendations concerning the data and the results provided by an LCA, so that they can be used effectively to assist Highway Authorities in decision making situations.

The methodology used in this work involves:

- Evaluate the CO_2-e during the maintenance phase and the use phase of two road pavement case studies, with special focus on the work zone impact and the rolling resistance influence. The GHG emissions resulting from the traffic delay during M&R treatments were estimated to evaluate the work zone impact. In order to investigate the impact of the rolling resistance in the use phase on CO_2-e emissions, the influence of pavement conditions on the fuel consumption were assessed, in terms of roughness and macrotexture (overall called effective rolling resistance). To evaluate the overall relevance of these two components in the life cycle of a pavement, the other components of the construction and maintenance phases were estimated for both case studies.
- Calculate a pavement carbon footprint by using different models and tools to estimate the impact of the work zone traffic delay and the rolling resistance. The work zone traffic delay impact was calculated using a macroscopic analytical approach and a microsimulation model, characterized by different level of sophistication. The impact of the pavement surface properties on the fuel consumption was estimated through the use of two models developed, respectively, in USA and in Europe, to evaluate how their worldwide implementation in pavement LCA studies affects the results.

- Perform a sensitivity test on the results to assess the potential impact of several input variables and methodological choices. For the work zone traffic delay, the sensitivity test was performed on the traffic volume, the EF model, the selected TM strategy and the network boundary. The impact of the traffic growth, EF/fuel efficiency improvement and pavement deterioration rate was investigated on the rolling resistance results.
- Assess all the results obtained and investigate the sensitivity of pavement LCA results to methodological assumptions and generate recommendations regarding the introduction of these two components in the system boundary of pavement LCA studies.

1.2.2 Impact of the study

This study has added further knowledge to the continuously growing pavement LCA literature regarding the extension of the system boundary to the work zone traffic delay and the rolling resistance components. The analysis developed on the models used and the methodological assumptions to analyse these components have shown limitations and potential issues in the current research. The outcome conclusions and recommendations provided in this research thesis will address future research needs and increase the confidence in the implementations of the maintenance and the use phases in pavement LCA studies.

1.2.3 Structure of the study

The second chapter of this thesis includes a critical review mainly focused on the implementation of the LCA approach in pavement domain. It describes and analyses the main features of the LCA approach when applied to a generic product or service, how it has been used in the pavement field so far and the main outstanding research gaps and questions. The following two chapters describe in detail two main components of the road pavement LCA, which are the focus of this thesis – the work zone traffic delay impact and the rolling resistance. In particular, the third chapter defines the traffic delay in the work-zone during maintenance activities and identifies the elements that characterize this component in pavement LCAs. A review of the main models, approaches and tools available in literature is presented. The last two sections describe the implementation of the work zone traffic delay in pavement LCAs and the parameters affecting it.

The fourth chapter defines the rolling resistance and identifies the main components and mechanisms related to this force. It also includes a review of the main studies relating the impact of the pavement surface properties on the rolling resistance and, in turn, on the vehicle fuel consumption and emissions. Finally, it describes the implementation of this component in pavement LCAs and the parameters affecting it.

Chapter 5 and 6 are focused on the methodology developed in this research to pursue the aims and objectives stated in the previous chapter, and the results obtained, implementing this approach. These two chapters are split into sections, one related the work zone traffic delay impact and one related the rolling resistance impact. They describe models used and sensitivity parameters tested and the results obtained.

Chapter 7 discusses the implications and impact of the results obtained in this study, in the context of the literature review and the methodology adopted. It describes how the study has met the research aims and objectives and filled some relevant research gaps.

Finally, the last part identifies future research needs in this research area and provides recommendations to pavement LCA practioners to introduce the work zone traffic delay and the rolling resistance impact in pavement LCAs.

Additional information and detailed calculations are provided in the appendixes and in the supplementary material, attached to this thesis:

- **Appendix A**

OD matrix flows for different network boundary extensions;

- **Appendix B**

Aimsun calculation for the A1(M) case study;

- **Appendix C**

HCM calculations:

- A17: example of calculation procedure for the Base case scenario, approach 1 (see Figure 5.10) during phase 1 of works.
- A1(M): example of calculation procedure for the Base case scenario.

- **Appendix D**

Coefficients of tailpipe CO_2 emission factors combination of factorial variables, adopted for the A17 and the A1 (M) case studies, from Wang et al. (2014a).

- Supplementary material 1. and 2.

Excel spreadsheets including detailed calculations performed with the UCPRC and VTI models for the A1(M) case study.

2 Literature review: LCA and its application to road pavement structures

This chapter includes a critical review related to the implementation of the LCA approach to road pavements. The main aim is to identify the outstanding questions and knowledge gaps in this topic. After a brief introduction, the LCA approach is described in section 2.2, in terms of standard and framework. Section 2.3 looks at the implementation of LCA and carbon footprint into road pavement structures.

The next Chapters 3 and 4 describe in detail two components of the road pavement LCA – the work zone traffic delay impact and the rolling resistance and the related issues.

2.1 Introduction

Life Cycle Assessment (LCA) is a technique developed to assess, understand and quantify the environmental impact of a generic product or service, providing an important support in different sectors of the industry. To this end, LCA has been increasingly applied in recent years to analyse the emissions of GHGs and other substances of environmental concern, associated with road pavements. In particular, the growing number of pavement LCAs available in the literature in the last years underlines the increased awareness and the interest in improving the sustainability of this critical infrastructure system (Santero et al. 2011b).

This part of the report has the purpose of analysing and summarizing the existing literature in the following areas:

- Life Cycle Assessment. This part is focused on the description of the main elements that characterize this analysis methodology. Starting from the current standards and specifications, the methodological framework of an LCA will be described, with special regard to the specific impact category, called Global Warming Potential (GWP) (carbon footprint).

- Pavement LCA. In this part, a review of the current pavement LCA literature will be presented, with special regard to the framework for quantifying the environmental impact of a pavement. This is followed by a look into pavement LCA research gaps.

2.2 LCA and Carbon Footprint

LCA is a standardized method to assess the environmental impact of a product or activity over its entire life cycle, “from cradle to grave”. It provides a holistic approach that considers all the stages of a product’s life interdependently.

Currently, the most widely accepted definition of LCA - provided by the International Organization for Standardization (ISO) – is: "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle".

Figure 2.1 shows a generic product ’life cycle’, including raw material extraction, production, use, recycling and/or landfill, and transport phases. All these activities generate an environmental impact due to the consumption of resources and the production of emissions (Rebitzer et al. 2004).

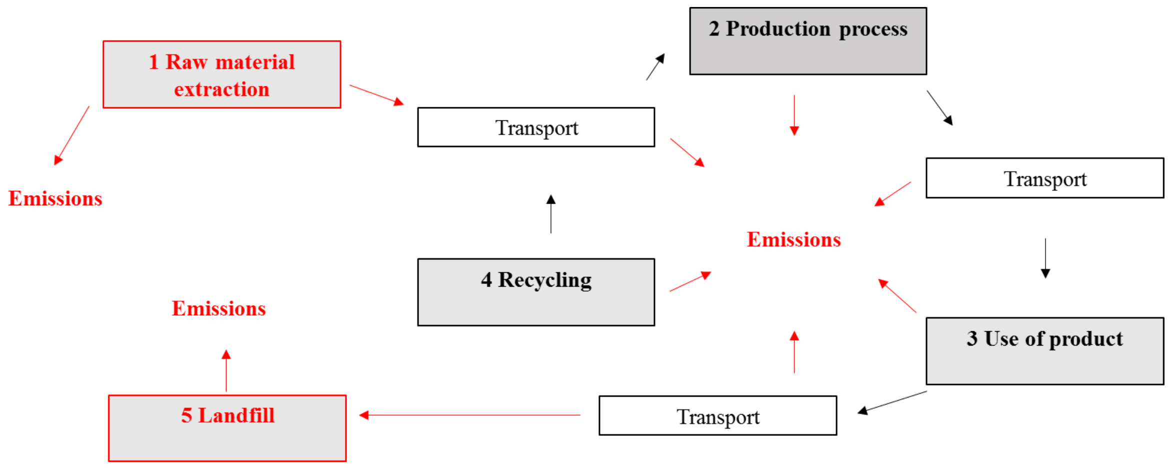


Figure 2.1: Schematic representation of a generic life cycle of a product, adapted from Carlson et al.(2003)

LCA is applied by several governmental and non-governmental organizations and industries, in a wide range of applications and sectors to improve the environmental performance of a product or service through their life cycles. The earliest application of this approach involved the improvement of a specific product system - original product-based scope - to support corporate internal decision-making (eco-design of products, process optimizations, supply – chain management and marketing and strategic decisions) (Hellweg and Canals 2014). Currently, the applications of LCA have a wider scope. Across sectors of interest, product development and improvement, strategic planning, public policy making and marketing, (Rebitzer et al. 2004) represent the most significant.

To assess the environmental impact of a product or service, all inventoried inputs and outputs are linked to their environmental consequences, using some category indicators. One of the most assessed in LCAs is the GWP and the assessment of it, as the only environmental indicator in an LCA, is often called 'carbon footprint'. Therefore, the carbon footprint is an integral component of a LCA study, which analysis is restricted to the estimation of the GHG emissions over the lifecycle of a product or service. Whereas LCA analyses a range of environmental impacts associated with a product, a carbon footprint covers just the measurement of emissions and total removals of climate-altering gases and resulting GWP.

The main benefit coming from the use of the carbon footprint compared to a full LCA approach is the ability of communication and understanding by the public, and the direct link to one of the environmental priorities commonly considered and addressed by governmental environmental policies across the world (TREE 2017). In this PhD thesis, a carbon footprint analysis was carried out and only the GHG emissions were considered.

2.2.1 LCA and Carbon Footprint specification

It is not simple to identify when and where the first LCAs where performed. Currently, it is widely recognized that the first partial contributions - focused on energy and resources - to LCAs dates back between the early 1960s and the late 1970s and were performed both in America and in Europe (Jensen et al. 1998).

The period between the 1970 and 1990 can be defined as the period of the "conception" of LCA (Guinee et al. 2010), since diverging approaches, methodologies and terminology were used, without taking into account a common and comparable theoretical framework. LCAs performed by different practioners resulted in different and sometimes conflicting conclusions, even if the object of the study was the same (Russell et al. 2005). Under these conditions, the LCA approach could not become an overall and worldwide accepted and used analytical tool.

The period between 1990-2000 is associated to a process of "standardization" (Guinee et al. 2010), where a number of initiatives, studies and worldwide activities were undertaken to harmonise LCAs. In 1990, the Society of Environmental Toxicology and Chemistry

(SETAC) organization started to play a key leading role, coordinating the activities of LCA practioners and scientist to harmonise the LCA procedure. The main outcome of this process was the SETAC Code of practice (Consoli et al. 1993), a document describing a procedural standardized framework for LCA.

In the late 1990s the ISO published two standards to harmonize methods and procedures (International Organization for Standardization (ISO) 2006a; International Organization for Standardization (ISO) 2006b). These standards represent the state of the art of the LCA methodology and are generally accepted and followed by the LCA practitioners and scientists. In particular, if the ISO14040 provides a clear overview of the practice, applications and limitations of LCA, ISO 14044, instead, is designed to allow practioners to perform an LCA. This period (late 1990s) is particularly relevant for the development and the success of the LCA, which became a focus of policy document and legislation aimed to reduce the environmental impact. During this period, in fact, the discussion related to consequential and attributional LCA (CLCA and ALCA) and allocation methods (Ekvall 1999) (Brander et al. 2009; Nicholson et al. 2009) (see section 2.2.2 for further information on CLCA, ALCA and allocation methods) has produced an increase of the level of sophistication of this methodology.

From 2000 the application of LCA and carbon footprint has strongly increased in European policies and strategic applications, and the combined effect of LCA, with life cycle costing (LCC) and social life cycle assessment (SLCA) has been investigated (Kloepffer 2008). At the same time, several life cycle based carbon footprint policies were produced:

- Publicly Available Specification (PAS 2050) has been developed and published by the British Standards Institution (BSI) in 2008 (BSI 2008) and revised in 2011 (BSI 2011) .
- The GHG Protocol product standard has been developed by a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The GHG Protocol product standard has been published in 2011 (WRI 2011).
- ISO/TS 14067 specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product (CFP). It is based on International Standards on life cycle assessment (ISO 14040 and 14044) for quantification and on environmental labels and declarations (ISO 14020, 14024 and 14025) for communication.

- ISO 14064 (parts 1 and 2), an international standard for determination of boundaries, quantification of GHG emissions, and removal.

A detailed comparison between these methods and approaches can be found in Garcia and Freire (2014).

LCA has developed fast over the last years and this reflects the growing interest in environmental issues from not only the academic sector and the raising awareness of the need to use a worldwide accepted methodology, reducing the associated limitations.

2.2.2 LCA framework

As already mentioned, the ISO 14040 series of standards provide a generalized methodology, accepted worldwide and adopted as British Standard. According to this standard, an LCA consists of four iteratively related phases (see figure 2.2). The four phases should be carried out in this order, but, since it is an iterative process, every phase can be reassessed later, based on interpretation of the obtained results.

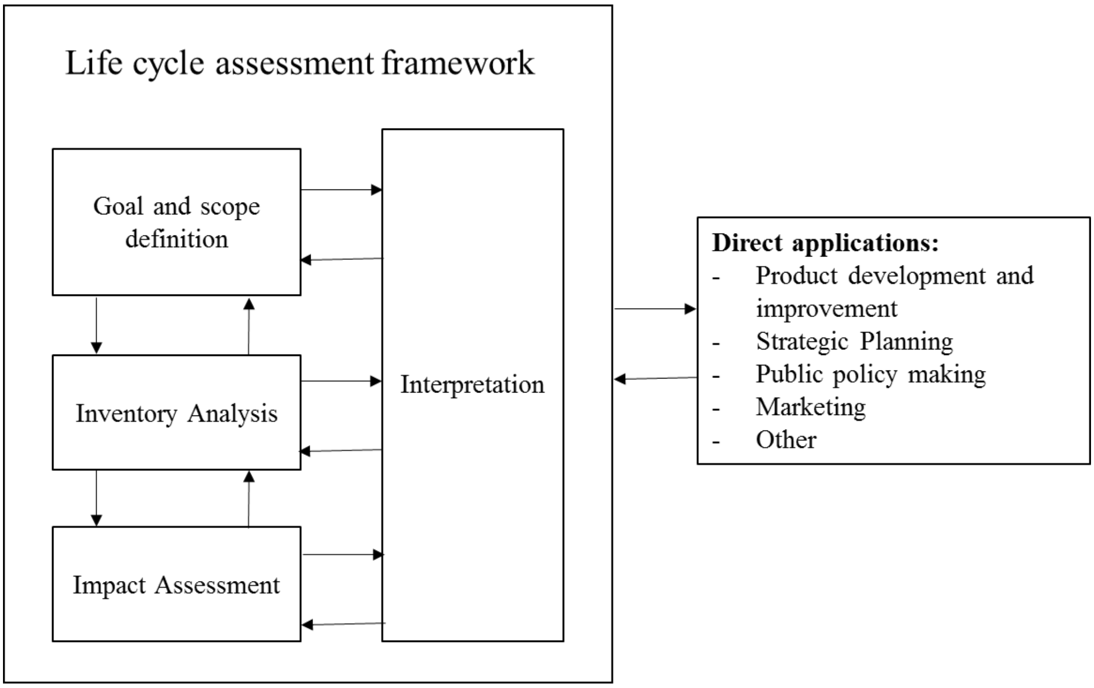


Figure 2.2: Stages of an LCA, adapted from International Organization for Standardization (ISO) (2006a)

The goal and scope definition phase provides a description of the product system, in terms of system boundary and functional unit, and defines the reasons for carrying out the LCA, the intended audience, geographic and temporal considerations, impact assessment, and interpretation methods.

This is a complex and critical phase, due to the strong influence that it has on the LCA result (Jensen et al. 1998), but sometimes underestimated. Such underestimation can make the study more complex and time-consuming, especially if the data collected – based on the choices made in this phase - proves to be inadequate for achieving the goal of the study and the data must consequently be collected again. A proper plan during goal and scope definition phase can avoid these complications (Klüppel 1997). Rebitzer et al. (2004) underline the importance of choices and assumption made during system modelling, especially for the definition of the system boundary, since they can heavily influence the final results of the study.

The life cycle inventory analysis phase (LCI) is an inventory of input/output data of the system being studied, done by quantifying life-cycle energy use, emissions, and land and water use for technology use in each life cycle stage. It involves collection and calculation of the data necessary to meet the goals of the defined study and it is the most time-consuming phase of a LCA. Figure 2.3 shows and underlines that LCA methodology is an iterative process, as LCI inventory phase can require a redefinition of the system boundary, established in the previous phase.

In order to simplify this complex LCA phase, through several publicly funded and industry initiatives, a number of database have been developed, over the last years, including national or regional databases, industry databases and consultants databases, often in combination with software tools (Finnveden et al. 2009). Among them, Ecoinvent, created by the Ecoinvent Centre, U.S. LCI, developed by National Renewable Energy Laboratory (NREL) and its partners and European Reference Life Cycle Database (ELCD). Further information about LCI database and software tools for modelling subsystems and unit process, can be found in Finnveden et al. (2009) and Rebitzer et al. (2004).

As stated above, the LCI phase is strongly affected by the decisions made in the scope definition phase, including the life cycle inventory modelling principles and method approaches that are to be applied in the modelling of the system; allocation or system expansion/substitution approaches and attributional or consequential modelling (Handbook, I. L. C. D 2010).

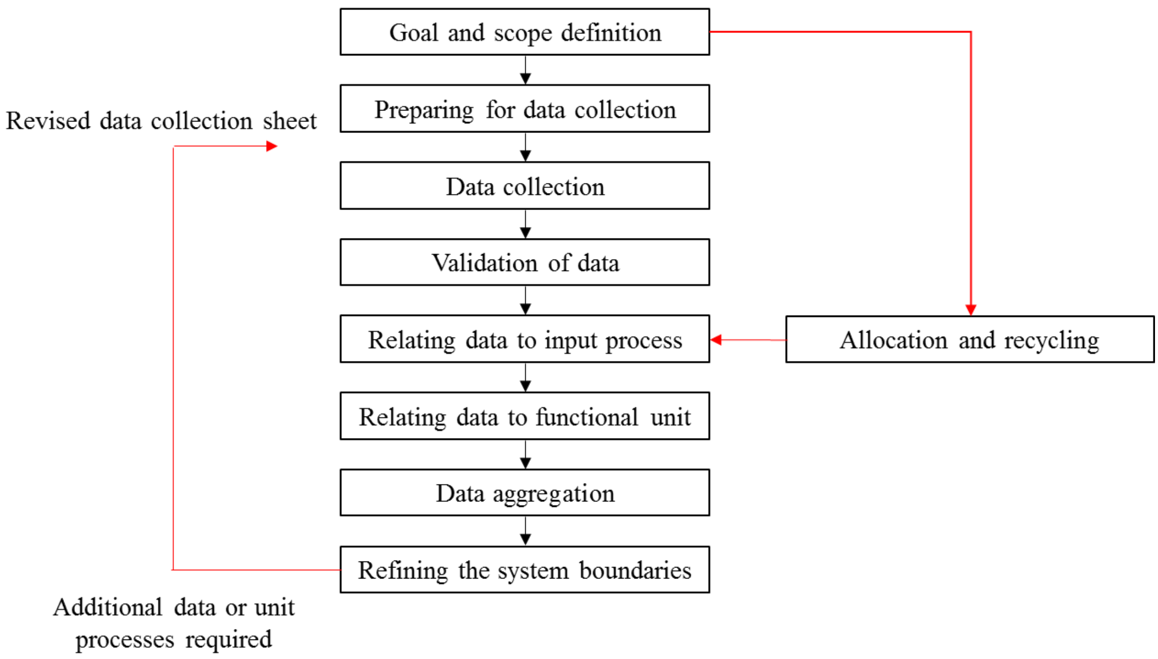


Figure 2.3: Inventory analysis, adapted from Carlson et al. (2003)

The allocation of emissions/burdens between processes with shared inputs/output is one of the most controversial issues of LCA since its conception (Rebitzer et al. 2004) . There are two types of allocation problems, multifunction process and open-loop recycling. A multifunction process is "*an activity that fulfils more than one function*" (Ekvall and Finnveden 2001). This happens when several co-product are produced from a single process in a system (multi-Output process) or when a specific input to a single process in the system results from a process that produces several co-products (multi-Input process) (Gaudreault, 2012). In this case the problem is to define the amount of the environmental burdens of the activity that should be allocated to each of the resulting products. A typical example of a multifunctional process requiring allocation is oil refining, where a wide range of products are generated from a single process.

An open - loop process is associated with a material from a product system which is recycled back into another product system (Carlson et al. 2003). In this case, it is necessary to establish where to allocate the environmental impacts of the products that have been recycled.

These two allocation problems have several aspects in common, however different approaches should be used for them (Ekvall and Finnveden 2001). In multifunction processes, different strategies can be adopted to solve a co-product allocation. The ISO standard requires the following stepwise procedure is used in co-product allocation (International Organization for Standardization (ISO) 2006b):

1) Wherever possible, avoid allocation through:
    a. Unit process subdivision into sub-processes and collection of input and output data for each sub-process;
    b. Unit process expansion to include the additional functions related to the co-products;
2) Partition using an underlying physical relationship between the environmental burdens and the functions;
3) Partition using another relationship, for example, based to the economic value of the products.

For open-loop recycling process allocation, the ISO Standard states that the same stepwise approach can be used, even if it considers further options: if during the recycling process, the material does not undergo changes in inherent properties, the allocation may be avoided, considering the environmental burdens as if the material was recycled back into the same product. Otherwise, the allocation may be based, in order of preference, on physical properties, economic value, or the number of subsequent uses of the recycled material"(Ekvall and Finnveden 2001). Gaudreault (2012) describes and discusses several approaches and methods specifically mentioned in the ISO standards as well as other methods that have been applied in the literature for pulp and paper case studies, for open-loop recycling process allocation (see table 2.1). The author recommends that the allocation methodology selected needs to take into account the goal of the study, the available data and information, and the type of shared process to be allocated. Further information on these approaches can be found in the reference.

The issue related the distinction between ALCA and CLCA raised in the process of discussing the methodological debates related the allocation of co-product. The two topics are, therefore, strongly correlated (Thomassen et al. 2008). If the ISO 14044 standard does not provide any recommendations to link the type of allocation with the objective of the study, several researchers have been making this distinction, based on the study objective: 1) LCA studies which allocate environmental loads to a specific product system; 2) LCA studies which assess the environmental consequences of a change in the product system. The distinction between ALCA and CLCA was originally made at an international workshop on electricity data in 2001 (Ekvall 1999; Ekvall et al. 2016) and has changed over time.

Table 2.1: Recycling Allocation Methods discussed in Gaudreault (2012)

Allocation approach	**Method Name**	**Description**
Avoid allocation through system subdivision	N/A	Separation of the multifunction process into sub-processes, and collection of separate data for each sub-process.
Avoid allocation by applying a closed-loop procedure	Closed-loop procedure	A closed-loop allocation procedure can be applied to open-loop product systems where no changes occur in the inherent properties of the recycled material. The approach assumes that recovered material leaving the system boundary of the investigated product will replace virgin material in subsequent product systems. In this case, the material losses are not allocated to the product system that produces them but rather to the product system that has an outflow of recovered material.
Avoid allocation through system expansion	Direct system enlargement	Direct system enlargement refers to the system expansion, described in ISO 14044 (ISO 2006b), and involves changing the objective of the study and the system boundary to include the co-products or their functions.
	Substitution: credit for end-of life recycling	A recycling process provides two different functions: waste management for the upstream product system and secondary raw material production for the downstream product system. The credit for end-of-life recycling method consists of including the recycling processes within the boundary of the system supplying the recovered material and crediting the system by subtracting an alternate material production process.
	Substitution: credit for use of recovered material	The credit for use of recovered material consists of including the recycling processes in the system boundary of the product using the recovered material and crediting the product system by subtracting an avoided waste management process.
	Substitution: Ekvall	This method can be used both for open-loop recycling allocation situations or when recovered/recycled material is used in the studied product system. It consists in the expansion of the system boundary to include (by addition or subtraction) the unit processes that are directly affected by the inflows and outflows of recovered material.
Partitioning using underlying physical relationship	N/A	According to ISO standards, the partioning methods used for co-product allocation can be applied also to recycling process, if it is not possible to avoid allocation. The ISO hierarchy involves: - allocation based on underlying physical relationships, which represent the way in which the environmental loads are changed by quantitative changes in the products or functions delivered by the product system.
Partitioning using other relationships	Physical properties (i.e. mass)	
	Economic value	

Allocation approach	Method Name	Description
	Number of USES (NOU)	- allocation based on physical properties, economic value and on the number of subsequent uses of the recovered material (these three options are not based on underlying physical relationship).
Other methods not mentioned in ISO 14044 or ISO 14049	Cut-off	It consist in splitting the material life cycle into the different product systems by applying an arbitrary definitive allocation between them.
	Extraction – load	In this method, both virgin material production and waste management processes are allocated to the product system that is using the virgin material.
	50/50	In the 50/50 method, the recycling processes are allocated 50% upstream and 50% downstream: 50% of the environmental load of virgin material production and final waste management to the product using the virgin material, and the remaining 50% to any products not further recycled.
	Others	Other methods have been proposed, but they have very few applications in literature.

The two types of LCA answer different questions. The ALCA takes into account the flows in the environment in a specific range of time. Instead the CLCA evaluates how a specific decision could affect – in a positive or negative way – the flows (Brander et al. 2009).

Therefore, an ALCA is focused on the description of the environmentally relevant physical flows to and from a product, a process or a service. An example of an ALCA is describing the impacts attributable to a generic product by collecting data on existing life-cycle systems for it. A CLCA assesses how relevant environmental physical flows and emissions can change as results of a decision or a proposed change in a system under study, which means that market and economic implications of a decision may have to be taken into consideration. For instance, in a biofuels CLCA, one might consider how changes to land use for biofuels affect regional and global food supply systems.

As mentioned above, these two approaches affect the LCI inventory phase. ALCA tends to use average data and includes in the system boundary only processes and material flows directly used in the process. By contrast, CLCA uses marginal data representing the effects of a small change in the output of a product and takes into account also material flows indirectly affected by a marginal change in the output of the product. Moreover, the choice of the type of LCA to perform affect the allocation of environmental impacts to co-products. If in ALCA allocation, co-product allocation is the most frequently used approach, for CLCA, avoiding allocation by system expansion is the only option available since it reflects the consequences of a change in production (Weidema 2003). According to (Brander et al. 2009), the results obtained performing a ALCA are subject to a lower uncertainty, as the relationship between input and output are usually stoichiometric. On the other hand, CLCA is usually based on models that try to represent complex systems, involving random elements.

The life cycle impact assessment phase (LCIA) can be defined as a correlation between all inventoried input and output and their environmental consequences. They provide additional information to help assess a product system's LCI results.

It consists of several mandatory steps:

- Selection of impact categories (e.g. acidification, terrestrial toxicity, climate change, eutrophication, resource depletion), category indicators and characterisation models. An impact category can be defined as "*class representing environmental issues of concern to which life cycle inventory analysis results may be assigned*" (International Organization for Standardization (ISO) 2006b). These categories represent environmental impacts on different levels, describing effects on nature like acidification, eutrophication, global warming, ozone depletion etc. (mid-point effects) or the consequences these effect will have, like biodiversity (end-point effects). Table 2.2 shows some of the more commonly used impact categories, the scale of impact and some potential characterization factors, used to describe them.
- Classification: assignment of the LCI results to impact categories;
- Characterization: calculation of category indicator results, multiplying the LCI results by the conversion factors.

There are also some optional elements: normalisation (different characterised impact scores are related to a common reference), grouping and weighting (performing a ranking of the different impact categories reflecting the relative importance of the impact considered in the study).

Table 2.2: Commonly Used Life Cycle Impact Categories, adapted from Curran (2006)

Impact Category	Scale	Example of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrous oxide (N_2O) Methane (CH_4) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to CO_2 e.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydreochloric Acid (HCL) Hydrofluoric (HF) Ammonia (NH_4)	Acidification Potential	Convert LCI data to hydrogen (H+) ion equivalent.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Convert LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic Chemicals with a reports lethal concentration to rodents	LC_{50}	Converts LCI data to equivalents: uses multimedia modelling exposure pathways
Aquatic toxicity	Local	Toxic chemical with a reported lethal concentration to fish	LC_{50}	Converts LCI data to equivalents: uses multimedia modelling exposure pathways
Human Health	Global Regional Local	Total release to air, water and soil	LC_{50}	Converts LC_{50} data to equivalents: uses multimedia modelling exposure pathways

Impact Category	Scale	Example of LCI Data (i.e. classification)	Common Possible Characterization Factor	Description Characterization Factor
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Remove Depletion Potential	Converts LCI data to a ration of quantities of resources used versus quantity of resources left in reserve.
Land Use	Global Regional Local	Quantity disposed in a landfill or other land modifications	Land availability	Converts mass of solid waste into volume using an estimated density.
Water Use	Regional Local	Water used or consumed	Water Shortage Potential	Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.

Life cycle interpretation summarizes and discusses the results of LCI or an LCIA, or both, as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition. As described in (International Organization for Standardization (ISO) 2006b), the main elements of this phase are:

– identification of the significant issues based on the results of the LCI and LCIA phases of LCA;

– an evaluation that considers completeness, sensitivity and consistency checks;

– conclusions, limitations, and recommendations.

2.2.3 LCA uncertainty and sensitivity Analysis

Sensitivity and uncertainty analyses have been identified as relevant and appropriate tools to enhance the understanding of the model's structure and ensure reliability and consistency of the LCA results, reducing the uncertainty and variability that affect this methodology (Lacirignola et al. 2017). Their implementation in LCAs is suggested in the ISO standard and SETAC code of practice (Fava 1994), but without any recommendations, and several more recent studies have introduced elements to enhance their application. However, uncertainty and variability analysis are still not a common practice in LCAs.

Although, usually uncertainty is used to consider both uncertainty and variability, they refer to different issues (Heijungs and Huijbregts 2004). Uncertainty is related to the lack of knowledge due to inaccurate measurements, unavailability of data, model assumptions, etc. Variability is a natural variation of data that cannot be reduced with further measurements. They are usually associated in LCAs, because the approaches used to address the two issues have several common elements (Heijungs and Huijbregts 2004).

Several classifications of types of uncertainty have been proposed in literature (US EPA 1989; Bedford and Cooke 2001; Bevington and Robinson 2003; Funtowicz and Ravetz 1990; Huijbregts 2002; Morgan et al. 1992). One of the most comprehensive classification was provided by Huijbregts (1998) that identified several types of uncertainty that may occur in specific LCAs (see table 2.3). The criteria used to classify the uncertainty should not be a main concern for LCA practioners. By contrast, the tools used to address uncertainty issues are relevant to provide reliability to LCA results (Heijungs and Huijbregts 2004). In this respect, Huijbregts (1998) identifies several available tools to deal with different types of uncertainty and variability (see table 2.4). Reap et al. (2008) identify two main classes of techniques to estimate the effect of uncertainty:

- uncertainty analysis that models the uncertainties in the input parameters and propagates them to the results;
- sensitivity analysis that assesses the effect of changing inputs on LCA results.

If the first one may be relevant in comparative LCAs, the second one allows to estimate "sensitive" input parameters whose uncertainty has yet to be or cannot be quantified. When the uncertainty of a parameter can be expressed as a statistical function, the analysis is usually carried out by calculating the uncertainty of each parameter, expressing this as an uncertainty distribution and then propagating it through models to the final outcome (Bjorklund, 2002). So far, the introduction of uncertainty analysis has been limited to academic studies (Heijungs and Huijbregts 2004). This is because the evaluation of the uncertainty in LCA studies is made critical by several methodological issues, which can be divided into four categories: the modelling of uncertainty; the incorporation of multiple uncertainties; the completeness of analysis; and the cost of analysis (Reap et al. 2008).

Modelling of uncertainties is a problem because there are multiple methodologies to assess uncertainty and the mathematical representation of a specific uncertainty is not straightforward, since there is not a universal mathematical formalism (Ross and Cheah 2016). Several methodologies have been implemented in literature, namely, stochastic processes, interval analysis, fuzzy numbers and Bayesian statistics. Some of these techniques may provide unreliable output and overconfidence in results (Lloyd and Ries 2007), however, according to Ross and Cheah (2016), the stochastic modelling is effective in assessing uncertainty in LCA results. Recently, several studies (Mattinen et al. 2015; Noshadravan et al. 2013; Weber 2012) have implemented Monte Carlo analysis for stochastic modelling, showing that, with the availability of sufficient data, stochastic models are the most relevant for estimating uncertainty in LCA.

Another relevant issue, according to some studies (Bojacá and Schrevens 2010; Heijungs 2010), is the correlation between input variables when an uncertainty analysis is performed. If all the parameters can be described through a probabilistic distribution, as mentioned above, the incorporation of multiple uncertainties is relatively simple. However, usually, it does not happen and the combination of uncertainties may produce further uncertainty.

Finally, completeness of uncertainty analysis in all stage of an LCA and the cost of the analysis represent two significant issues with evaluating uncertainty in LCA studies. The process requires, in fact, high time and cost consuming elements, namely computing power, significant data collection and statistical analysis and high level of expertise.

Sensitivity analysis is a tool to address specific types of uncertainty. Sensitivity represents the impact that one parameter has on the value of another and a sensitive parameter is a variable in which a change significantly affects the output results, or that contributes to the variance of them. The implementation of this analysis in LCAs provides a support to identify “sensitive” and “non –sensitive” parameters that should be known and understood accurately before drawing conclusions (Groen et al. 2014). _In order to perform a sensitivity analysis, several methodologies can be implemented, such as, tornado diagrams, one-way sensitivity analysis, scenario analysis, factorial design and multivariate analysis, ration sensitivity analysis, critical error factor (Bjorklund 2002).

The combination of sensitivity and uncertainty analysis was explored in De Koning et al. (2009) that analysed the impact of different uncertainty and sensitivity choices on carbon footprint results. They concluded that, in order to compare different products or services, the same assumptions need to be considered.

In this thesis, the impact of the models used and of specific parameters was tested, by performing a sensitivity test on the carbon footprint results. The outcome from a sensitivity analysis can be used by researchers and policy makers as a guidance in the selection of appropriate methods for pavement LCA and carbon footprint and concentrate future research in areas of significant interest.

Table 2.3: Type of uncertainty in LCA and example of sources, adapted from (Huijbregts 1998)

Types	**LCA phases**				
	Goal and scope	**Inventory**	**Choice of impact categories**	**Classification**	**Characterisation**
Data inaccuracy		Inaccurate emission measurements			Uncertainty in life times of substances and relative contribution to impacts
Data gaps		Lack of inventory data			Lack of impact data
Unrepresentative data		Lack of representative inventory data			
Model uncertainty		Static instead of dynamic modelling. Linear instead of non-linear modelling			Static instead of dynamic modelling. Linear instead of non-linear modelling
Uncertainty due to choices	Choice of functional unit, system boundaries	Choice of allocation methods, technology level, marginal/average data	Leaving out known impact categories		Choice of characterisation methods
Spatial variability		Regional differences emission inventories			Regional differences in environmental sensitivity
Temporal variability		Differences in yearly emission inventories			Choice of time horizon. Changes in environmental characteristic over time
Variability between objects/sources		Differences in performance between equivalent processes			Differences in environmental and human characteristic
Epistemological uncertainty	Ignorance about relevant aspects of studied system	Ignorance about modelled processes	Impact categories are not known	Contribution to impact category is not known	Characterisation factors are not known
Mistakes	Any	Any	Any	Any	Any
Estimation of uncertainty		Related to inventory parameters			Related to characterisation parameters

Table 2.4: Tools to address several types of uncertainty, based and adapted from (Huijbregts 1998)

	Data inaccuracy	**Data gaps**	**Unrepresentative data**	**Model Uncertainty**	**Uncertainty due to the choice**	**Spatial variability**	**Temporal variability**	**Variability on objects/sources**	**Epistemological uncertainty**	**Mistakes**	**Estimation of uncertainty**
Standardisation					x					x	
Data bases		x	x								x
Data quality goals	x		x								
Data quality indicators	x		x								
Validation of data										x	
Parameter estimation		x									
Additional measurement	x	x	x					x			
Higher resolution models				x		x	x				
Critical review		x	x		x				x	x	x
Sensitivity analysis	x		x	x	x	x	x	x			
Uncertainty importance analysis	x		x	x	x	x	x	x			
Classical statistical analysis	x					x	x	x			
Bayesian statistical analysis	x					x	x	x			
Interval arithmetic	x										
Vague error intervals	x										
Probabilistic simulation	x							x			
Scenario modelling			x	x	x	x	x	x			
Rules of thumb	x										

2.3 Pavement LCA

Transport infrastructure consists of different components, among which the roadway pavements are the most critical (Santero et al. 2011c). The criticality comes from the complexity of a suitable strategic management of such infrastructure, in order to minimize the environmental impact, which generates costs that the authorities have to support.

In the UK, road infrastructure continues to be one of the largest assets, since the maintenance and expansion of the current network remains a significant part of the construction sector. This increase in construction work should be combined with an increasing interest about the sustainability of current practises (Spray 2014). In order to reduce the environmental impact of the transport infrastructure, governmental policy has historically focused on vehicle fuel consumption and tailpipe emissions, neglecting the potential benefits coming from a suitable management of the roadway infrastructure.

However, the pavement network itself represents an opportunity for significant environmental impact (Santero et al. 2011c), since the impacts of roadway construction, operation and maintenance on energy use and GHG emissions are not unimportant, compared with vehicle operation impacts (Chester and Horvath 2009). Moreover, the impact from pavements pertains to each phase of their life cycle, also extraction and production of pavement materials.

To analyse the environmental impacts from pavement, the LCA approach represents a valid tool, looking at every phase of its life cycle. In the last ten years, this methodology has received a growing interest from academia (Carlson 2011). However, performing a pavement LCA is much more complex than it is for a generic product or service, making its implementation infrequent in pavement asset management. Among the reasons, the uncertainty related to this methodology, the lack of suitable and customisable tools, the lack of specific pavement LCA guidelines and the generalized opinion that environment-friendly solutions have a high initial cost (Santos et al. 2015).

This section is split into two parts. The first part is a review of the main frameworks proposed in the literature for pavement LCA. The second one is a critical review of the current state of the art. It describes the main issues related to pavement LCA and how research is addressing them and, in light of the pavement LCAs performed, it investigates the research gaps.

2.3.1 Pavement LCA system definition

Overall, the ISO 14040 series standards represent commonly accepted guidelines for carrying out pavement LCAs. However, they only provide basic support for conducting comprehensive and transparent LCAs of generic products and services, leaving a considerable degree of freedom for the analysts and decision makers that are performing the study.

Consequently, several efforts have been made to propose solutions for a standardised LCA protocol for pavements. The first step involved the identification of system definitions for elements of pavement LCA to establish the specific phases of a pavement life cycle.

Several schemes have been proposed in the literature. The most relevant are described in this section. Overall, the life cycle of pavement includes the material production, construction, use, maintenance and rehabilitation and end of life phases, but different authors refer to them in different ways.

In Santero and Horvath (2009) and Santero et al. (2011b), the authors identify the following life cycle phases : Material, Construction, Use, Maintenance and End-of-life.

The analysis and the study of the impact of each of them requires the identification of the components that represent the direct processes by which pavement impacts the environment (indirect or upstream components are not represented in the picture) during these phases. In this system, the maintenance phase is linked to the materials and construction phase, since the impacts from maintenance are handled through components native to the materials and construction phases, as shown in figure 2.4.

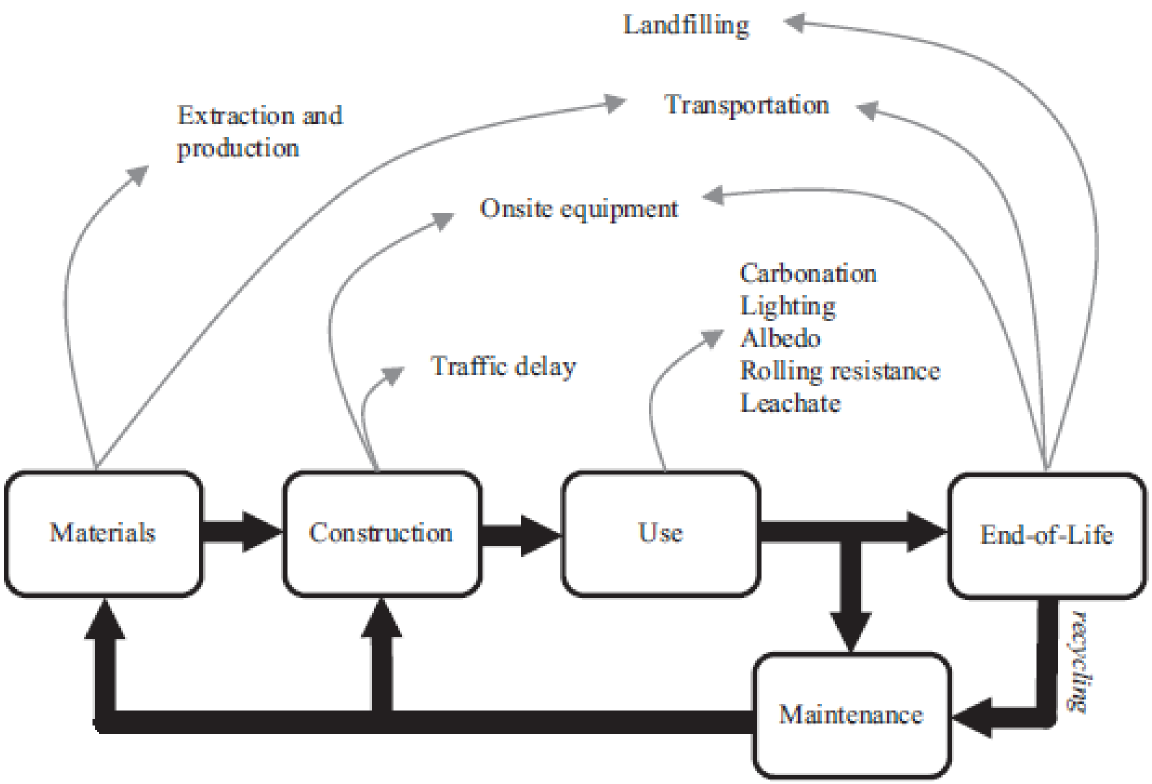


Figure 2.4: Phases and component of an LCA, from (Santero et al. 2011b)

The components considered are as follows:

- Extraction and production of materials, which includes all the processes to manufacture pavement materials, namely their acquisition (e.g. mining and crude oil extraction) and processing (e.g. refining, manufacturing and mixing).
- Transportation includes all the activities to move raw and finished materials between stages (Materials and EOL phase).

- Onsite equipment is related to the equipment used on site to build or maintain the road pavement, such as pavers, dozers, and millers. This component includes the equipment manufacturing and capital investment solely allocated to this construction event, the mobilization and demobilization and its use. However, usually, LCAs do not include the equipment manufacturing and capital investments in construction related production facilities.
- Traffic delay or work zone impact, considers changes to traffic flow, during construction and maintenance activities (lane closure, detour, traffic lights) and includes work zone speed changes, delay and diversions where applicable.
- Concrete carbonation is a natural process through which cement pavement sequesters a portion of the CO_2 that was originally liberated from limestone during cement kiln processes (calcination).
- Pavement lighting represents the energy demand needed to illuminate the roadway. The amount of lighting necessary for a proper illumination of a pavement is influenced by several parameters affecting the power requirement, such as material type, age, and aggregate choice affecting the reflectivity of the road. In general, lighter materials require less lighting than darker materials.
- Albedo refers to the solar reflectance of a pavement. Urban pavements with higher albedos reduce GWP by mitigating the urban heat island effect and by increasing the radiative forcing of the surface.
- Rolling resistance is one of the forces resisting vehicle movement. Both the pavement structure and the pavement roughness affect the rolling resistance, thus altering the fuel economy of the supported traffic.

In 2010, the University of California Pavement Research Center (UCPRC, Davis and Berkley) and the University of California Institute of Transportation Studies produced the UCPRC Pavement LCA Guideline (Harvey et al. 2010), including a high-level LCA framework for pavements, and some recommended data and models that were used in the US. In the same year, during a workshop in Davis, California, to discuss the first draft of the guideline, a final version was published (Harvey et al. 2010), including a new pavement LCA framework (see figure 2.5).

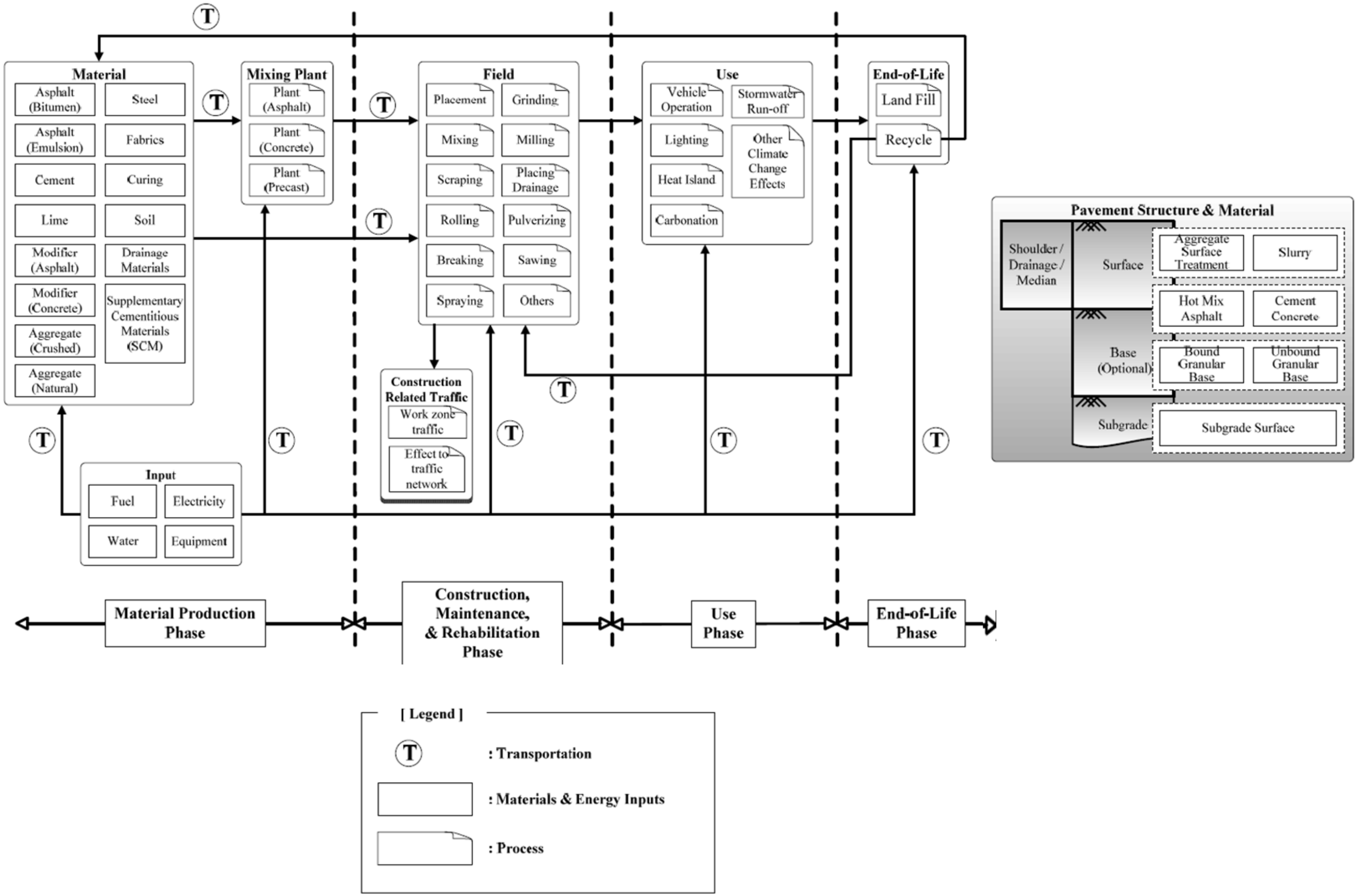


Figure 2.5: UCPRC framework - phases and component of an LCA, adapted from (Harvey et al.(2010)

In this quite detailed framework, the construction and the maintenance and rehabilitation phases are included in the some process box. The reason is because the system boundary of the M&R phase is consistent with the system boundary of the construction phase, including the construction equipment and the affected traffic flow components. In this framework, the impact of the construction zone on the traffic is considered both in terms of work zone traffic and effect to traffic network (outside the work zone). In case of preservation, maintenance or rehabilitation event, where the base, subgrade and the drainage system do not change and are not used for comparison, they can be excluded from the system boundary.

In 2016, the Federal Highway Administration (FHWA), under the sponsorship of the U.S. Department of Transportation, published a pavement LCA framework document (Harvey et al. 2016), including a computational framework to perform LCA on pavement systems and guidance on the overall methodology, system boundaries and knowledge gaps for the pavement community in U.S.

In this document, in addition to the five phases generally identified in the pavement LCA (material production, construction, use, maintenance, EoL), the pavement design stage was included (see figure 2.6).

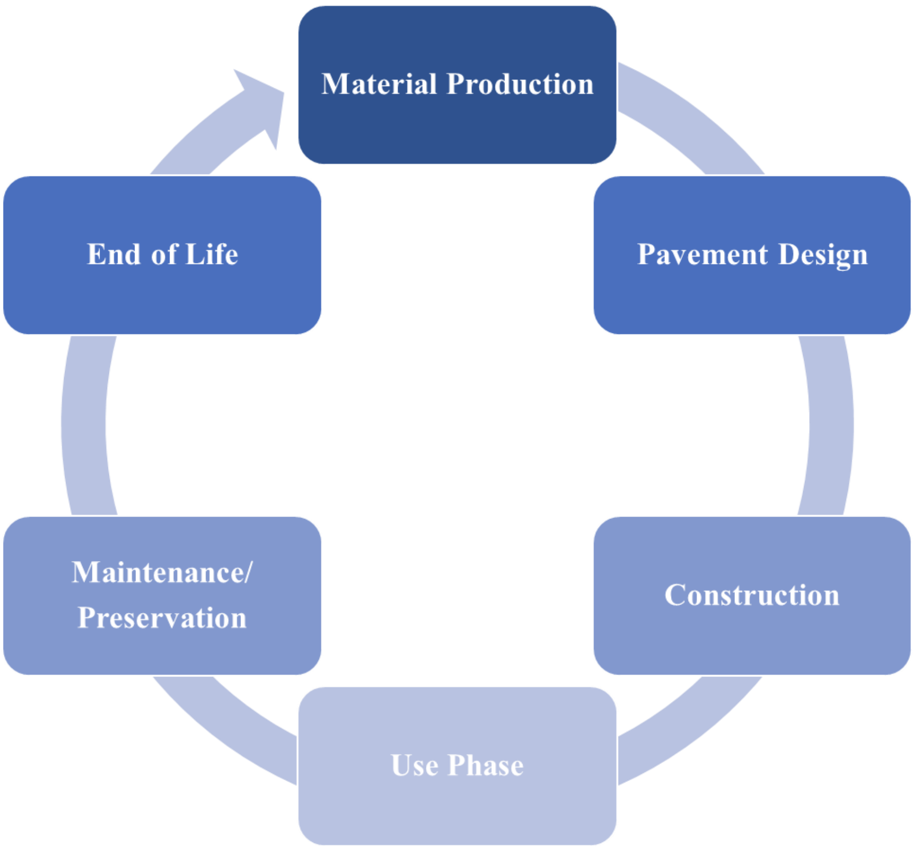


Figure 2.6: FHWA - pavement life cycle stages, adapted from (Harvey et al. 2016)

Based on this classification the UCPRC framework was updated, as in figure 2.7.

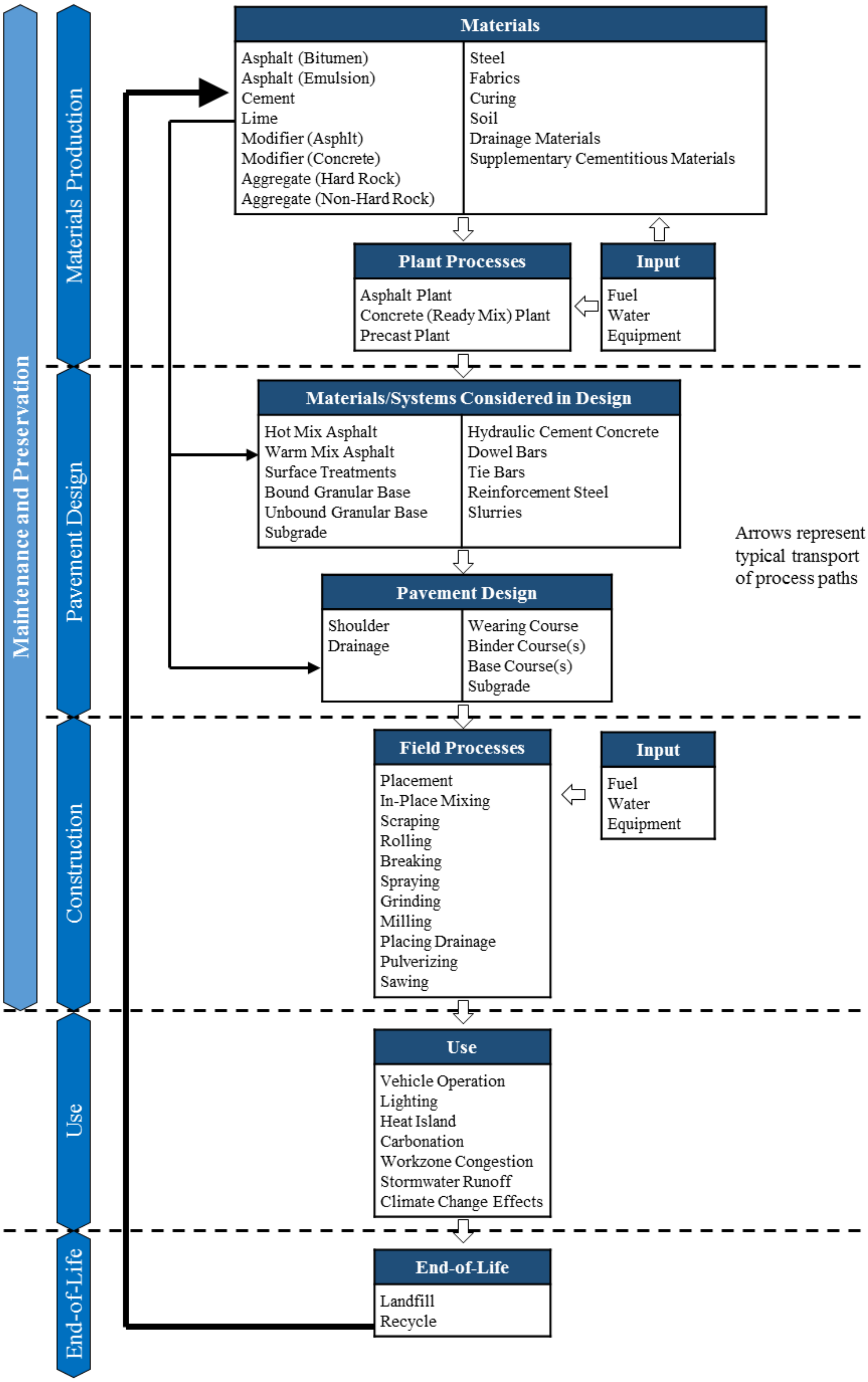


Figure 2.7: FHWA, UCPRC pavement life cycle stages, adapted from (Harvey et al. 2016)

The maintenance and preservation phase incorporates the material, design and construction stages and in the report, the authors confirm that, in order to define the inputs and the outputs of the product system and, therefore, the system boundary, the new construction, preservation, maintenance and rehabilitation activities can be considered and modelled in the same way. Although the work zone congestion in the figure is included in the use phase, in the report it is considered an element common to the construction and maintenance phases.

As mentioned above, the FHWA framework includes the design/development phase, which is traditionally excluded from the system boundary of LCAs, since it is assumed that it does not give a big contribution. However, the decisions during this phase can strongly affect the other phases. On this matter, Rebitzer et al (2004) argue that if the LCA aims at improving a product or service, then the study should take into account the design process and carried out along with the other design procedures.

The system boundary identifies the unit processes (the smallest elements in the LCI for which inputs and outputs are quantified) of a product system that are assessed in a LCA study. Multiple unit processes can be jointed in aggregated unit processes that represent more complex processes. Based on these considerations the FHWA report (Harvey et al. 2016) provides a system boundary with a partial list of major aggregated process that could be used in pavement LCAs to support the LCI analysis step (see figure 2.8). Several components were aggregated and the maintenance was included in the use phase (considering it more as a unit process, rather than a LCA phase), the material production phase was split into two phases, raw material acquisition and material production.

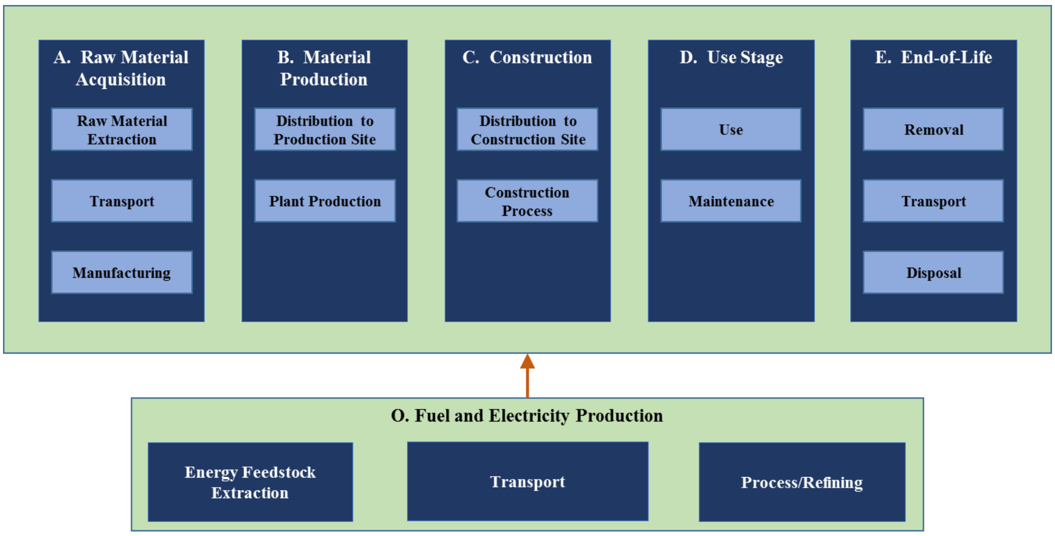


Figure 2.8: FHWA pavement life cycle stages with aggregated unit processes (Harvey et al. 2016).

In June 2016, the National Asphalt Pavement Association (NAPA) published a product category rule (PCR) for U.S. companies seeking Environmental Product Declarations (EPDs) for asphalt mixtures (NAPA 2016). In this report, the authors provides a detailed and comprehensive system boundary to conduct a LCA on 1 short ton of asphalt mixture, only for the product stage (see figure 2.9, red box). Although the study was only focused on the product stage phase, on overall and general system boundary of a pavement LCA was presented and it is based on the system boundary defined in BS EN 15978:2011 (International Organization for Standardization (ISO) 2011) for buildings. In this framework, if the product stage is similar to the others until now defined, the other phases show some substantial differences. The maintenance is not considered a phase but a unit process included in the use phase and the traditional components of the use phase are not identified. In the construction phase, only the transportation is considered, since the onsite equipment are included in the plant production.

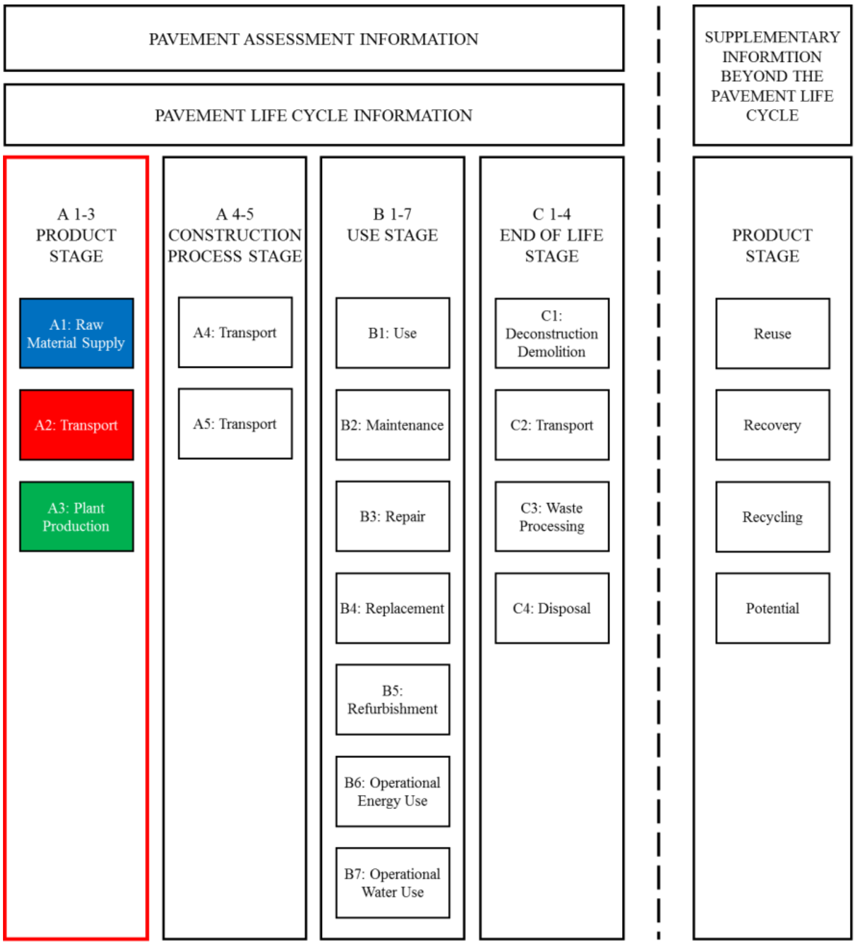


Figure 2.9: NAPA Diagram of designations of modular information used for life cycle assessments for pavements, adapted from (NAPA 2016). The PCR's boundaries are in the box outlined in red.

The analysis of the previous studies shows that if the identification of the life cycle stages of a road pavement is quite clear, more complex is the definition of the framework, system boundary and system definition of a road pavement LCA. The comparison of the previous schemes is made complex by the fact that each of them intends to accomplish different analysis.

The first one (figure 2.4) – which from now on will be referred to as Santero scheme - tries to identify all the phases, their mutual interaction and the components that express the direct correlation between the pavement and the environment during that specific phase. That is the reason why the maintenance stage, although it could be included in the use phase from a temporal prospective, is considered individually and directly correlated to the material and construction phase. Indeed, the analysis and study of the maintenance phase requires the identification of the same components that characterize the material and production phases.

The same concept is taken into account in the UCPRC schemes, in particular, in the most recent version (figure 2.7), where the design phase is added and the maintenance phase incorporates the production and the construction phase. Actually, in the UCPRC schemes, in the boxes describing each phase, several elements of a different nature are listed. If in the use phase, the elements in the boxes still represent the components describing the interaction between pavement and environment during the use phase, in the production and construction phase, different types of materials, designs and scenario are listed. However, in the report, the description of the computational framework to perform pavement LCA in USA uses the same scheme described by (Santero and Horvath 2009).

The NAPA scheme that is significantly focused on the description of only the product stage, is generated according to the BS EN 15978:2011 that defines a framework for LCA applied to buildings. Indeed, in the use phase, it also introduces components such as operational use of water that is characteristic of buildings, more than of pavements. With the exception of the product stage, the other phases are not clearly described.

In this PhD research, the general structure described by Santero and adopted by the UCPRC will be considered for the description of the methodology used, being the most suitable to explain the interaction between pavements and the environment.

2.3.2 Pavement LCA critical review and research gaps

Several detailed summaries of existing pavement LCA literature have been published in the last years (AzariJafari et al. 2016; Carlson 2011; Santero 2010; Santero et al. 2011a;

Santero et al. 2011b). One of the most comprehensive reviews was released in two parts by Santero et al. (2011a, 2011b), summarizing existing pavement LCA studies, frameworks, and major research gaps.

In these papers, the authors reviewed 15 studies carried out in several areas of the world, from 1996 to early 2010. The scope of the review was bounded by documents, such as research reports and papers related to LCI and LCA studies. Works only focusing on recycled materials and documents, such as industry briefings, magazine articles and other similar media were, instead, excluded.

Table 2.5 identifies the phases and components included in the system boundary of the LCAs assessed in Santero's studies. The critical review was carried out through considering several methodological issues, including the system boundary comparison.

In this regard, the main findings of the critical review were:

- Material extraction and production phase was included in the system boundary of every reviewed LCAs, but the transportation was assessed only in nine of them.
- The onsite equipment impact, during the construction activities, was estimated in the majority of the studies (11 out of 15), but the consequential traffic delay due to the work zone was mostly omitted.
- The use phase was omitted from nearly all the studies and the rolling resistance impact was not considered in any.
- The maintenance is described as a simplified series of events over the analysis period.
- The EoL is least considered.
- None of the studies included all the phases.

The omission of these phases may be acceptable for attributional LCA studies (e.g. to estimate the environmental impacts of a paving material) but is a problem for comparative LCA studies where different use phase outcomes could result (e.g. where different materials or maintenance programmes will lead to different surface condition) (Butt et al. 2015)

Since 2010, several other pavement LCAs have been performed, introducing in their system boundary general omitted phases. Table 2.6 identifies the pavement LCA components considered in LCAs performed since 2010.

From 2010, despite the several attempts to fill the research gaps in the pavement LCA field to extend the system boundary of the studies, in many of them, the use, the maintenance, the Eol phases and the traffic delay components are not assessed.

Table 2.5: Life cycle component in pavement LCAs reviewed in Santero et al.(2011b)

Author (year)	**Country**	**Phases assessed**													
		Material		**Construction**		**Use**					**Maintenance**		**End of Life**		
		Extraction and production	**Transportation**	**Onsite equipment**	**Traffic delay**	**Carbonation**	**Lighting**	**Albedo**	**Rolling resistance**	**Leachate**	**Materials phase**	**Construction phase**	**Onsite equipment**	**Transportation**	**Material production (recycling)**
Häkkinen and Mäkelä (1996)	Finland	x	x	x	x	x	x				x	x			
Horvath and Hendrickson (1998)	USA	x													
Roudebush (1999)	USA	x		x							x	x			
Berthiaume and Bouchard (1999)	Canada	x									x				
Mroueh (2000)	Finland	x	x	x						x	x	x			
Stripple (2001)	Sweden	x	x	x							x	x			
Nisbet et al. (2001)*	USA	x	x	x							x	x			
Park et al. (2003)	Korea	x		x							x	x	x	x	
Treloar et al. (2004)	Australia	x									x				
Zapata and Gambatese (2005)	USA	x		x											
Meil (2006)	Canada	x	x	x							x	x			
Chan (2007)	USA	x	x	x	x										
Muga et al. (2009)	USA	x	x	x							x	x			
Huang et al. (2009)*	UK	x	x	x	x										
White et al. (2010)	USA	x	x												

*studies performing a sensitivity/uncertainty test.

Table 2.6: Life cycle component in pavement LCAs from 2010

Author (year)	Country	Phases assessed: Material		Construction		Use					Maintenance		End of Life		
		Extraction and production	Transportation	Onsite equipment	Traffic delay	Carbonation	Lighting	Albedo	Rolling resistance	Leachate	Materials phase	Construction phase	Onsite equipment	Transportation	Material production (recycling)
ECRPD (2010)	Europe	x	x	x					x		x	x			
Zhang et al. (2010)*	USA	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Weiland and Muench (2010)	USA	x	x	x								x			
Cross et al. (2011)*	USA	x	x	x											
Cass and Mukherjee (2011)	USA	x	x	x											
Tatari et al. (2012)*	USA	x	x	x											
Yu and Lu (2012)*	USA	x	x	x	x	x	x	x	x	x			x	x	x
Wang et al.(2012b)*	USA	x	x	x					x						
(Noshadravan et al. 2013) *	USA	x	x	x											
Santos et al. (2014)	Portugal	x	x	x	x				x		x	x	x	x	x
Reza et al. (2014)*	Canada	x	x	x											
Chen et al. (2015) *	USA	x	x	x	x				x		x	x	x	x	x
Huang et al. (2014) *	UK	x	x								x	x			
Galatioto et. al (2015)*	UK	x	x								x	x			

*studies performing a sensitivity/uncertainty test.

In this PhD research, the focus is on two specific components; the rolling resistance impact during the use phase and the traffic delay or work zone impact during construction and maintenance activities. This interest is due to mainly two reasons:

- These two components can have, under specific conditions, a dominating impact in the life cycle of a pavement.
- Their impact can span a huge emission range (Santero and Horvath 2009) (figure 2.10). Their estimation is, therefore, a source of high uncertainty, depending on the methodological assumptions and the models used to describe their behaviour.

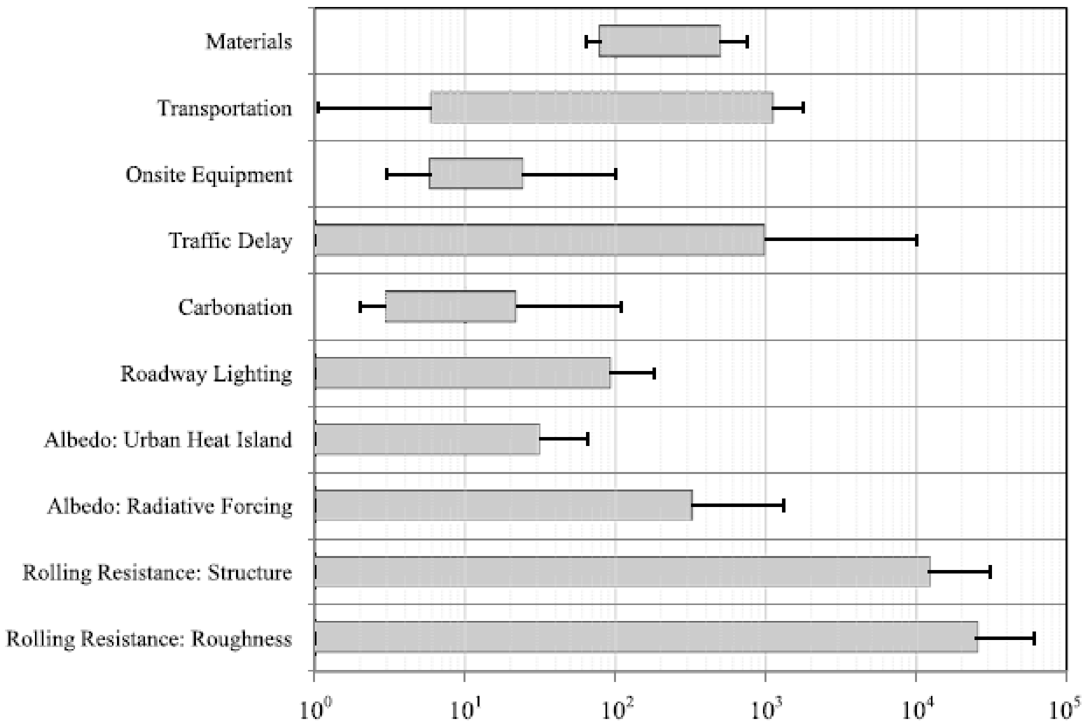


Figure 2.10 Global Warming Potential (Mg CO_2e/lane-km), from Santero and Horvath (2009). The thick, grey bars represent the probable ranges and the thin, black lines represent the extreme ranges

In section 2.2.3, the importance of carrying out uncertainty and sensitivity analyses in LCA studies was mentioned. In terms of pavements in particular, as they are complex and long-lasting, uncertainty represents an important component of any analysis conducted on them. The main sources of uncertainty in pavement analysis include:

- Data variability.

- Input uncertainty.
- Model imprecision.

For the first two, the major components of uncertainty are related to changes in location and time. The location includes two main source of uncertainty. Site/local specific characteristics of a road segment – in terms of design, material production, construction and EOL - make the data obtained for this location not necessarily representative for others. In addition, pavement performance and its deterioration over time is a highly variable factor and depends on several factors, namely local construction quality, subgrade support conditions, materials types used, traffic type, and climate conditions.

In terms of time, the prediction of future pavement performance over time is based on extrapolations and empirical data from existing pavements. This process is particularly complex for new types of pavement or pavement practices that do not have established records of performance. When available, data from pavement management systems can be used in order to assess performance histories for previous practice. Other components that raise uncertainty issues in pavement LCA studies are the traffic mixes, vehicle characteristics, configurations and technologies and growth patterns.

Finally, model imprecision is mainly caused by the limits of current knowledge in a specific area (Harvey et al. 2016). In fact, these models sometimes need to describe complex processes and unknown relationships between variables, introducing a further level of uncertainty.

In pavement LCAs performed before 2010, the recourse to uncertainty and sensitivity analysis to assess the impact of a specific variable was not common (see Figure 2.5). Most of these studies were based on a case study approach and compared different road sections, usually characterized by different pavement design alternatives or materials and sometimes by different traffic volumes. Nisbet et al. (2001) and Huang et al. (2009) are the only two publications that perform a sensitivity test on some input variables before 2010. The first one performs a sensitivity test of the material content of several mix designs during the construction phase on several output results. The second one estimates the impact of the emission models and of the number of days of road works, in the assessment of the traffic delay of a work zone during a maintenance activity.

More recent studies performed since 2010 show a greater awareness of the impact that uncertainty may have on the conclusion of a study.

Table 2.7 summaries studies since 2010 previously mentioned and describes the type of approach used to investigate the impact of some input parameters and/or the uncertainty on the results.

Table 2.7: Uncertainty and sensitivity analysis studies

Author (year)	**Test performed**	Phase/ Components
Zhang et al.(2010)	Sensitivity analysis performed for different traffic growth rates and fuel economy improvement scenarios.	Use and traffic delay
Cross et al. (2011)	Sensitivity analysis performed for different allocation of asphalt cement - related environmental burden scenarios.	Construction
Tatari et al (2012)	Sensitivity analysis of critical input parameters (moment correlation). A Monte Carlo simulation was used to estimate the impact of the variability of consumption and emissions associated with the Warm – mix asphalt (WMA) additives, the transportation distance of the chemical additives to mixing sites, and the transportation modes, including single-unit truck and diesel powered train, on the LCA model output.	Construction
Yu and Lu (2012)	Sensitivity analysis performed for different traffic growth rates, fuel economy improvement and pavement deterioration rate scenarios.	Use and traffic delay
Noshadravan et al. (2013)	A Monte Carlo simulation was used to estimate the measurement and data -quality uncertainty related the prediction of roughness.	Use
Reza et al. (2014)	Sensitivity analysis for petroleum fuel consumption as input variable, based on the variation of two parameters Unit Emergy Values (UEV) and quantity of fuel consumption.	Construction
Chen et al. 2015	Sensitivity analysis performed on stress developing rate, recycling, feedstock energy of asphalt binder and maintenance strategy and traffic volume.	All
Galatioto et. al 2015	Sensitivity analysis performed on TM options and traffic volume	Traffic delay

In addition, some studies have been carried out to analyse specific key issues of uncertainty in pavement LCA. Noshadravan et al. (2012) performed a probabilistic environmental life cycle analysis for an urban interstate concrete pavement, estimating the statistical distribution of overall GWP. A global sensitivity analysis was carried out to investigate the level of impact of different parameters in the life cycle assessment of pavements under uncertainty, in order to identify the elements to focus on to improve the characterization of pavement environmental impact. The sensitivity was expressed as the percentage of variation in impact accounted for by variability in each input parameter (see figure 2.11). The results show that, for this case study, pavement albedo, fuel efficiency of cars, traffic growth and fuel loss due to the roughness of the road represent the greatest source of variation in GWP.

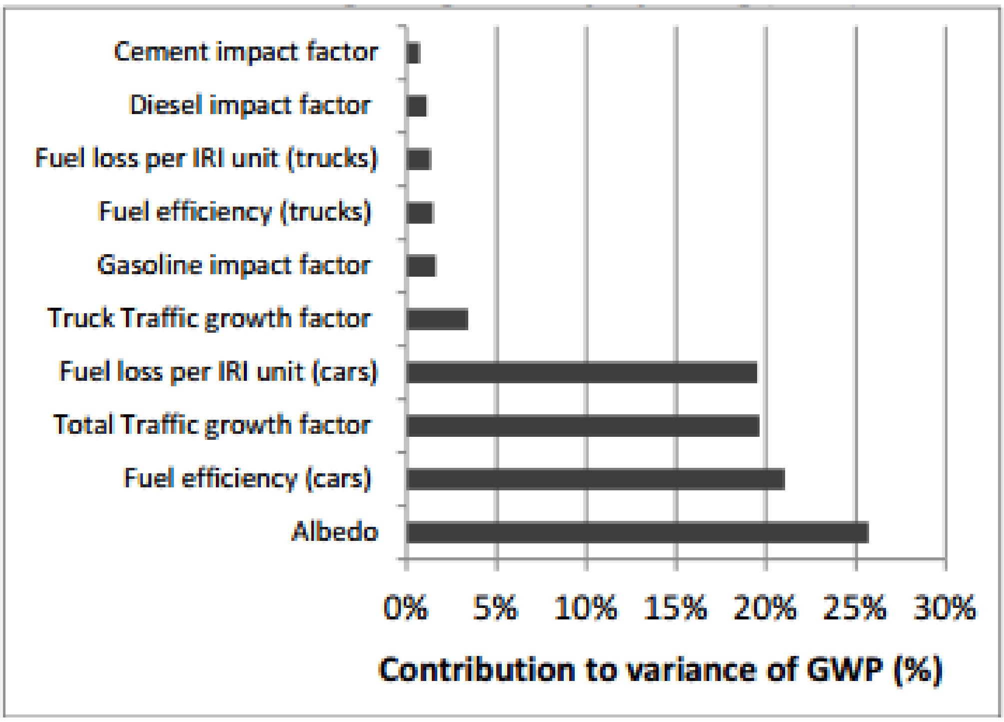


Figure 2.11: Impact to variance of several uncertain factors from Noshadravan et al. (2012)

Huang et al. (2013) focused on the impact of methodological choices made in UK PAS 2050 (BSI 2011) and asphalt Pavement Embodied Carbon Tool (asPECT) (Wayman et al. 2014) and the allocation methods available in road pavement LCA. In particular, a sensitivity analysis was performed for a UK case study road section to assess the impact of allocation amongst co-products (bitumen and blast furnace slag) and the influence of allocation at EOL recycling.

Yu et al. (2016) proposed a methodology to build a probability density function (PDF) of energy intensity coefficient (EIC) of pavement materials which differ considerably among data sources. The quality of each data was evaluated by the data quality pedigree matrix and converted to PDF. Finally, a Monte Carlo simulation was run with the weighted PDF of each data as input to obtain the ultimate PDF for EIC.

These studies performed in the last years show the growing interest in this issue and the growing awareness in the academic environment of the possible impact of ignoring the consideration of uncertainties in pavement LCA studies. However, there is still a lack knowledge to define a standardised framework to perform uncertainty and sensitivity analysis in pavement LCA.

3 Work zone traffic delay

This chapter describes the main issues related to the analysis of traffic delay in pavement LCAs and identifies the components that produce additional fuel consumption on a road segment with a work zone. In addition, it illustrates the existing approaches for estimating the traffic delay in work zones and their implementation in pavement LCAs.

3.1 Traffic delay definition and models

Overall, traffic delay is defined as the difference between the travel time on a road segment without a work zone and the longer travel time due to the work zone (Weng and Meng 2013). It is due to the lane and road closures or detour during construction and maintenance activities that modify the roadway traffic assets and its capacity (Santero et al. 2011a).

In pavement LCAs, the main interest is to evaluate the impact of the work zone on the overall vehicle emissions, namely to estimate the additional fuel consumption. The extra fuel consumption and consequential air emissions related to the work zone are due to:

- The speed reduction in the work zone, based on the installed speed limits. This variation always results in an increase in traffic delay, but may generate an overall reduction in vehicle emissions.
- Idling of the vehicles in the queue in a congested network or due to temporary traffic lights.
- Acceleration and deceleration manoeuvres to enter/exit the work zone and in the queue.

The estimation of the impact of the work zone during construction or maintenance activities can be based on several approaches (Weng and Meng 2013): macroscopic analytical approach, macroscopic simulation approach and microscopic simulation approach.

The first one is usually based on the deterministic queuing theory, which compares the demand volume with the capacity during normal conditions (freeway capacity) and operational conditions (work zone capacity), (see figure 3.1).

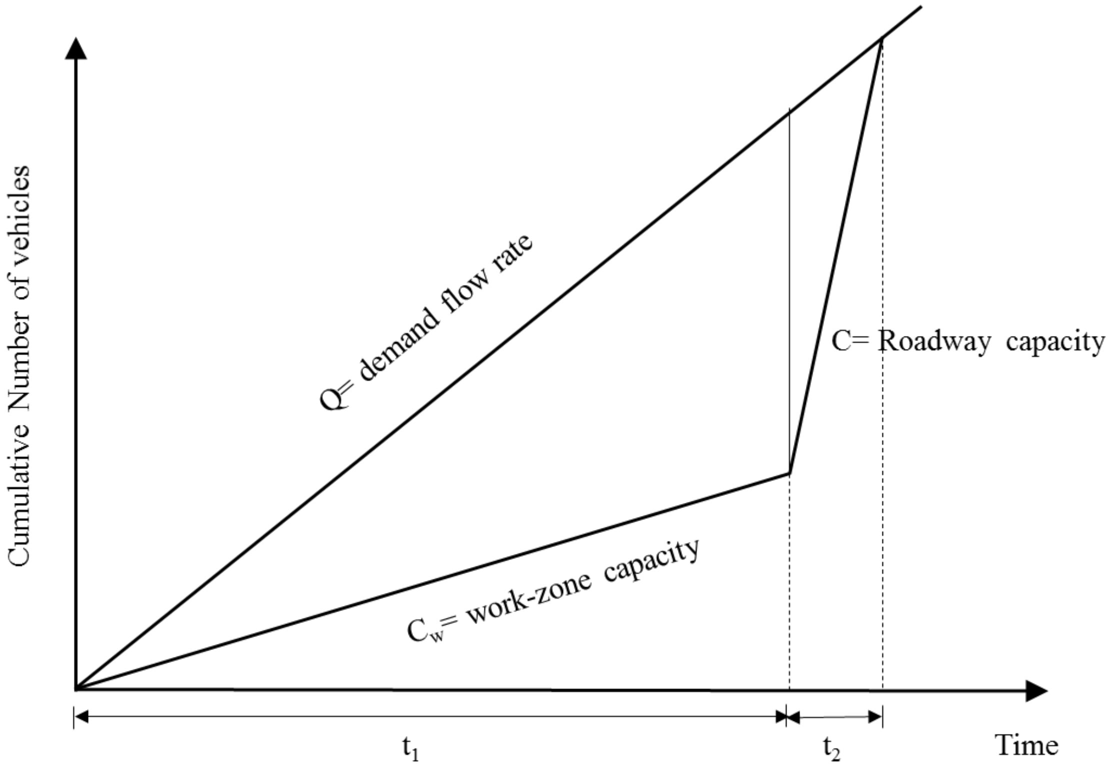


Figure 3.1: Deterministic/analytical queuing approach, adapted from (Weng and Meng 2013). During the time t_1, the work zone installation reduces the roadway capacity and, since the demand volume is bigger than capacity, a queue develops. During the time t_2, the work zone is removed and the capacity is bigger than the demand (higher slope), therefore the queue starts to reduce. When the two lines meet, the queue dissipates. The total delay is given by the area inside the triangle.

The analytical/deterministic tools currently available to assess the impact of the work zone are usually based on the procedures and methodologies described in the HCM (Transportation Research Board 2010). In most of the studies using this approach (Chien and Schonfeld 2001; Jiang and Adeli 2003; McCoy et al. 1980), when the road capacity is greater than the traffic demand, there is no queue and the traffic delay is only due to the vehicle speed reduction in the work zone (moving delay). Based on the new work zone speed limits, this may produce a reduction or a rise of the air emissions. When the traffic demand exceeds the work zone capacity, a queue will be generated at the upstream of the work zone, producing a further delay and traffic emissions (queuing delay). In this case, the overall vehicle delay can be estimated as the sum of the moving delay and the queuing delay in the work zone.

The main advantage of this approach is the ease of implementation, requiring a reduced number of input data. Further, it is generally considered a quick and reliable tool to predict if a road is operating under or above its capacity. However, the accuracy of the results could be affected by several limitations:

- Overestimation of the queuing delay in the time interval; the queue may dissipate before the end of a time interval, when the work zone capacity is bigger than the demand at the time interval.
- Assumption that the vehicle departure rate is always equal to the arriving traffic flow. Instead, when there is a queue, the first one could be bigger than the second.
- The hypothesis that the speed of the moving delay (delay due to the reduction of the speed of vehicles in the work zone) is constant.
- Neglecting of the delay caused by acceleration and deceleration manoeuvres.
- Underestimation of the queue delay, caused by the randomness of the traffic flow that could generate a queue even if the demand is smaller than the capacity.

To reduce the impact of these limitations, adjustments and improvements have been implemented in several studies. Meng and Weng (2013) developed an improved deterministic model to overcome the first three limitations, modifying the estimation formula of previous studies and considering the variations of the traffic speed in the moving delay estimation. Jiang (1999 and 2001) developed a model to consider the effects of the acceleration and deceleration manoeuvres in the delay and introduced a queue – discharge table instead of the deterministic queuing approach.

Another significant limitation of this approach is related to the identification of the extent of the network impacted by the work zone. Indeed, the modelling should cover and consider the whole network affected and not only the work zone. The deterministic approach, instead, assumes that operations in a road segment are not affected by and do not affect the operational conditions of the surrounding network. Therefore, they do not consider the possible interference that a long queue in a location could have on another location. The impact of this limitation will be different for each case study, based on the specific characteristics of the road network and of the layout of the work zone.

The simulation models are a set of tools reproducing real-world interactions, identifying specific relationships between the road network components. They are particularly effective in exploring the dynamic evolution of traffic congestion scenarios on transportation systems (Alexiadis et al. 2004). In order to estimate the traffic delay in the work zone, the most used simulation models are at macroscopic (regional) and, more frequently, at microscopic (street) level of detail.

Macrosimulation models are described by the deterministic relationships of flow, speed and density of the traffic stream and the simulation is based on a section by section basis. Microsimulation models, instead, are models that continuously or discreetly predict the behaviour of individual vehicles based on car-following and lane changing theories (Alexiadis et al. 2004; Boxill and Yu 2000). Usually, the vehicle arrival demand is based on a stochastic approach and each entry vehicle is described by a destination and vehicle type. These models require a great computer time and storage, large amount of data for calibration and considerable error checking of the data. In addition, the algorithms are usually developed independently and not subject to peer review from the scientific community.

Many traffic simulation models, characterized by different features, have been introduced in the market. Several reviews have been carried out to describe the main advantages and disadvantages of these tools and the most relevant software (Boxill and Yu 2000; Weng and Meng 2013). Overall, microsimulation models are the best option to analyse and compare different scenarios and TM strategies at local level, in terms of traffic, congestion and environmental impact. However, they are a time consuming and resource intensive activities, requiring a large amount of site specific data and time to run accurate simulations. Therefore, the choice of the appropriate tool, the availability of resources, time and good quality data are the basic requirements to efficiently select these models.

3.2 Implementation of the traffic delay component in pavement LCAs

The prediction of the potential impact of traffic delay during construction/maintenance activities is characterized by high uncertainty. It is contingent upon the project and site characteristics and, therefore, it is not possible to draw general conclusions in advance and its assessment is required in each individual LCA project (Santero et al. 2011a). If in the past, the traffic delay was generally omitted from LCAs, in the last years, several studies have introduced this component in the system boundary of the LCA project or have investigated its overall impact in the life cycle of a pavement.

Table 3.1 summarises some relevant LCAs including or related the traffic delay component and describes the traffic model, the emission model used and the TM adopted, where they were specified in the study.

Unfortunately, it was not possible to determine all the results obtained from these studies - in terms of traffic delay - and compare them. Based, in fact, on the scope of the study and of the methodology used in the paper, the results, in terms of traffic delay, not always are directly deductible as a “single figure” absolute value (sometimes the results for the traffic delay were incorporated in other phases or presented as difference between different scenarios). However, analysing three of these studies, it is possible to notice that the potential impact of traffic delay during construction/maintenance treatments on the life cycle of a pavement can have different order of magnitude, in terms of CO_2 emissions:

- Häkkinen and Mäkelä have determined under 3 Mg of CO_2 emissions per lane-kilometre during a 50 – year analysis period (Häkkinen and Mäkelä 1996);

- Chan has calculated CO_2 emissions from traffic delay for different locations, finding a wide range spanning between very small values (close to 0) to over 600 Mg of CO_2 per lane-kilometre (Chan 2007);

- Huang has estimated 0.4 Mg of CO_2 per day, resulting in an increase of 2.4% of additional emissions, compared to operational normal time service (no work zone) (Huang 2007).

Therefore, the impact of traffic delay is difficult to predict in advance, since it may be non-existent or a significant contributor to the life cycle GWP for a project, depending on a variety of elements: traffic volume, capacity, maintenance strategies (time closures, number of days, and impact of detours) and road network characteristics.

Regarding the models used to assess the work zone traffic delay in these pavement LCAs, the macroscopic analytical/ deterministic approach and the micro simulation approach are the most implemented in these studies.

The first one is mainly used through methodologies developed to determine road user costs: Kentucky User Cost Program (KyUCP) (Rister and Graves 2002) and the program developed by the Federal Highway Administration (FHWA), called “Life Cycle-Cost Analysis in Pavement Design”, during the demonstration project 115 (DP-115) (Walls III and Smith 1998) - which from now on will be referred as the LCCA method. The FHWA has never released a computer copy of this program, but the algorithm behind it and a step-by step

Table 3.1: LCAs including or related the traffic delay component

Author (year)	**Country**	**Traffic model**	**Emission model**	**Traffic Management**
Häkkinen and Mäkelä (1996)	Finland	Not specified	Not specified	Not specified
Chan (2007)	USA	Macroscopic analytical approach (KyUCP)	EPA MOBILE6	Lane closure
Huang et al. (2009)	UK	Microsimulation (VISSIM)	EnvPro (packed with Vissim)	Lane closure and contraflow
Zhang et al. (2010)	USA	Macroscopic analytical approach (KyUCP)	EPA MOBILE 6	Lane closure and detour
Yu and Lu (2012)	USA	QuickZone model	EPAMOBILE 6.2	Lane closure and detour
Santos et al. (2015)	Portugal	Macroscopic analytical approach HCM	COPERT4	Use of lateral hard shoulders
Wang (2014c)	USA	Macroscopic analytical approach (RealCost)	MOVES 2014	Lane closure
Kang et al. (2014	USA	Macroscopic analytical approach (KyUCP)	MOVES 2014	Lane closure
Galatioto et. al 2015*	UK	Microsimulation (AIMSUN)	Model implemented in Aimsun	Lane closure, traffic lights and detour
Huang et al. 2014*	UK	Microsimulation (AIMSUN)	Model implemented in Aimsun	Lane closure, traffic lights
Chen et al.(2015)	USA	QuickZone model	Not specified	Lane closure and detour
Inti (2016)	USA	Macroscopic analytical approach (RealCost)	MOVES 2014	Lane closure

*assessing the same case study

procedure to set it up in Microsoft Excel was described in a technical bulletin (Walls III and Smith 1998).

KyUCP developed by the Kentucky Transportation Center, is a Microsoft Excel based program that calculates the User cost and, therefore, the traffic delay during maintenance activities, based on the algorithm developed in FHWA DP115. This means that the two methodologies - KyUCP and LCCA method - use the same calculation procedure, based on the analytical deterministic approach of the HCM. This step-by step procedure is described in depth in the methodology chapter.

Another model used in the U.S. to analyse the impact of the work zone on traffic is QuickZone, developed by the Turner-Fairbank Highway Research Center of the FHWA (Federal Highway Administration 2017a). The software is a spreadsheet and Visual Basic – based application to analyse the traffic delay and the average and maximum queue length due to work zone, involving lane restrictions. As with the other macroscopic analytical approaches above mentioned, it is based on standard queue theory and Volume Capacity ratio. It works comparing the capacity of the roadway and the demand of traffic on an hour by hour basis. The excess of traffic volume represents the queue that produces traffic delay. Although it cannot be defined as a highly accurate model (Curtis and Funderburg 2003), compared to the other analytical macroscopic approaches it is more sophisticated, taking into account diversion to a detour route, demand management techniques and intelligent transportation system traveller information services.

Table 3.1 shows that the studies analysed adopt different emission models to evaluate the vehicle tailpipe emissions. Most of the studies performed in the USA, use the emission model MOVES (MOtor Vehicle Emission Simulator) or Mobile 6.

MOVES, developed by the U.S. Environmental Protection Agency (EPA), replaced Mobile 6 as EPA's official model for estimating emissions from cars, trucks and motorcycles. This model is able to simulate the engine running status, calculating the rolling resistance forces, aerodynamic forces, inertial forces (in acceleration) and gravitational forces and converting them to engine power. Thereafter, it combines engine power, speed and vehicle mass in a factor representing the engine running status and, based on this, it estimates the base emissions factors. These are, then, converted to the final emissions factors depending on engine technology, vehicle age, meteorology and other factors. Finally, it estimates vehicle fuel consumption and, therefore, tailpipe emissions based on the calculated emissions factors and vehicle activities.

The emission model EnvPro (Environmental Program) was developed by the Planung Transport Verkehr (PTV) AG in collaboration with the Transport Operations Research Group (TORG) at Newcastle University (PTV and TORG 2004). It estimates the environmental impact of the traffic – in terms of CO, NOx, CO_2, HC, PM and fuel consumption- using the simulation output results (instantaneous vehicle position, the vehicle speed and the vehicle acceleration) obtained running the microsimulation model VISSIM, a German acronym for Traffic in Town Simulation (Fellendorf 1994) . The emission inventory included in the emission model is based on two models developed under EU project in the early 1990s: QUARTET (Quadrilateral Advanced Research on Telematics for Environment and Transport) (QUARTET 1992) and MODEM (PTV and TORG 2004). The most significant difference between the two models stands on the approach used to calculate the FC and the emissions. The first one provides the emissions based on the average value of speed and flow, the second one is an instantaneous model able to estimate emissions due to accelerations, decelerations, stop and go phenomena, of a typical congested network. Based on Huang's observations (2007), the computing of micro-scale (second by second) emissions is better performed by the MODEM model, that systematically provides lower estimation for all types of pollutants.

COPERT 4 (COmputer Programme to calculate Emissions from Road Transport) (Gkatzoflias et al. 2007) is a European Microsoft Windows® tool to calculate emissions (GHG, air pollutants and toxic species) from the road transport sector. It was developed by the Laboratory of Applied Thermodynamics (LAT) in the Aristotle University of Thessaloniki and funded by the European Environment Agency (EEA), through the European Topic Centre on Air and Climate Change. The model is able to calculate vehicle emissions for more than 240 vehicle types and from different types of road vehicle modes: 'hot emissions' (thermal stabilised engine operation), 'cold start' emissions (warming-up) and non-exhaust emissions (fuel evaporation, tyre and break wear emissions). Moreover, the model includes several emission control technologies and others can be included by the users. For these reasons, it is largely used by the EU member states for the official submission of road transport inventories to international convention (Kioutsioukis et al. 2004).

The selection of the emission model is a significant component of a pavement LCA study. As discussed in section 3.3, the use of different emission models can lead to significantly different results, affecting the outcome of the LCA.

Most of these studies assess road sections where the TM of the work zone involves a lane closure (with reduction of the total number of running lanes in one direction) or road closure (and contraflow in the other direction), with an overall reduction of the roadway capacity. Some of them take into account a detour of a small percentage of the flow (with possible reduction of the vehicle speed and longer route). Only in one case (Galatioto et al. 2015), the TM involves two significantly different work zone layout scenarios. The first one consists in the use of temporary traffic lights at an intersection and the second one a road closure with the detour of 100% of the vehicles. The detour scenario takes into account not only the impact on the vehicles changing their route, but the impact on the entire network.

3.3 Parameters affecting the results of the work zone traffic delay component in LCA studies

The estimation of the traffic delay, through the use of these models requires the calculation, the assessment and the selection of some potentially sensitive parameters on the final result, such as the traffic volume, the TM, the vehicle EF and the network boundary.

Traffic volume

The Annual Average Daily Traffic (AADT) is a measure of the volume of traffic of a highway or road, used in transport planning and transportation engineering. It represents "t*he total volume of traffic passing a point or segment of a highway facility in both directions for one year divided by the number of days in the year"*(Mallela and Sadasivam 2011). The Department for Transport in the UK uses manual traffic counts and permanent automatic traffic counters (ATC) stations, which are magnetic induction loops in the road surface that are installed through the network and collect traffic counts all day (UK Department for Transport, 2017). The estimation of this parameter is essential to assess the transportation data sets and it represents a key variable in all traffic models. However, AADT value is usually based on simple rough estimates of traffic counts along the vast majority of roadway sections and statistical calculations.

Several researches (Davis and Yang 2001; Gadda et al. 2007; Rossi et al. 2012) have shown how the estimation of this parameter is characterized by uncertainty that reduces the reliability of the results.

A sensitivity analysis of this parameter is necessary not only to evaluate the level of uncertainty related to the available data and their estimation (data uncertainty), but also to take into account daily and monthly fluctuations (data variability) that could affect the modelling and to evaluate future scenarios of maintenance treatments for the same road segment.

Traffic management

During maintenance activities of highway networks or minor roads, it may be necessary to set temporary TM measures, in order to optimise safety, road space and work efficiency and to minimize congestion, delay and inconvenience to the traffic (Department for Transport/Highways Agency, 2009). An effective TM should be anticipated by an assessment of the work zone and a deep understanding of the strategies to mitigate its impact on the road users. The TM assessment should take into account the type of road, number of carriageways and/or lanes, volume of traffic during week and during weekend, time extension of the road works. In addition, it should evaluate the possible impact on nearby intersections and interchanges, railroad crossings, and public transit and other junctions in the network, on evacuation routes and affected public property and on affected businesses and residences (Federal Highway Administration 2017b). Typical TM solutions could include lane or road closure, contraflow in a single carriageway, detour, use of hard shoulder as running lanes, arrangement of speed limits or use of traffic control systems.

All these factors make the choice of the TM solutions during road works a complex element. As shown in table 3.1, in the pavement LCAs reviewed in this research, the TM typically involved a lane closure and a reduction of the total roadway capacity and only one of this studies (Galatioto et al. 2015) performs a sensitivity test on some selected TM options, showing that under specific conditions the TM strongly affects the LCA results.

Emission factors

Vehicle EF can be defined as empirical functions able to predict the amount of a pollutant that is emitted by a specific vehicle per distance driven, energy consumed, or amount of fuel used, depending on the activity that generates them. If the analysis of the traffic emissions is performed at national level, the use of EF based on the mean speed of vehicles may be representative. By contrast, for the analysis of local traffic measures - such as interventions that do not affect the average speed but affect stop-and-go patterns of vehicles - EF based on the mean speed of vehicles may not be representative (Franco et al. 2013).

These values are usually incorporated in vehicle emission models that, over time, are becoming more sophisticated with increasing numbers of vehicle types, fuel types, pollutants and emission modes (e.g. hot running, start, non-exhaust) being considered (Smit et al. 2009) and increasing the level of complexity of these models.

Based on the input data of the model emissions required, Ntziachristos et al. (2010) identify five major categories with different level of sophistication:

- 'Average-speed' models (e.g. COPERT, MOBILE, EMFAC), which only require mean travelling speed and vehicle kilometres travelled (VKT) to estimate emissions;
- 'Traffic-situation' models, where EF are functions of a specific traffic situation (e.g. 'stop-and-go-driving', 'free- flow motorway driving'). For these models, the VKT represent an input data which need to be calculated through traffic models.
- 'Traffic-variable' models, in which the input parameters – provided by both macroscopic and microscopic traffic models - are traffic flow variables (average speed, traffic density, queue length and signal settings).
- 'Cycle-variable' models in which EF are based on various driving cycle variables (e.g. idle time and average speed) at high resolution (seconds to minutes) and require specific data on vehicle movements (e.g. instantaneous speed and acceleration) from microscopic traffic models or GPS equipment.
- 'Modal' models where engine or vehicle operating models at the highest resolution (one to several seconds) are used to generate EF, through detailed information (see cycle-variable models).

MOBILE (18%) and COPERT (16%) are, currently, the most used emission model (Smit et al. 2009).

The UK Department for Environment Food & Rural Affairs (2014) has published the Emissions Factors Toolkit (EFT) (last version n.6) that allows users to calculate road vehicle pollutant emission rates for oxides of nitrogen (NOx) and Particulate Matter (PM - PM10 and PM 2.5), for a specified year, road type, vehicle speed and vehicle fleet composition. CO_2 emission rates can also be calculated for petrol, diesel and alternative fuelled vehicles. The EF are taken from the EEA COPERT emission calculation tool, with the exception of the CO_2 emissions that are those published by the Department for Transport in 2009 (UK Department for Transport 2009)

The use of different emission models can lead to significantly different results, as proved in several studies, comparing the results of different models (Borge et al. 2012; Demir et al. 2011; Panis et al. 2006; Zachariadis and Samaras 1997). In particular:

- Different emission models take into account different components, in terms of input parameters.
- As shown in Ntziachristos et al. (2010), several emission models are partially validated or not totally validated and the mean prediction errors of some of them can be high, based on the pollutant analysed. Unfortunately, usually the models do not provide the prediction errors to estimate the expected accuracy.
- Models are often used beyond their capabilities (e.g. average-speed models for micro-scale modelling of road sections), resulting in errors.

This may produce inaccurate and variable results depending on the model used compared to the “true” values.

Network Boundary

The traffic modelling requires the identification of the extent of the network impacted by the work zone (Transport for London 2010). For a comprehensive understanding, the modelling should cover the whole network affected. During a maintenance event, the behaviour of the vehicles is affected by the congestion occurring in the work zone which may lead them to take alternative routes, affecting the volume of traffic of adjacent roads in the network. Or, in the worst case scenario, the congestion could extend to an area not included in the modelling boundary. This means the analysis should take into account both the delay in the work zone and in all the network that may affected by the TM layout. From this point of view, the simulation approach is more flexible, allowing the area of analysis to be extended, taking into account the interaction of elements, such as traffic lights, roundabouts, other junctions, etc.

As shown in table 3.1, usually pavement LCA studies including the traffic delay during maintenance activities do not take into the effect on the whole network, resulting in modelling which is not fit for purpose and reducing the accuracy of the results.

4 Rolling resistance

This chapter focuses on defining rolling resistance force, the parameters that affect it, the models available in literature to describe this component and its implementation in pavement LCAs. The interest in this parameter is due to the fact that the deterioration of pavement surface properties over time provokes an increase in rolling resistance that, acting opposite to the motion of vehicle, in turn, increases the energy and the fuel consumed by traffic. An increase in traffic fuel consumption corresponds with a growth in environmental impact, due to the increase in emission of pollutants.

Actually, rolling resistance is one - and not the most relevant - of the forces or energy losses resisting the movement of vehicles (for a driving speed in the range of 70-90 kM/h, the rolling resistance is about the 11% of the total driving resistance in a car (Haider and Conter 2012)). However, this force is the focus of this dissertation because is the only one due to the interaction between tyre and pavement.

4.1 Rolling resistance definition

The movement of a vehicle requires that the engine overcomes the driving forces or energy losses, resisting the movement of the vehicle. To overcome these forces, the engine of the vehicle must produce power, using the energy in fuel or in battery. The "driving resistance" (Hammarström et al. 2008) or "resistance to movement" (Michelin 2003) is due to different components (Sandberg et al. 2011b), shown in figure 4.1.

Rolling resistance arises from the physical interaction between tyre and road and has historically been considered a force resisting a motion of a vehicle, by opposing the rolling of the tyres. In particular, the rolling resistance is a force resulting from the formation of a torque opposing tyre rotation, dissipating energy in the form of heat (Michelin 2003).

Under the concept of vehicle rolling resistance, several types of energy loss are included:

- The energy loss in tyres, due the visco-elastic properties of the rubber elements present in the tyre that provoke the deflection and the deformation of the rolling tyre and the hysteresis of the tyre rubber (Sandberg et al. 2011b). This represents the main loss and it is affected both by pavement properties (*pavement-induced tyre losses*) and tyre properties (*tyre rolling resistance*).

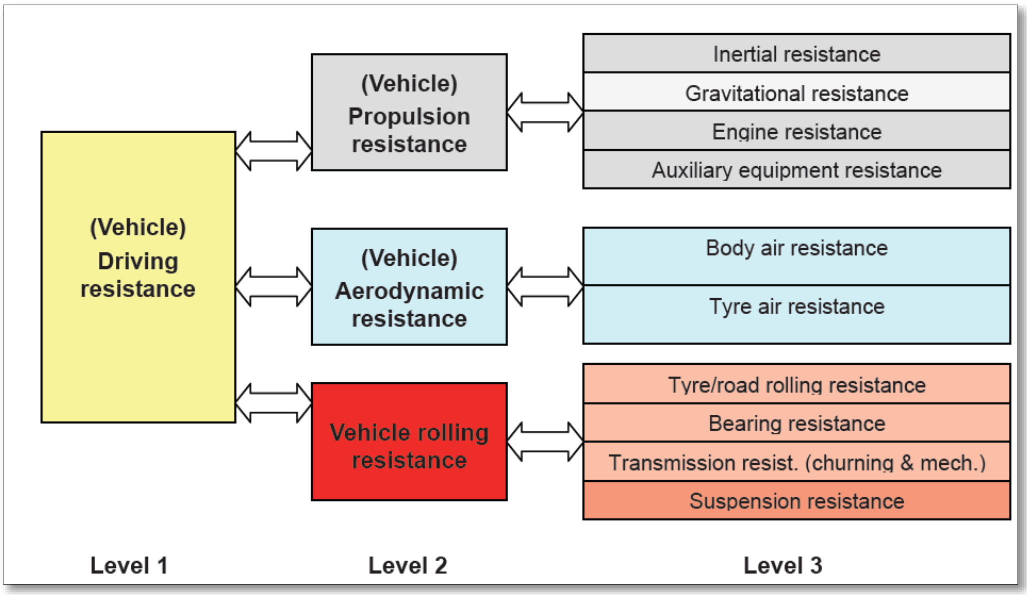


Figure 4.1: Illustration of suggested terminology structure and distinction between resistances at various level in the vehicle driving system, from Sandberg et al. (2011b)

- The road rolling resistance that is the *energy loss in pavement*, due to the hysteresis of the viscoelastic material used in pavement: the deformation or deflection in the pavement is not totally recovered and some of the energy is dissipated in the form of heat.
- Suspension energy loss in the vehicles, caused by road unevenness that produces a deformation and vibration of the tyre/wheel suspension system. This deformation is partially absorbed by the shock absorbers of the vehicle, and partially it produces an additional deformation of the tyre. Since, with some rolling resistance measurement methods, it is hard to separate these two components (shock absorber loss and rolling resistance loss) it may be practical to include the effect of shock absorber in the energy loss in the tyre. This is also justified by the fact that this phenomenon is caused by a rolling road on an uneven road (Sandberg et al. 2011b).
- Bearing friction loss, transmission resistance, tyre rotational, aerodynamic resistance, and tyre drag (aerodynamic resistance when moving through the air).

Road pavement LCAs tend to focus and include only the energy losses directly affected by the road pavement infrastructure, namely pavement-induced tyre losses, suspension energy loss and energy loss in pavement that overall can be defined as "*Pavement Vehicle Interaction (PVI) rolling resistance*".

For this reason, in this study, only the influence of road pavement properties on the rolling resistance, and, therefore, on the fuel consumption will be discussed. Vice versa, the impact of the tyre on the rolling resistance is not a focus of the pavement LCA e will not be taken into account in this research. Therefore, from now on we will refer to the rolling resistance, only considering the fraction of rolling resistance due to the pavement infrastructure.

Defining and estimating the influence of the pavement properties on the rolling resistance is particularly complex. Overall, the mechanisms affecting this force and directly related to pavement design and maintenance are unevenness, texture and pavement structure. Pavement structure refers to the thicknesses and characteristics of the pavement materials, affecting its stiffness and, therefore, the deflection of the road under a specific load (Sandberg et al. 2011a)). The pavement surface texture (texture and unevenness) represents the longitudinal profile of the pavement surface along the rolling path of the vehicle tyres and it is due to the asperities present in a pavement surface.

Actually, there are other two mechanisms that could have an influence on rolling resistance: rutting (a longitudinal surface depression in the wheelpath) and transverse or cross slope. However, their correlation with the rolling resistance is still uncertain and not defined (Bryce 2014), therefore, it will not be addressed in this study .

Pavement structure

The pavement structure and is deflection under the tyre load is mainly correlated to the rolling resistance losses, through two processes:

- Changing in the geometry of the pavement causing curvature in the pavement surface, resulting in a sort of constant “uphill” (positive grade), that increase vehicle fuel consumption.
- Dissipation of energy in the pavement structure due to viscoelastic properties of the pavement (Wang et al. 2012a).

The influence of pavement deflection on rolling resistance is not properly defined. If, on the one hand, Sanderberg et al. (2011) and Beauving et al. (2004) consider this mechanism is not negligible, at least for bituminous pavements (pavement deflection decrease tyre deflection and, therefore, tyre losses), on the other hand, Santero et al. (2011b), underlines that there are numerous caveats, limitations, conflicts of interest associated with these studies. Overall, although there are some studies that have explored the link between fuel consumption and pavement structure, the exact mechanistic relationships is not knew (Santero et al. 2011a).

Moreover, as mentioned in Wang et al. (2012a), the research on deflection effect has not been implemented in a comprehensive and overall accepted pavement LCA framework. Consequently, usually it is not included in studies about pavement LCA.

Pavement surface texture

Road surface characteristics affect the rolling resistance. In order to better understand the correlation between these two components, described in the paragraph 4.3, an analysis of the road surface texture characteristics could be useful.

The ISO (International Organization for Standardization (ISO) 2004) defines the pavement texture as "*the deviation of a pavement surface from a true planar surface*". Based on the maximum dimension of the deviation of the surface profile or wavelength, it is possible to identify four components of the pavement surface texture (see figures 4.2 and 4.3):

- Microtexture (wavelength less than 0.5 mm) refers to the roughness of the surface aggregate, which depends on the aggregate particles mineralogy and petrology (crystalline of coarse aggregate in asphalt and sand particles in the surface laitance of a brushed concrete surface) and not the spacing between the particles.
- Macrotexture (wavelength between 0.5 mm to 50 mm) refers to the shape, size, spacing and arrangement of coarse aggregate particles. It can be positive – representing the height above a road surface of the aggregate chipping (e.g. for HRA and surface dressing) - or negative – indicating the depth of texture below the road surface (e.g. for porous asphalt and thin surfacing).
- Megatexture (wavelength between 50 mm to 500 mm) represents the degree of smoothness of the surface.
- Unevenness or roughness (wavelength between 0.5 m to 50 m) describes amplitudes of longer wavelengths, which affect vehicle suspensions.

A pavement surface is, therefore, a combination of different wavelengths ranging from microscopic to long that affect the vehicle/tyre interaction, producing different types of effects at different levels.

For the macrotexture and unevenness, specific measures have been standardised and are usually used, Mean Texture Depth (MTD), Mean Profile Depth (MPD) and International Roughness Index (IRI). Table 4.1 shows a brief summary of the specific measures used for these parameters.

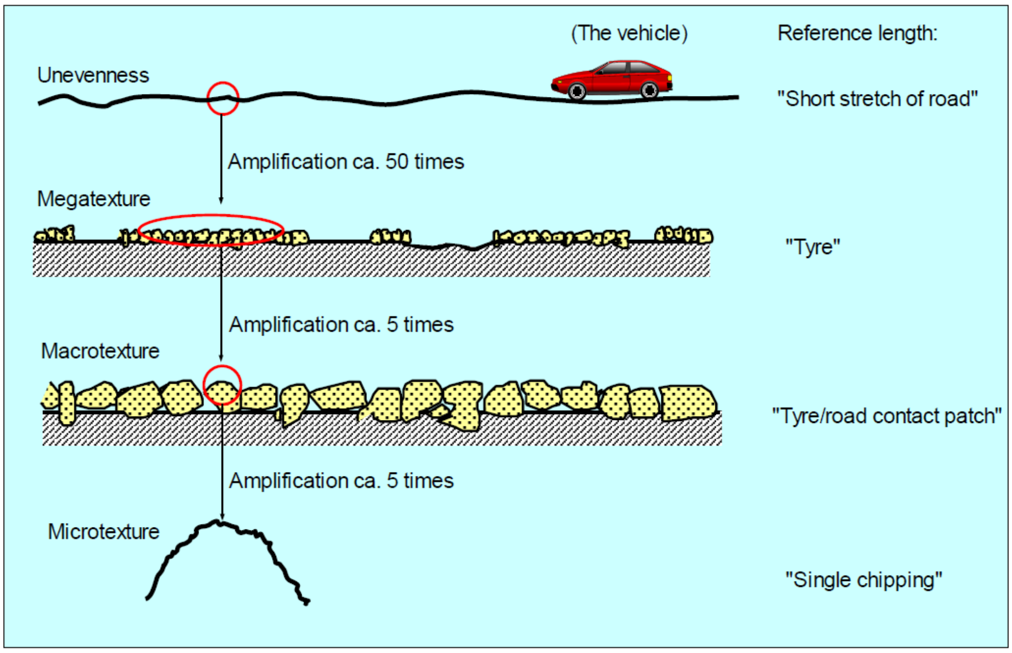


Figure 4.2: Illustration of the various wavelength ranges, from (Sandberg et al. 2011a)

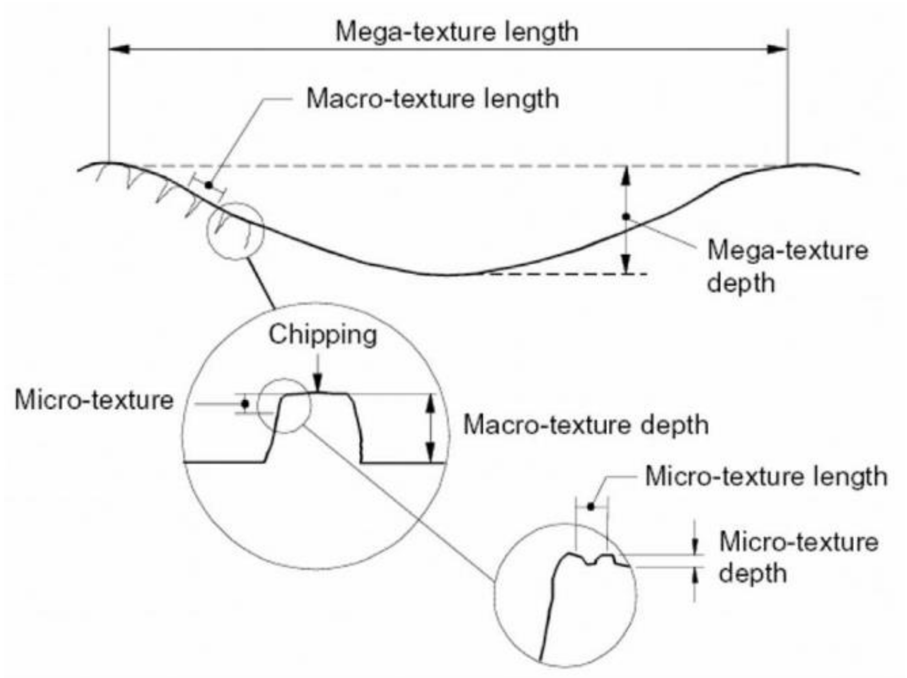


Figure 4.3: Texture Length and depth, adapted from UK Goverment (1999b)

Table 4.1: Standardised measure for macrotexture and unevenness

Parameter	Measures	Procedure
MACROTEXTURE	MTD Mean texture Depth ISO 10844:1994	Volumetric patch method or sand patch method: where a certain volume of sand or glass spheres is spread out with a rubber pad flush to form an approximately circular patch on the road surface, the diameter of which is measured. From the patch diameter and the sand volume, the mean depth of the texture over this patch is calculated, by dividing the volume of material by the area covered (International Organitazation for Standardization (ISO) 1994) (figure 4.4).
	MPD Mean profile Depth ISO 13473-1:2004	The MPD is obtained by averaging several main Segment Depth (MSD) values over a certain road section. The MSD is calculated from two halves of a 100 mm long profile (two 50 mm long segments), as shown in figure 4.5 (Sandberg et al. 2011a). Typically, used on concrete surface pavement.
	ETD Estimated Texture Depth ISO 13473-1:2004	The ETD is an estimation of the MTD obtained from a measurement of the MPD, with a transformation equation proposed in ISO 13473-1 (International Organization for Standardization (ISO) 2004): $EDT = 0.2mm + 0.8 \cdot MPD$ where *ETD* and *MPD* are expressed in mm.
UNEVENNES	IRI International Roughness Index ASTM E 1926 -08	The IRI is useful to estimate road roughness from longitudinal profile measurements. Longitudinal profile measurements for one wheel track are transformed mathematically by a computer program and accumulated to obtain the IRI numbers that increase in proportion to roughness.

Figure 4.4: Sand Patch Test, from Miller et al. (2012).

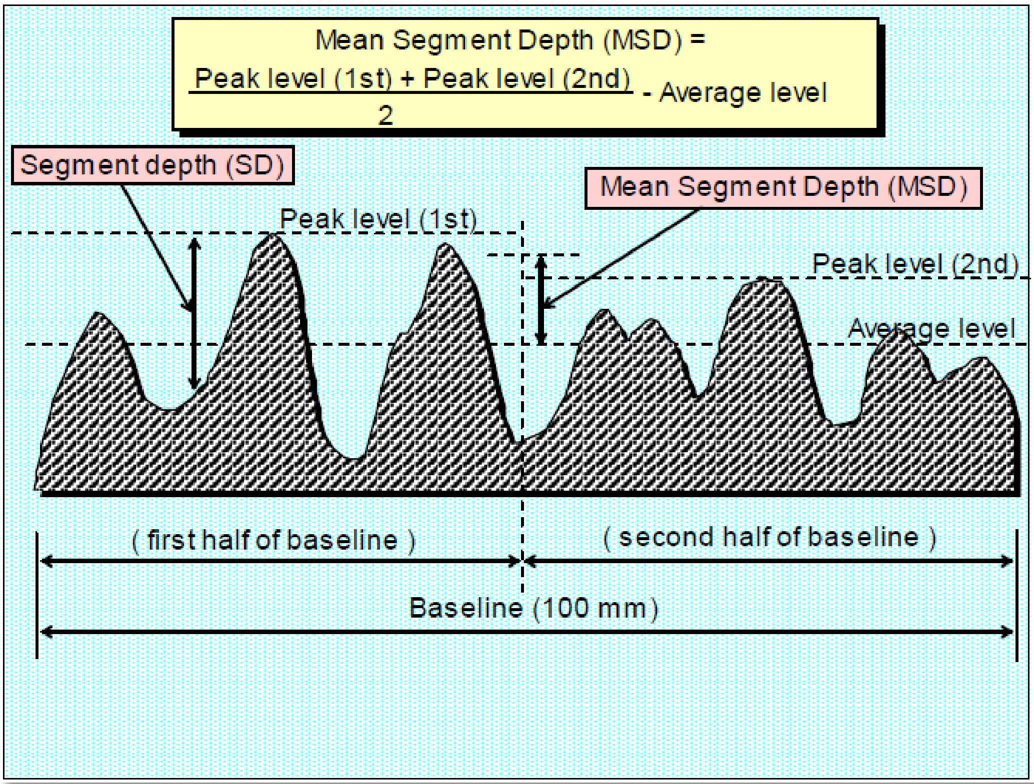


Figure 4.5: Illustration of the terms Segment, Baseline, Segment Depth (SD), and Mean Segment Depth (MSD) (SD and MSD are expressed in millimetres) from Sandberg et al. (2011a)

As mentioned above, road texture and its deterioration over time affect the vehicle/tyre interaction, producing different types of effects at different levels, based on texture wavelength. During the construction of a road, the control of the macrotexture and megatexture is particularly relevant affecting the skid resistance and the surface drainage. The unevenness, in particular the longitudinal one, influences the ride comfort of the road pavement, producing the reduction of the vehicle speed, vibrations in the wheel suspensions and affecting the Rolling Resistance (Haider and Conter 2012).

Sandberg et al. (2003) analysed the range of potential impact (positive or negative) that each component of the texture could have (figure 4.6). Based on this study, the impact on the rolling resistance is mainly due to the unevenness and the megatexture components. In most recent studies, this range has been updated, as will be described in the section 4.2.

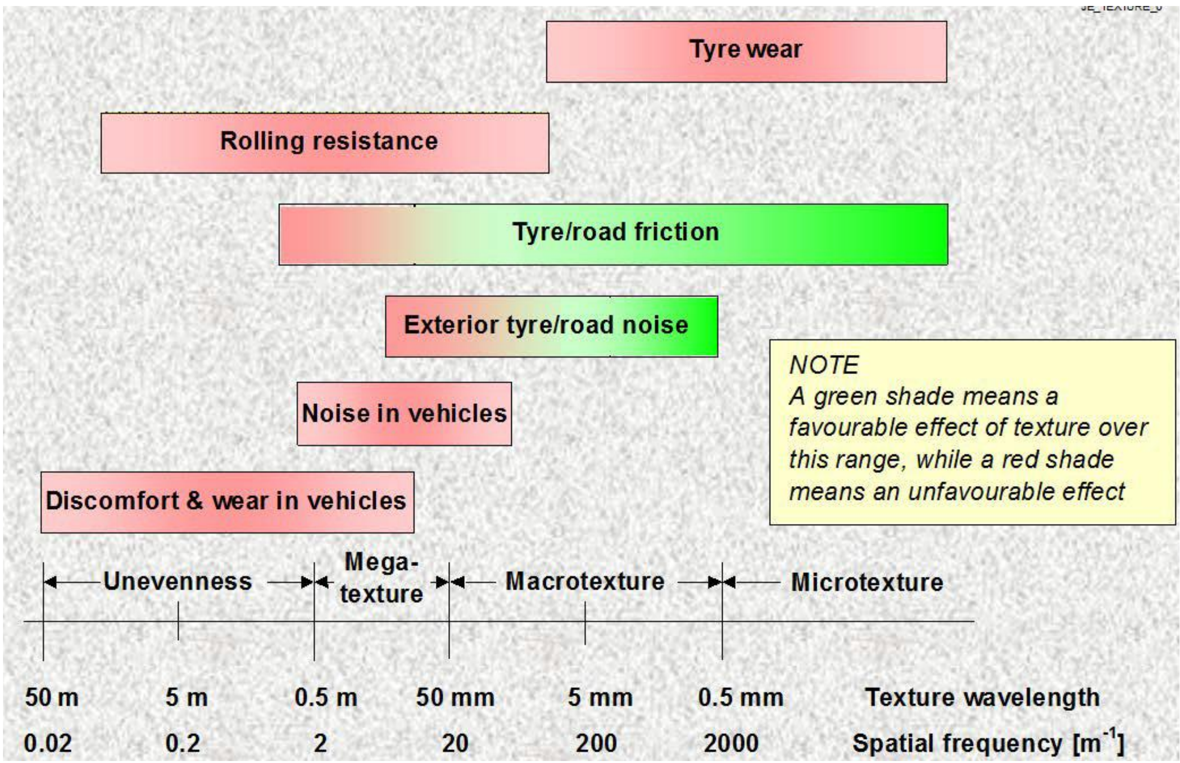


Figure 4.6: Anticipated effects, adapted from Sandberg and Ejsmont (2003)

4.2 Rolling resistance measurement methods

Different methods can be applied to measure the rolling resistance, based on the parameter measured, on the used tools, on the place where they are performed. Overall, they can be grouped in four categories:

- Measurements of the rolling resistance force on the actual roads with a special trailer and test tyres;

- Coast-down measurements and measurement of deceleration;

- Indirect method – measurement of fuel consumption for driving a fixed distance, with the same tyres on the vehicle, on different pavements.

- Laboratory measurements, including especially drum measurements (Bendtsen 2004b; Haider et al. 2011).

The ISO have published different standards that specify methods of measuring rolling resistance under specific conditions (International Organization for Standardization (ISO) 1992; International Organization for Standardization (ISO) 2009).

According to them, the main problem of these methods is that they tend to take into consideration additional measurements (e.g. suspension forces), reducing the possibility to achieve a good accuracy in the measurement of the rolling resistance force.

In particular, ISO (2009) introduces and defines the Parasitic Losses as: "l*oss of energy (or energy consumed) per unit distance excluding internal tyre losses, attributable to aerodynamic loss of the different rotating elements of the test equipment, bearing friction and other sources of systematic loss which may be inherent in the measurement*." This standard describes, therefore, which sources of loss are to be excluded from the result of the measurement, though measured:

- tyre spindle friction;
- measurement drum aerodynamic and bearing losses;
- tyre and wheel aerodynamic losses (due to air pulled around by the rotating tyre in the still surrounding air);
- bearing friction (bearing between wheel and axle).

Table 4.2 shows, for three of the above mentioned methods, the parameters measured and not measured. It is clear that any chosen method will result and imply some assumptions, and consequently, some limitations related to the model derived from the results (Haider et al. 2011). For more details, refer to Sandeberg et al. (2011).

Table 4.2: Parameters measured and not measured for three methods, from (Sandberg et al. 2011b)

Method	Parameter measured	Parameter/losses not measured
Drum (laboratory facility)	• Tyre/road rolling resistance + parasitic losses (including bearing resistance)	- Pavement deflection - Driving force resistance - Side force resistance - Losses on plane surfaces
Coastdown (full vehicle)	• Vehicle rolling resistance • Vehicle aerodynamic resistance In principle, "everything at coasting is measured: the problem is to separate put the effects in the data processing stage	- Data processing allow separation of aerodynamic resistance and vehicle rolling resistance; - Mechanical transmission resistance (depending on driving torque)
Trailer	• Tyre/road rolling resistance • Bearing resistance • (Trailer) suspension losses	- Driving force resistance - Side force resistance - Transmission resistance

4.3 Rolling Resistance mechanisms and models

As shown in section 2.3.2, the introduction of the rolling resistance in the system boundary of pavement LCAs is quite recent. However, the physical relationship between pavement properties, rolling resistance and vehicle fuel consumption has been an area of study for several years. The definition of the contribution of the rolling resistance, in terms of IRI and MPD, in the vehicle fuel consumption during the use phase of a pavement requires the identification of both a rolling resistance model (relating rolling resistance to pavement surface properties) and an emission model (relating traffic fuel emissions to the rolling resistance).

The first studies date back to the 1980s, when several rolling resistance measurement studies were carried out in Europe, in order to explore the impact of pavement properties on rolling resistance and their correlation with the vehicle fuel consumption, by using different test methods (Sandberg et al. 2011b).

Generally more recent is the research on pavement-induced rolling resistance performed in North America (Chatti and Zaabar 2012; Taylor et al. 2002; Taylor and Patten 2006; Zaniewski 1989). However, the absence of suitable laboratory or field test standards to address the effect of pavement condition on rolling resistance has produced research mainly focused on the direct correlation between pavement properties – IRI - and fuel consumption, neglecting the relationship with the rolling resistance. In addition, most of these studies are based on the comparison of the fuel consumption between the asphalt surfaced and concrete surfaced pavement (Wang 2013).

The relevance of the topic in the academic and industry environment is also highlighted by several EU and international projects that in the last years have investigated the correlation between these variables, in one way or in another, such as 'Integration of Energy Usage into Road Design" IERD (IERD 2002), "Energy Conservation in Road Pavement Design, Maintenance and Utilisation" (ECRPD) built on the IERD-project (ECRPD 2010), "Models for Rolling Resistance In Road Infrastructure Asset Management systems" MIRIAM, "Tyre and Road Surface Optimisation for Skid resistance and Further Effects" Tyrosafe and "Coordination and Implementation of Road Research in Europe" ERA-net ROAD.

From an analysis of the existing literature on the influence of road surface properties and vehicle rolling resistance, hence emissions, different studies provides differing results. This is due to a number of reasons:

- The road surface properties contributions are a relatively small part of the driving resistance or of just the rolling resistance and hence are difficult to measure;
- In the measurement of the rolling resistance and the identification of the components affecting it, it is complex to isolate the road surface effects from other effects (i.e. tyres) and quantify only the contribution of IRI and MPD;
- Different methods of measuring rolling resistance can provide different results (Hammarström et al. 2012), since any measurement method will imply some assumptions and some limitations.

Several detailed summaries of existing literature about rolling resistance have been published recently (Sandberg et al. 2011a; Wang 2013; Willis et al. 2015), reviewing the most significant studies around the world related to the correlation between pavement properties, rolling resistance and fuel consumption. Overall, they draw the following conclusions:

- An increase in the rolling resistance coefficient provokes an increase in the vehicle fuel consumption. This effect is particularly relevant on roads with no gradient and at constant speed (typically high highway speed) (Bendtsen 2004a).
- Rolling resistance is affected by both tyres and pavement properties.

- Macrotexture (MPD), unevenness or roughness (IRI) and stiffness represent the most significant pavement parameters influencing rolling resistance. In particular, the MPD can be considered currently the major variable to quantify the effect of the pavement properties on rolling resistance. The direct effect of the IRI on rolling resistance is considerably smaller due to the long wavelengths involved, which correspond to movements of larger sections of the whole vehicle than tyre tread elements.
- Texture and unevenness affect the rolling resistance producing an increase of its value; greater values of MPD and IRI correspond to greater rolling resistance.
- For light vehicles, the impact of MPD is around three times that of the IRI effect.
- The effect of roughness on rolling resistance may be affected by the vehicle speed. This is not true for the texture.
- The impact of the stiffness on rolling resistance has not been consistently explained and is as yet, uncertain.
- The research on the rolling resistance property of pavements needs further development, due to the high uncertainty that still characterize this discipline.

Based on these findings, a model describing the impact the pavement influence on rolling resistance should take into account both the effect of the MPD and IRI parameters, while the impact of stiffness cannot be included yet, since it is not yet clear.

There are just few models in the literature that have explored the combined effect of IRI and MPD: Highway Development and Management Model - version 4 (HDM-4), the model developed by the Swedish National Road and Transport Research Institute (VTI), within the European Commission project Miriam and a model developed by the University of California Pavement Research Center (UCPRC, Davis).

HDM-4 is an empirical - mechanistic model software tool developed by PIARC (World Road Association) to perform cost analysis for the maintenance and rehabilitation of roads (Kerali et al. 2000). It includes both a model for simulating rolling resistance from IRI and MPD and an engine model to link the effects of rolling resistance to vehicle fuel consumption**.** The mechanistic part of HDM-4 analyses all driving resistances on the engine, based on the vehicle speed and road gradient, while the empirical part uses coefficients which convert the driving resistances to energy consumption, determined through various experiments and calibrated with measured data**.** In 2011, the fuel consumption model was calibrated for U.S. conditions as part of the NCHRP Project 1-45 (Chatti and Zaabar 2012). The results of this study showed that IRI and road gradient had a statistically significant relationship with fuel consumption at low and high speed, while macrotexture (MPD) was not statistically significant at high speed. This is contradictory to the observations of other studies, as described above. The authors explained this result by the fact that at higher speed the air drag is the predominant component of the fuel consumption and minimizes the increase in rolling resistance due to macrotexture. In order to use HDM-4 as a road decision support tool in UK, the UK Department for Transport (DfT) and the University of Birmingham calibrated the model under English conditions (Odoki et al. 2013). Unfortunately, the calibration factors are not published.

The VTI model, instead (Hammarström et al. 2012), includes a general rolling resistance model and a fuel consumption model; the first is mainly based on empirical data from coastdown measurements in Sweden, and incorporated into a driving resistance based fuel consumption model. The fuel consumption model has been calibrated based on calculated values from the computer program, a theoretical model developed at VTI to calculate fuel consumption and exhaust emissions from traffic due to various characteristics of vehicles, roads and driving behaviour (Hammarström et al. 2012). The VTI model allows the calculation of the fuel consumption related to the pavement surface properties for a car, for a heavy truck and for a heavy truck with trailer, by using two different equations: the first one relates the rolling resistance to the surface properties of a pavement (IRI and MPD) (eq. 1), the second one expresses the fuel consumption as a function of the rolling resistance, speed and other road condition variables, such as gradient and horizontal curvature (eq. 2).

Rolling resistance for a car:

$$F_r = m_1 \times g \times (0.00912 + 0.0000210 \times IRI \times v + 0.00172 \times MPD) \qquad (1)$$

Where m_1 is the vehicle mass (kg), g is the gravitational constant, v is the vehicle speed (m/s), *IRI* is the road roughness (m/km) and *MPD* is the macrotexture (mm).

Fuel consumption function for a car:

$$F_{cs} = 0.286 \times \left(\begin{pmatrix} 1.209 + 0.000481 \times IRI \times v + 0.394 \times MPD + 0.000667 \times v^2 + \\ +0.0000807 \times ADC \times v^2 - 0.00611 \times RF + 0.000297 \times RF^2 \end{pmatrix}^{1.163} \times v^{0.056} \right) \qquad (2)$$

Where *ADC* is the average degree of curvature (rad/km) and *RF* is the road gradient (m/km).

Recently, Wang et al. (2012b) developed an approach to estimate the net life cycle impact from pavement M&R strategies considering both materials, production and construction phases with the use phase. The LCA model described in this paper for the estimation of the rolling resistance impact includes a new method, incorporating both pavement roughness and macrotexture, in terms of IRI and MPD. This model was included in the framework for pavement LCA, proposed by the FHWA (Harvey et al. 2016) and involves the use of two software, already mentioned in this review, HDM-4 and MOVES.

The methodology consists in three main steps:

- The development of IRI and MPD time progressions for different pavement types and rehabilitation strategies from Caltrans Pavement Condition Survey (PCS) database.
- Calculation of the rolling resistance by using the equation proposed in the HDM-4 model, including IRI and MPD parameters. The calculated value of rolling resistance is used to update the corresponding value in the MOVES software.
- Calculation of the vehicle emissions with MOVES, based on the traffic information introduced.

Although HDM-4 is able to estimate the rolling resistance impact due to pavement roughness and macrotexture, some limitations affect its use. Indeed, it does not take into account speed fluctuation (only steady speed) and vehicle technology improvement and it does not address air emissions from vehicles. For these reasons, the model was only used to estimate the rolling resistance (then provided to the MOVES software to estimate the emissions), by using the equations (3) and (4):

$$F_r = CR2 \times FCLIM \times \left[b11 \times Nw + CR1 \times \left(b12 \times M + b13 \times v^2 \right) \right] \quad (3)$$

$$CR2 = Kcr2 \times (a0 + a1 \times MTD + a2 \times IRI + a3 \times DEF) \quad (4)$$

Where *Fr* represents the rolling resistance; *CR1* and *CR2* are respectively functions of tyre type and surface characteristics; FCLIM is the climatic factor related to the percentage of driving done in snow

and rain; *b11, b12,* and *b13* are the coefficients related with tyre type and technologies; *v* is the speed; *Kcr2* is a calibration factor; *a0, a1, a2,* and *a3* are coefficients for pavement surface characteristics from HDM-4 model; *MTD* is the mean texture depth from the sand patch method; *DEF* is the Benkelman Beam rebound deflection; *M* is the mass of vehicles; *Nw* is the number of wheels.

As mentioned above, MOVES is a vehicle emission model that provides emissions based on the Vehicle Specific Power (VPS) parameter, an indicator of the engine running status. It can be defined as the power required by the vehicle to move at various conditions of speed and it takes into account the aerodynamic drag, the rolling resistance, the engine inertial delay and the gradient force (see equation (5)).

$$
\begin{aligned}
VSP &= F_{RR} / M + F_{AR} \times v / M + F_{IR/GR} \times v / M = \\
&= C_R \times g \times v + 0.5 \times \rho_a \times C_D \times A_{front} \times (v + v_w)^2 \times v / M + \left[a \times (1 + e_1) + g \times grade \right] \times v = \\
&= A \times v / M + B \times v^2 / M + C \times v^3 / M + \left[a \times (1 + \varepsilon_1) + g \times grade \right] \times v
\end{aligned} \tag{5}
$$

Where *FRR*, *FA*R and *FIR/GR* represent respectively, the rolling resistance, the aerodynamic resistance the inertial force and the gradient resistance. C_R is the rolling resistance coefficient; ρ_a is the ambient air density; v is the vehicle speed; v_w is the speed of headwind into the vehicle; A_{front} is the front area of the vehicle; C_D is the aerodynamic drag coefficient; ε_i is the equivalent translational mass of the rotating components of the powertrain; *grade* is the vertical rise divided by slope length; *g* is the acceleration of gravity; *M* is the mass of vehicles; and *a* is vehicle acceleration. *A*, *B*, and *C* represent coefficients of different order terms of velocity. The one order term “*A*” coefficient roughly relates to the rolling resistance component, the two order term “*B*” coefficient includes higher order rolling resistance factors and mechanical rotating friction losses (normally, it tends to be small). Finally, the “*C*” coefficient (three order term) corresponds to the air drag coefficient component.

These three coefficients are provided by the Track Road Load Horse Power (TRLHP) from the Mobile Source Observation Database (MSOD) (EPA 2010) and obtained by dynamometer tests on a wide range of vehicles and tyre types, running on smooth surface where RR $\cong$ MPD $\cong$ 0. This means that the term A related to the rolling resistance component only takes into account the effect of the tyre type and vehicles and excludes the effect from the pavement. Therefore, when the rolling resistance is related to a real pavement, the coefficient A in MOVES needs to be updated by increasing proportionally the effect of surface characteristic from dynamometer to a real pavement. This is done through the equation (6)

$$
\begin{aligned}
A_{updated} &= A_{default} \times CR2_{pavement} / CR2_{dynamometer} = \\
&= A_{default} \times \left[a0 + a1 \times MTD + a2 \times IRI + a3 \times DEF \right] / \left[a0 + a1 \times (1.02 \times 0 + 0.28) + a2 \times IRI + a3 \times DEF \right] = \\
&= A_{default} \times \left[a0 + a1 \times MTD + a2 \times IRI + a3 \times DEF \right] / \left[a0 + a1 \times 0.28 \right]
\end{aligned} \tag{6}
$$

Where, based on the HDM-4 document:

$$
MTD = 1.02 \times MPD + 0.28 \tag{7}
$$

This approach allows to estimate the vehicle fuel consumption and emissions, for each specific combination of IRI and MPD values, road and road access type, vehicle type and year.Based on this methodology, Wang et al. (2014a); (2014b) developed an equation model where the CO_2 EF for the rolling resistance are developed as a continuous function of MPD and IRI, for each combination of factorial variables (pavement type, road type, road access type, vehicle type mix) for a total of 400 equations.

$$T_{CO_2} = a_1 \times MPD + a_2 \times IRI + Intercept \tag{8}$$

Where T_{CO_2} is the tailpipe CO_2 emission factor, the terms a_1, a_2 and intercept are the coefficients derived from the linear regression, depending on surface type and access type, year and vehicle type, *IRI* is the road roughness (m/km) and *MPD* is the macrotexture (mm). In particular, the Intercept term represents the CO_2 emissions due to the total driving resistance, excepting the contribution of the pavement deterioration, estimated with the other two components.

4.4 Implementation of the rolling resistance component in pavement LCA studies

As mentioned above, in the last years some studies have started to include the impact of the pavement properties in the pavement LCA framework. Table 4.3 summarises the major LCA studies, which include the effect of pavement surface condition on rolling resistance within the system boundary or related the implementation of this component in pavement LCAs. The table shows that overall there are just a few recent studies including the effect of both roughness and texture and they use the HDM-4 or the VTI models, described above.

Most of the studies where performed in the U.S. and use rolling resistance models, taking into account only the effect of the roughness. This is justified by the fact that, as mentioned above, the majority of the researches involving rolling resistance in the U.S. considered only the IRI impact.

Table 4.3: LCAs including e rolling resistance in pavement LCAs

Study	**Country**	**Rolling resistance components included**	**Comments**

(Santero and Horvath 2009)	U.S.	Roughness	Rough estimation based on literature data
(Zhang et al. 2010)	U.S.	Roughness	Linear relationship between IRI and fuel consumption based on data from heavy duty trucks only, tested at low speed on test track
(Yu and Lu 2012)	U.S	Roughness	Linear relationship between IRI and fuel consumption based on Amos (2006)
(Wang et al. 2012b)	U.S.	Roughness and texture	HDM-4 was used to consider the rolling resistance and MOVES (Motor Vehicle Emission Simulator) (EPA's Office of Transportation and Air Quality (OTAQ) 2014) was used to model the vehicle emissions as a function of rolling resistance
(Yang 2014)	U.S.	Roughness	Model presented by (Zaabar and Chatti 2010)
(Bryce et al. 2014)	Portugual	Roughness	Model presented by (Yu and Lu 2014)
(Santos et al. 2015)	Portugual	Roughness and texture	Model presented by. (Hammarström et al. 2012)
(Bryce et al. 2014)	U.S	Roughness and texture	Model presented by (Hammarström et al. 2012) and from the National Cooperative Highway Research Program (NCHRP) (Chatti and Zaabar 2012)
(Araújo et al. 2014)	Portugual	-	The energy consumption variation associated with different rolling resistances of the surface layers is evaluated with laboratory tests
(Wang et al. 2014a)	U.S.	Roughness and texture	The vehicle CO_2 EF are estimated as a continuous function of MPD and IRI, by using HDM-4 and MOVES (Motor Vehicle Emission Simulator)
(Chen et al. 2015)	U.S	Rougness	Model presented by(Yu and Lu 2012)
(Xu et al. 2015)	U.S.	Roughness	Model presented by (Zaabar and Chatti 2010)

4.5 Parameters affecting the results of the rolling resistance component in LCA studies

The use of these models requires the identification of some specific input parameters that may affect the results, pavement condition deterioration rate with time, traffic growth and EF.

Pavement deterioration rate

During the use phase of a road pavement, pavement deterioration leads to changes in unevenness and macrotexture, that vary over time based on different variables; pavement material (asphalt or concrete), traffic volume and truck traffic, climate, pavement age and maintenance treatments (Wang et al. 2014). Roughness (IRI) tends to increase over time for a specific road but the variation of the texture depth (MPD) can be positive or negative, depending on several mechanisms. Unlike in the USA for instance, in the UK new surfaces are generally produced with high initial texture depth to maintain high-speed skidding resistance and a reduction in texture depth over time is observed, especially in the more trafficked lanes. The rate of reduction depends on several variables; for instance, after a surface dressing, the embedment of chippings into the underlying layer, under the action of traffic, produces a rapid drop in the texture depth over the first one or two years. The final value that the texture depth reaches depends on the substrate of the surface dressing and the type of aggregate used for chippings. Other surfacing materials, like rolled asphalt do not change so markedly during the first few years, but the average texture tends to reduce in subsequent years, at least in the more trafficked lanes (Jacobs 1982), (UK Goverment 1999). This type of behaviour has also been observed in other studies related to other European countries (Hammarström et al. 2012). Several studies have been performed in the UK in order to predict performance in terms of texture depth. In 2009, the UK Roads Board has developed and introduced SCANNER (Surface Condition Assessment for the National Network of Roads) surveys, to provide a consistent and network-wide method of measuring the surface condition, including ride quality, rut depth, intensity of cracking, texture depth and edge condition. The output results from the survey are then delivered in a UK Pavement Management System (UKPMS)-compliant format to local authorities, for loading into their pavement management systems (Transport Research Laboratory 2017). The main aim of this system is to support local authority maintenance management decisions through the systematic collection and analysis of condition data. Although road surface condition data are currently collected and stored through this methodology, there are no general models in the UK able to predict the change of texture depth over time

Traffic growth

Another important variable necessary to quantify the future level of traffic emissions is the traffic growth factor. It requires the understanding of how people make travel choices and the expected path of key drivers of travel demand. Recent studies (Masters 2015) have shown how in the UK the rates of traffic growth are consistently overestimated by the Department for Transport (see figure 4.7) and the same traffic congestion is a limiting factor for large traffic growth; so, this parameter is an uncertain factor that could significantly impact the results.

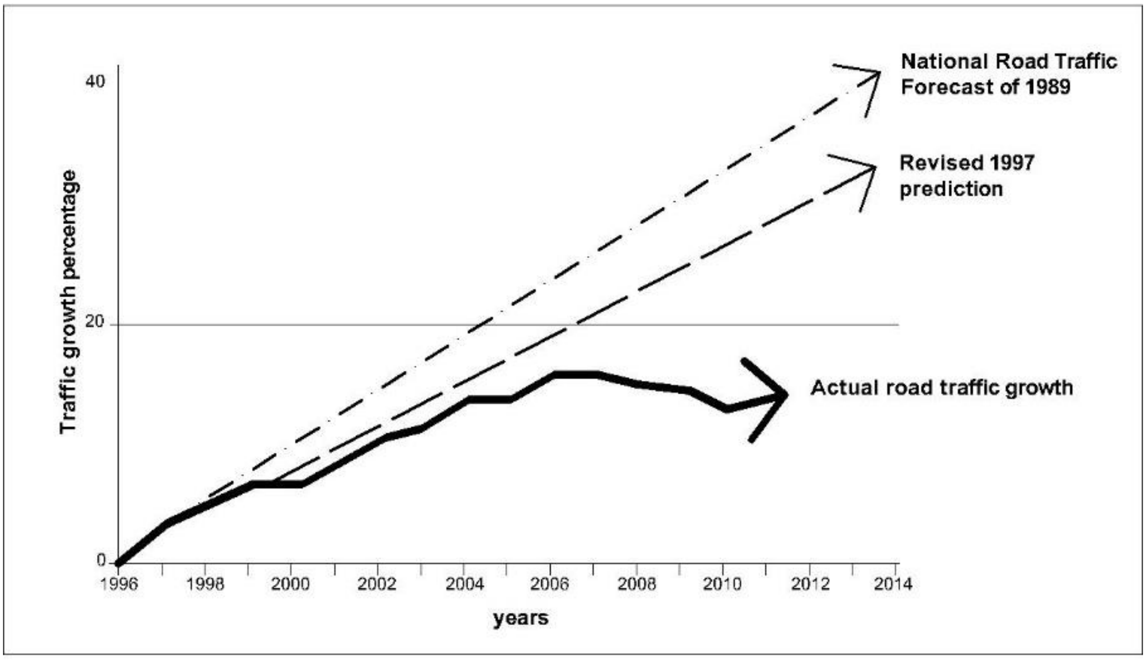


Figure 4.7: Prediction and actual traffic growth in the UK, adapted from Masters (2015)

Emission Factors

Finally, the EF and fuel consumption or efficiency improvements should be taken into account, in order to estimate future levels of emissions. This estimation is particularly complex, since it requires the prediction of future technological improvements, based on the announced government policy. The importance and the main characteristics of some of the main emission models was already described in sections 3.2 and 3.3. In the UK, the Department for Transport's National Transport Model (NTM) has provided forecasts of CO_2

emission changes by vehicle type between 2010 and 2040, taking into account technological improvements in fuel type and efficiency (UK Department for Transport 2013a).

4.6 Summary and discussion

LCA/Carbon Footprint has emerged as a methodology used by governmental and non gonvernmental institutions, organizations and industries in a wide range of sectors to improve the performance and to assess potential environmental aspects associated with a product (or service). The main advantage of this methodology is that it provides a holistic approach, allowing comprehensive evaluations of all upstream and downstream energy inputs and multimedia environmental emissions. In addition, a formal procedure for conducting LCA has been standardized by the International Organization for Standardization making it a structured evaluation methodology.

In the last two decades, LCA principles have been implemented and adopted in the pavement LCA domain. However, performing a pavement LCA is much more complex than it is for a general product or service, given the complexity of this structure. There are still methodological issues that reduce the accuracy and reliability of the output results of pavement LCA. Despite some divergences in the system definition of a road pavement LCA, overall the literature identifies the following phases in the life cycle of a pavement: material production, construction, maintenance, use phase and EOL.

The work zone traffic delay component during maintenance activities and the rolling resistance impact during the use phase can have a dominating impact in the life cycle of a pavement and their impact can span a very large range, based on the input parameters. However, the estimation of these components is particularly complex and for this reason, they were generally omitted from the system boundary of pavement LCA studies until 2010. In the last years, some efforts have been made from the research community to fill this research gap, however their estimation is still characterized by a high level of uncertainty, in terms of modelling and input parameters.

Regarding the work zone traffic delay component in pavement LCA studies, macroscopic analytical models and microsimulation models are the most used models to estimate the impact of the work zone during maintenance activities. Although the former are much easier and cheaper than the latter, they are subject to several limitations. Several studies have introduced improvements to increase the accuracy of these models, however in the pavement LCA domain, basic macroscopic analytical approaches are still used. Moreover, these obsolete models are usually based on the HCM that includes empirical data obtained for U.S. roads and highways. The microsimulation approach is clearly a more sophisticated and flexible method that need to be adapted to model work zone and require the introduction of many site - specific data to provide accurate results. The choice of the model used should be discussed in each pavement LCA, explaining reasons, resources and the aims of the study behind that specific choice. The choice of the most suitable method of modelling is not the only concern in the traffic delay analysis. Traffic volume, TM layout, EF and network boundary may significantly affect the LCA outcomes. Currently, pavement LCA studies including traffic delay tend to analyse the same TM configuration (probably the most common for U.S roads), including lane closure and reduction of the overall capacity and do not take into account the possible impact of the work zone on the larger network. Also, the selection of the appropriate emission model for the purpose of the study can be complex and different variables may affect the effectiveness of the model used.

The rolling resistance is a force resisting the movement of the vehicles. Although much of the rolling resistance can be tracked to tyre properties, it is also affected by other parameters related to the characteristics of the pavement, such as the pavement surface properties, macrotexture - usually represented by parameters mean profile depth (MPD) or mean texture depth (MTD) - and unevenness or pavement roughness - typically measured by the International Roughness Index (IRI), and the pavement structure. However, the research knowledge on pavement deflection is not sufficient to implement this component in a comprehensive pavement LCA framework. For this reason, this component was not included in the scope of this study.

Quantifying the influence of the pavement surface condition, in terms of IRI and MPD, on the rolling resistance is complex. Several studies have developed models to correlate pavement surface properties, rolling resistance and fuel consumption but only few models in the literature have explored the combined effect of IRI and MPD, both in USA and in Europe. However, there is still a high level of uncertainty concerning the lack of validated models used to analyse the vehicle emissions and the influence of specific variables and assumptions on the results. In order to obtain reliable results that can be interpreted by decision makers, it is necessary that methods of modelling and the assumptions adopted in LCA and carbon footprint studies are transparent.

The use of rolling resistance models requires the estimation of some parameters that can affect the final result, including the pavement condition deterioration rate with time (in terms of IRI and MPD), the traffic growth and the EF/fuel efficiency improvements.

In the UK, currently there are no validated models able to predict the relationship between rolling resistance and pavement surface properties and the use of the models in the literature could lead to unreliable results. In addition, there are no models to predict the deterioration of roughness and texture depth over time depending on maintenance treatments, traffic volume and type, surface properties and materials.

Despite the recognized importance of sensitivity and uncertainty analysis to ensure reliability of LCA results, these tools have traditionally been avoided in life cycle inventory and impact assessment phases. Results in LCAs are characterized by high uncertainty due to the combined effects of several elements, namely data variability, erroneous measurements, wrong estimations, unrepresentative or missing data and modelling assumptions. Overall, the main sources of uncertainty are data variability, input uncertainty and model imprecision.

Recently, an increasing awareness was placed on these issues and most of the pavement LCAs performed included sensitivity and/or uncertainty analysis. However, the procedures, methodologies and approaches used are not yet included in a standardized framework to carry out uncertainty and sensitivity analyses with a structured approach. The identification of suitable models and of the sensitive parameters in each phase of the pavement LCA results is a basic requirement to address this issue.

5 Methodology

This chapter describes the methodology adopted for the two case studies. After a general introduction, a brief description of the methodology and of the assumptions used for the Construction/M&R phases are presented. Although the work zone traffic delay impact (changes to traffic flow, including work zone speed changes and delay and diversions where applicable) can be considered a component of the construction and M&R phase, a specific section will be dedicated to this component, considering the aims and objectives of this thesis. Finally, the last section will be focused on the impact of the rolling resistance - in terms of pavement surface properties - on the fuel consumption and CO_2 emissions of vehicles.

The sections related to the impact of the work zone traffic delay and the rolling resistance are divided into two parts. The first one includes a comparison of the results obtained using two different models available in literature, while the second one the results related to a sensitivity test performed on several variables, discussed in Chapter 3.

5.1 Introduction

In order to pursue aims and objectives listed in Chapter 1, the methodology explained in this chapter will be adopted. Figure 5.1 represents the outline of the process used in this study.

The main aim of this research is not to perform a LCA, characterized by a specific framework and procedure, but to explore the influence of the used model and the methodological assumptions made to estimate the impact of the work zone during a construction/maintenance event and the PVI rolling resistance in the use phase of a pavement.

In particular, the main aims of this work are:

- to add to knowledge in the carbon footprint and LCA fields, investigating the limitations of this approach when applied to a complex system as pavement engineering;
- to add understanding of maintenance phase - in terms of traffic delay impact - and road pavement use - in terms of rolling resistance - by assessing their overall relevance during the life cycle, identifying the range of potential impact and their magnitude, in terms of CO_2 emissions.

- To investigate the impact of the models used to estimate these components and the level of maturity when implemented in a pavement LCA framework.

- To assess the variables and conditions that make the rolling resistance and the traffic delay components more significant.

- make recommendations concerning the data and the results provided by an LCA, so that they can be used effectively to assist Highway Authorities in decision making situations.

The GHG emissions due to these components (work zone traffic delay and rolling resistance) were estimated using different models available in literature and performing a sensitivity test on specific input variables. The comparison of the used models and the output results of the sensitivity test allowed to understand if the current level of knowledge is sufficient to implement these components in a standard pavement LCA framework in the UK. In particular, the sensitivity test provided information about which are the most sensitive input data and how to manage them in order to reduce the level of uncertainty that they generate.

Although this study is focused on the impact of the work zone and the PVI rolling resistance, in order to assess the relative environmental impact and the magnitude of these components in the life cycle of a pavement, the other components of the construction and maintenance phase were also taken into account, even if not in detail.

Climate change or GWP is the only impact category assessed in this research. This decision is due to two reasons:

- Large amount of GWP assessments carried out to date, and, therefore, large amount of data available for this study.

- The current interest for this approach makes the results of the study relevant to the majority of practitioners and stakeholders.

For the work zone traffic delay and the PVI rolling resistance impact, only the CO_2 emissions are considered for the GHG estimation, since this is the biggest component of the vehicle tailpipe CO_2e emissions (over 99.8%) (Wang et al. 2014c).

To facilitate the evaluation and the understanding of the used models (in terms of reliability and applicability), two case studies with different geometry and traffic volume will be analysed.

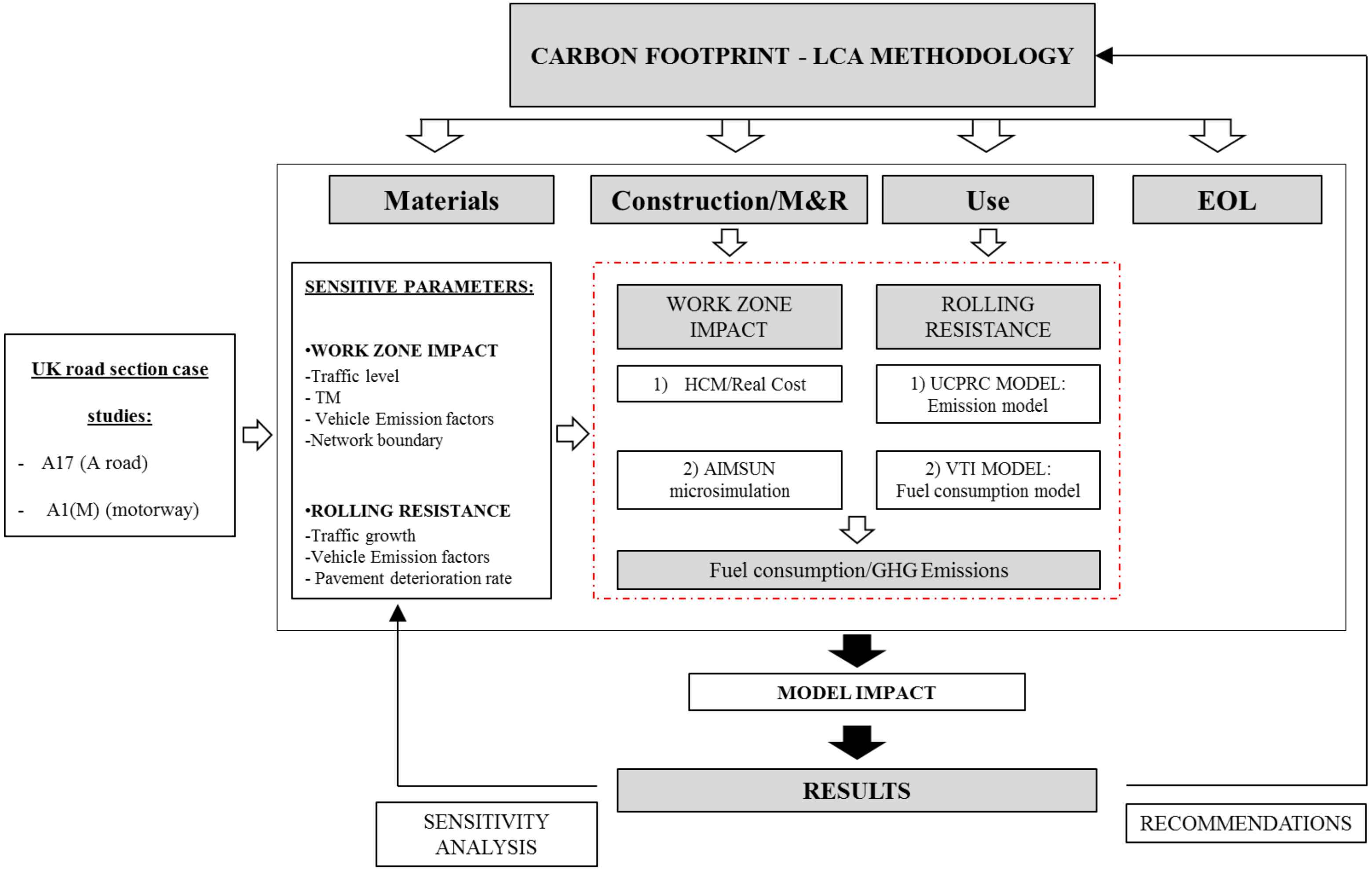


Figure 5.1: Outline process of the studied system

5.2 Case studies

Table 5.1 includes an overall description of the two case study models and the figures 5.2 and 5.3 show an overview of the selected pavement sections and their locations. Other specific input information, such as construction and TM data, are included in the related sections (sections 5.3 and 5.4).

Table 5.1: Case studies details

Case study	AADT in 2009		Road type	Length section [m]	Surface treatment in 2009
	Motor vehicles	HGVs			
A17	14,400	1,900	A road	200 - single carriageway 520 - dual carriageway	Hot Rolled Asphalt
A1(M)	45,862	5,640	Motorway	4000 (two lanes)	Thin Surfacing

Two very different case studies (road type, traffic volume and design) and multiple scenarios of analysis have been included in this study to underpin the validity of the research on a range of diverse conditions. A multiple case studies approach increases the explanatory power and generalizability of the research increasing its effectiveness. The aim of this study, therefore, is not to compare the results obtained for the two road segments, but to evaluate the impact of different approaches to estimating work zone traffic delay and PVI rolling resistance on the LCA results, for very different case studies, too see if general conclusions can be drawn.

The A17 case study is a 720-m section of road - 200 m length of dual carriageway and 520 m length of single carriageway - located in Lincolnshire on the A17 between Sutton Bridge and Kings Lynn, an interurban road in the UK East Midlands. Based on the AADF in 2009, it can be classified as a low to medium trafficked road.

The A1 (M) case study - 4 km section of a dual carriageway motorway located in the North East of England, UK - can be considered a medium–high trafficked road segment.

These two sections were chosen for a number of reasons. The first reason is that, although motorways and major trunk ‘A’ roads account for a small percentage of the UK road network in length, they carry a large and consistently increasing amount of traffic. In 2014, major roads combined accounted for 13% (1% motorway and 12 % ‘A’ roads) of road length and carried 65 % of total road traffic in Great Britain (21% motorway and 45% ‘A’ roads) (UK Department for Transport 2016).

The existence of previous studies focusing on other LCA phases of the A17 road segment (Galatioto et al. 2015; Huang et al. 2014; Huang et al. 2013; Spray et al. 2012; Spray 2014) and the appropriate level of information and data available provided by Lincolnshire Highways Authority are the main reasons why it was selected as a case study.

For the A1(M), the input data were provided by Highways England. It was chosen because of the significant differences to the A17 case study, in terms of traffic volume, design, road type and TM. A wider analysis on diverse road sections may be helpful to draw overall conclusions as to which methods may be most appropriate. In addition, they will also allow decision makers to understand the degree of confidence they can have in results and the uncertainty inherent in road LCA, under different scenarios.

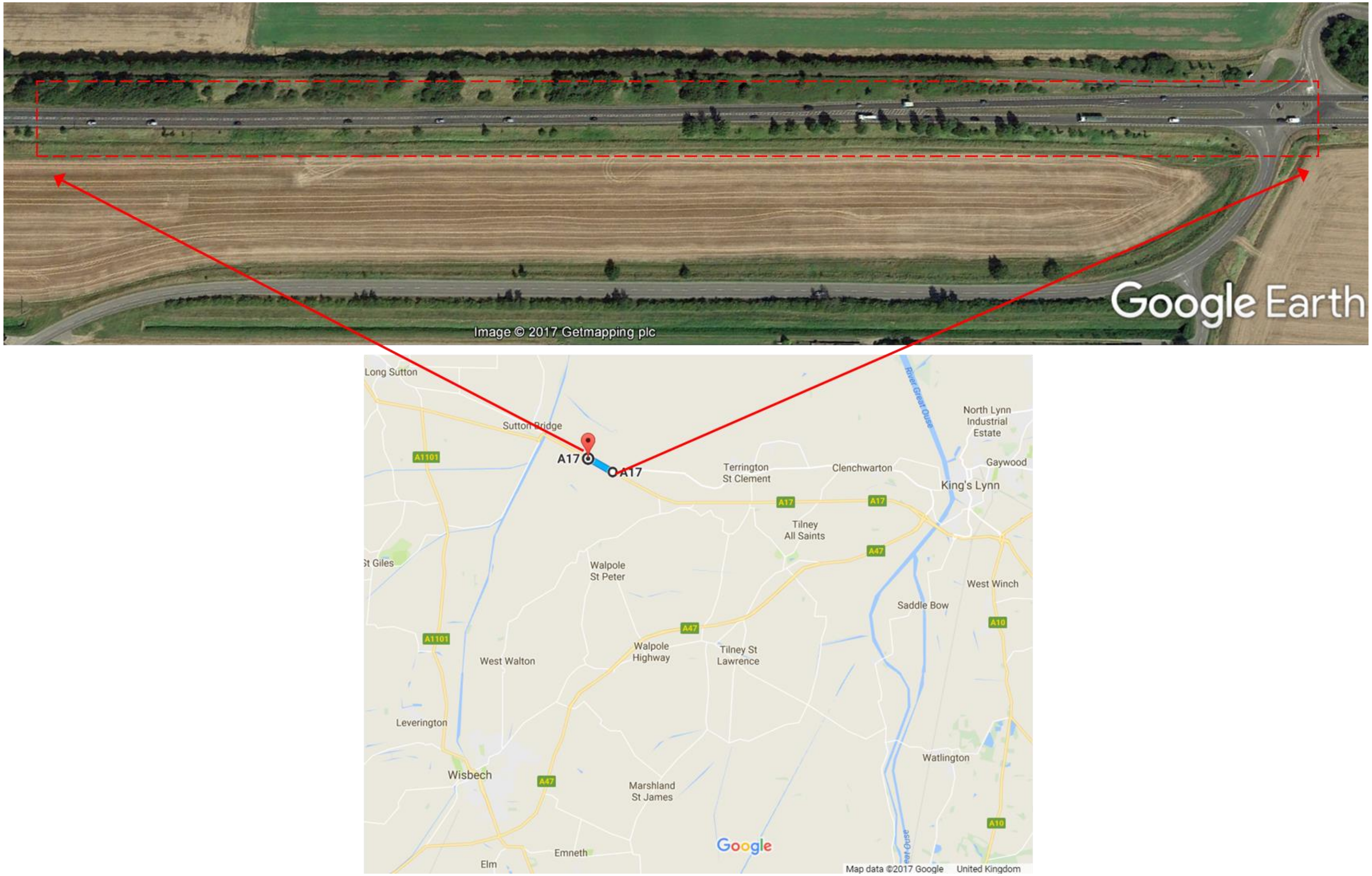


Figure 5.2: A17 overview and location

Figure 5.3: A1(M) overview and location

Figure 5.4 shows the construction history and assumed future maintenance of the two case studies.

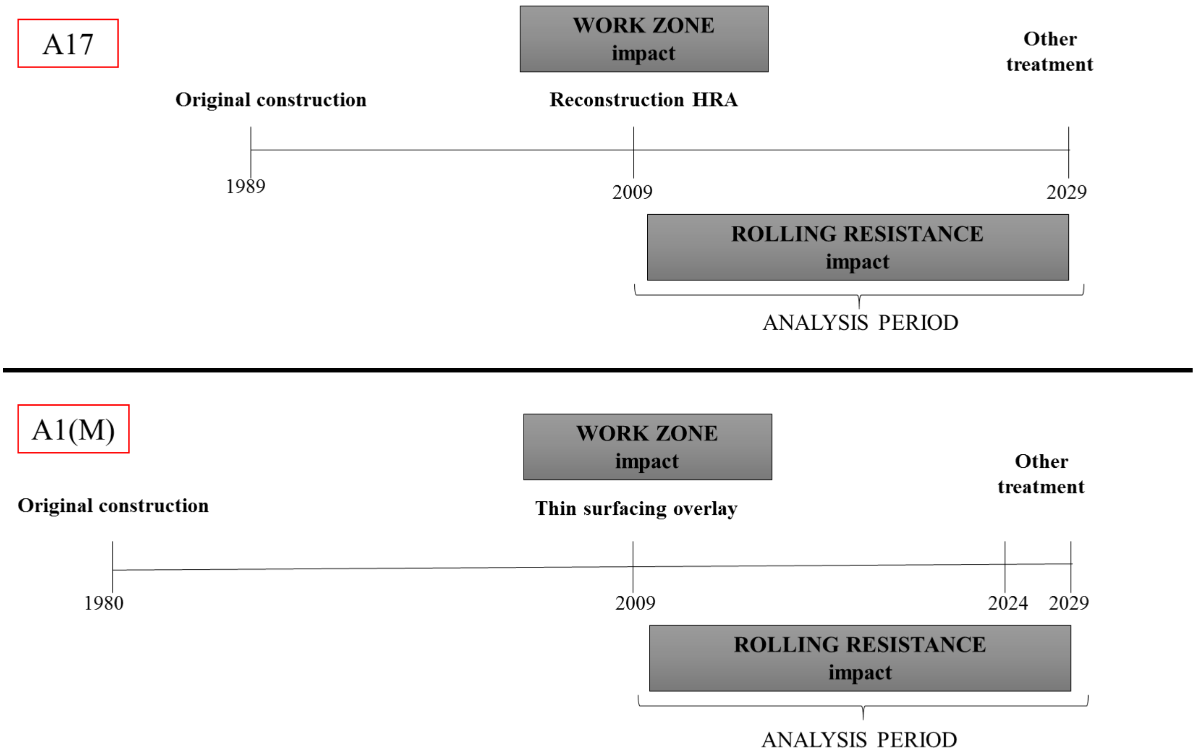


Figure 5.4: Analysis period of the selected case studies

The original construction of the A17 case study dates back in 1989, followed by some minor maintenance events until 2009, when a major rehabilitation was undertaken. The original construction of the A1(M) took place in 1980 and in 2009 a thin surfacing overlay was applied to a 4 km section of both carriageways.

The same analysis period of 20 years was selected for the two case studies, starting in 2009 until 2029 when a future rehabilitation is assumed to take place for both of them. For the A1(M), the life period of a thin surfacing is assumed to be 15 years (2009- 2024), but for homogeneity with the other case study, 20 years of analysis period was considered. This approximation was possible since the aim of this research is not to compare different maintenance strategies or compare the results from the two case studies, but to see if similar conclusions about the use phase in LCA can be drawn for different roads.

The analysis of the work zone traffic delay impact is based on the construction/maintenance event in 2009 (reconstruction for the A17 and thin surfacing overlay for the A1(M)). The impact of the rolling resistance on fuel consumption during the use phase will be assessed in the selected analysis period, starting in 2009 until 2029.

5.3 Material production and Construction/M&R phases

This section includes the description of the methodology used to calculate the impact of the material production and Construction/M&R phases in the pavement LCA framework. The analysis of the impact of the work zone traffic delay (speed change, delay and detour), that is a component typically included in the Construction/M&R phases, will be described in a specific section (5.4).

The CO_2e emissions associated with these phases were calculated modelling the two case study sections with the commercial LCA software Simapro. This program is characterized by the flexibility that allows the methodological assumptions to be tested and provides accurate calculations. Moreover, it includes the Ecoinvent database that allows data gaps to be filled, when primary data are not available.

For the A17 case study, the impact of these specific phases was investigated in another research thesis, involving the same road section (Spray 2014) and focused on sensitivity analysis of the co-product and EOL allocation models. In the above cited study, the calculation of the CO_2e emissions of the road segment was performed in accordance to the asPECT protocol that is based on PAS 2050 (BSI 2008, 2011). These represent, respectively, the most used and important protocol and standard used in the UK to quantify the life cycle GHG emissions from goods and services. The software Simapro was used to create an asPECT equivalent model for the case study.

For the A1(M), the same approach was applied and the same methodological assumptions were made.

Tables 5.2 and 5.3 show the construction details of the two road segments for the original construction and the maintenance event in 2009.

For the A17, the original design was typical of road construction at this time. It consisted of a CBM3 (Cement Bound Material) as a Base Course with a Dense Binder Course (DBC) and chipped Hot Rolled Asphalt (HRA) Surface Course. The DBC was laid in two layers with 40 mm nominal size gravel and 28 mm nominal size granite aggregate.

The rehabilitation in 2009 involved milling out of 150 mm of the old asphalt pavement and replacing with inlay of new asphalt mixtures. The reconstruction incorporated a proprietary reinforcing Gridseal system (composite asphalt reinforcement system (CRS)). The aggregate used in the 2009 reconstruction was Blast Furnace Slag (BFS). BFS is a co-product of iron production. It can be produced in a variety of forms for different uses. Commonly it is ground and used as a cement replacement (GGBS or GGBFS) or used as a virgin aggregate replacement.

Table 5.2: A17 Case study construction and maintenance details (from (Spray 2014))

Event	Layer	Total area (m^2)	Depth (mm)	Binder Content	Coarse Aggregate	Aggregates Fines	Filler
Original Construction 1989	Surface Course (HRA S/C 30/14)	10120	40	5.1%	Granite (66.4%)	Limestone (26.6%)	Limestone (2.9%)
	Binder Course (DBC 28mm)		50	4.7%	Granite (64.6%)	Granite (28.5%)	Limestone (1.9%)
	Binder Course (DBC 40 mm)		100	5.0%	Gravel (76.0%)	Granite (14.3%)	Limestone (4.8%)
	Base course (CBM 3)		258	3.0%	Limestone (74.7%)	Limestone (18.9%)	Limestone (3.4%)
Reconstruction 2009	Chippings	10120	n/a	1.5%	Gritstone (98.5%)		
	Surface Course (HRA 30/14)		45	8.4%	BFS (31.4%)	Sand (52.7%)	Limestone (7.5%)
	Binder Course (AC 20)		53	6.2%	BFS (70.4%)	BFS (20.6%)	Limestone (2.8%)
	Binder Course (AC 20)		53	6.2%	BFS (70.4%)	BFS (20.6%)	Limestone (2.8%)
	Binder Course (AC 20)		50	6.2%	BFS (70.4%)	BFS (20.6%)	Limestone (2.8%)

For the A1(M), the original construction was similar to the A17, with CBM 3 Base Course with a DBC and chipped HRA Surface Course. In 2009, a 40 mm overlay of thin surfacing was applied to a 4 km section of both carriageways.

Table 5.3: A1(M) Case study construction and maintenance details

Event	Layer	Total area (m^2)	Depth (mm)	Binder Content	Coarse Aggregate	Aggregates Fines	Filler
Original construction 1980	Surface Course (HRA S/C 30/14)	56000	40	5.1%	Granite (66.4%)	Limestone (26.1%)	Limestone (2.4%)
	Binder Course (DBM)		280	4.7%	Granite (66.7%)	Granite (23.3%)	Limestone (5.2%)
	Base Course (CBM 3)		150	3.0%	Limestone (74.7%)	Limestone (18.9%)	Limestone (3.4%)
Thin Surfacing 2009	Surface Course	10120	40	5.5%	Granite (70.9%)	Granite (18.9%)	Limestone (4.7%)

Table 5.4 shows the distances and the transport modes assumed for the A17 case study in Spray (2014). Given the lack of historical data for the A1(M), the same values used for the A17 have been assumed.

Table 5.4: Transportation distances

	Material	From	To	Distance (Km)	Mode
	Bitumen	Refinery	Mixing Plant	200	Artic. HGV>33t
	BFS	Factory Gate	Site	50	Artic. HGV>3.5-33t
	Cement	Factory Gate	Site	50	Artic. HGV>3.5-33t
	Aggregate	Quarry	Site	50	HGV>3.5-33t
	Filler	Quarry	Site	50	HGV>3.5-33t
Pavement Planning	RAP	Site	Stockpile	75	Artic. HGV>33t
2009 Reconstruction	Chippings	Specialist Quarry	Site	400	HGV>3.5-33t
2009Reconstruction	CRS	Factory Gate	Site	50	Artic. HGV>33t

Table 5.5 shows the road construction operation date used for the two case studies. The values – representing plant operating efficiencies and quantities – are taken from Huang (2007).

Table 5.5 Average figures material production and road construction in the UK from Huang (2007)

Process	Operation	Unit	Quantity
Hot mix asphalt production	Electricity in asphalt plant	kWh/tonne asphalt	7.4
	Combustion of heating oil in plant	L/tonne asphalt	8.3
	Combustion of heating oil in plant	L/tonne asphalt	0.5
Laying surface course	Combustion of diesel in plant	L/tonne asphalt	2.2
Laying binder course	Combustion of diesel in plant	L/tonne asphalt	1.7
Excavating asphalt material	Combustion of diesel in plant	L/m^2	0.29

For the A17 section, the results reported in the next chapter are related to a base case scenario, as defined in Spray (2014). This considers the following methodological assumptions in terms of allocation: Eurobitume "mixed" bitumen allocation (Eurobitume 2011), zero allocated emissions at point of BFS production and 60:40 end of life recycling benefit split. Further information on the allocation methods and on their impact can be found in the reference.

For the A1(M) road segment, the Eurobitume "mixed" bitumen allocation method was selected for the allocation of the bitumen. Recycled or secondary aggregate was not used.

5.4 Work zone traffic delay

Figure 3.5 shows the outline of the methodology used to assess the impact of the work zone for both case study roads. As described, the maintenance events modelled in this research are:

- for the A17, a rehabilitation event in 2009, involving milling out of 150 mm of old asphalt pavement and replacing with inlay of new asphalt mixture and CRS;
- for the A1(M), a 40 mm overlay of thin surfacing applied on both carriageways in 2009.

To estimate the additional emissions from traffic during road works, both the emissions during normal conditions (no work zone in place) and maintenance conditions (work zone) will be considered.

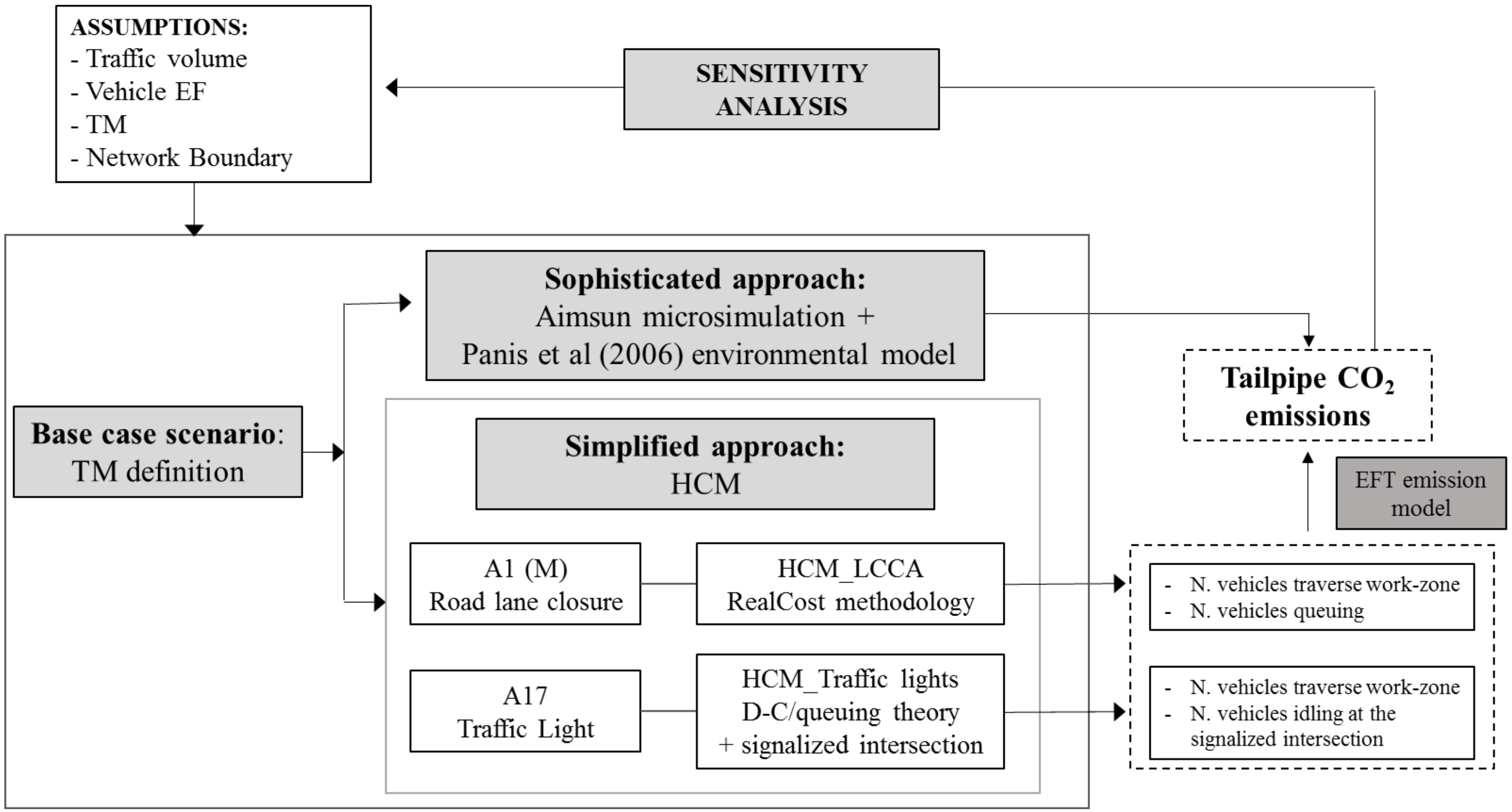


Figure 5.5: Outline of the adopted process for the work zone impact

The TM layout during road maintenance is established based on the location and the road layout and usually involves off peak lane closures (often with traffic light control) or road closures and diversion of traffic to other roads. In this study, in order to compare the different traffic model approaches (figure 5.5), a base case scenario involving a specific TM layout was defined for both case studies. Then, other TM layouts were assessed for the two case studies, in order to understand the impact of the TM layout selected on the results. The base case TM scenario for the A17 was the same as selected in a previous study performed on this same road segment (Galatioto et al. 2015). It involves an overnight TM with temporary traffic lights, starting from 19.30 and consisting in 4 phases of works over three consecutive nights. The first two phases (night 1) are related to the 400 m single carriageway in both directions; in phase 3 (night 2) work was carried out on the 320 m single carriageway, eastbound direction, including the junction, and in phase 4 (night 3), in the westbound direction (see table 5.6 and figure 5.6).

For the A1(M), Jean Lefebvre (UK) Technical Centre provided several suitable TM solutions for the maintenance work. The base case scenario TM layout assumed in this paper involves a carriageway closure and contraflow on the other carriageway and requires 24 hours to install the 40 mm Thin Surface Course per 1 km, three days to deploy the TM and three days to remove it (see figure 5.7), resulting in 17 days work to resurface both carriageways. During the three days to deploy and remove the work zone, one lane is closed in each direction. Therefore, both during the installation/removing of the work zone and during the work zone, there is a reduction of the number of lanes available in each carriageway and only one lane is available for traffic in each carriageway.

Table 5.6: Work zone TM phases for the A17

Day	Phase	Type	Length (m)	Work-time	Time
Night 1	Phase 1	Single carriageway West	400	19.30-00.45	5 h 15 min
	Phase 2	Single carriageway East	400	00.45-6.00	5 h 15 min
Night 2	Phase 3	Single-dual carriageway East plus junction	320	19.30-6.00	10 h 30 min
Night 3	Phase 4	Single-dual carriageway West	320	19.30-6.00	10 h 30 min

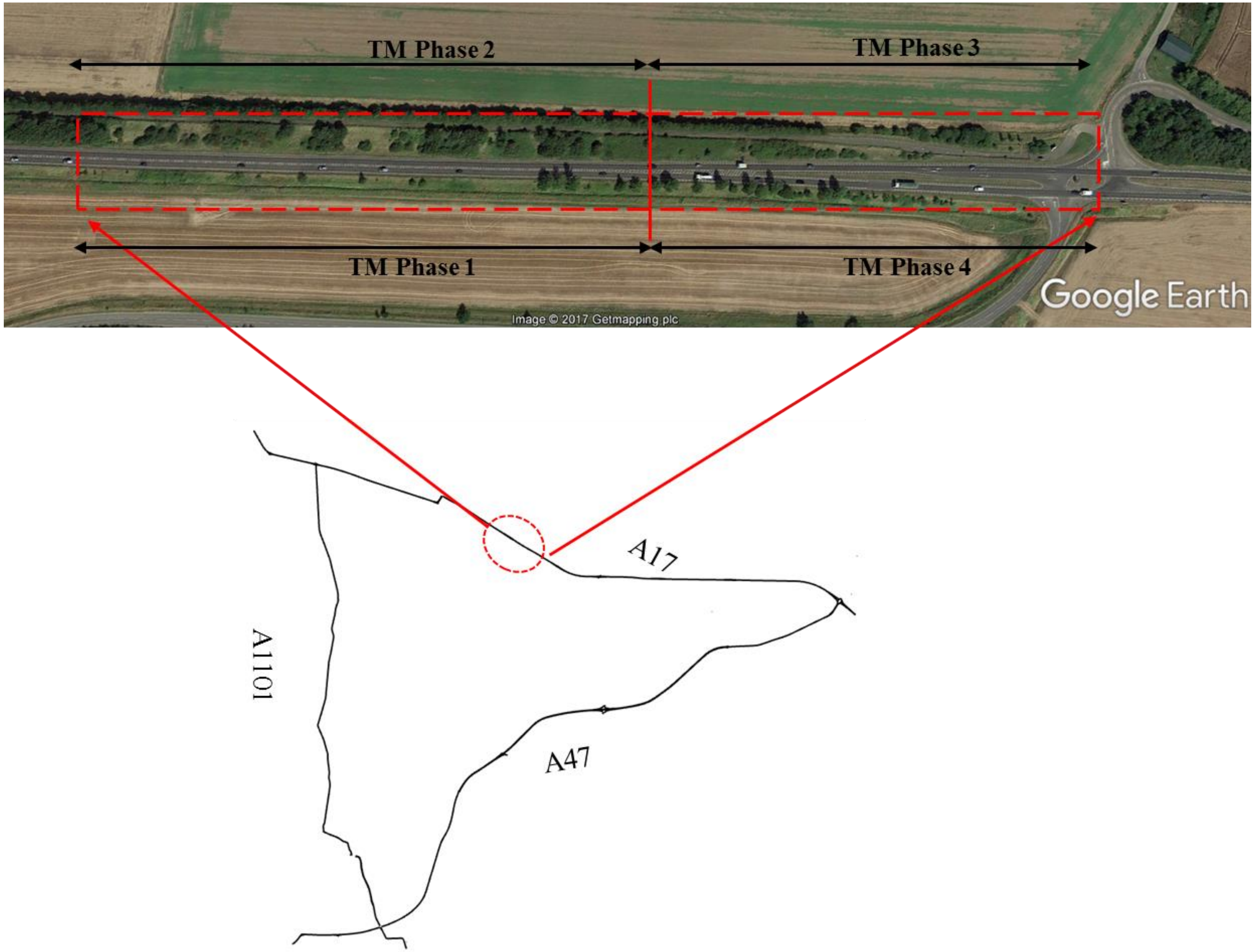


Figure 5.6: Base case scenario TM layout for the A17 , adapted from Galatioto et al. (2015)

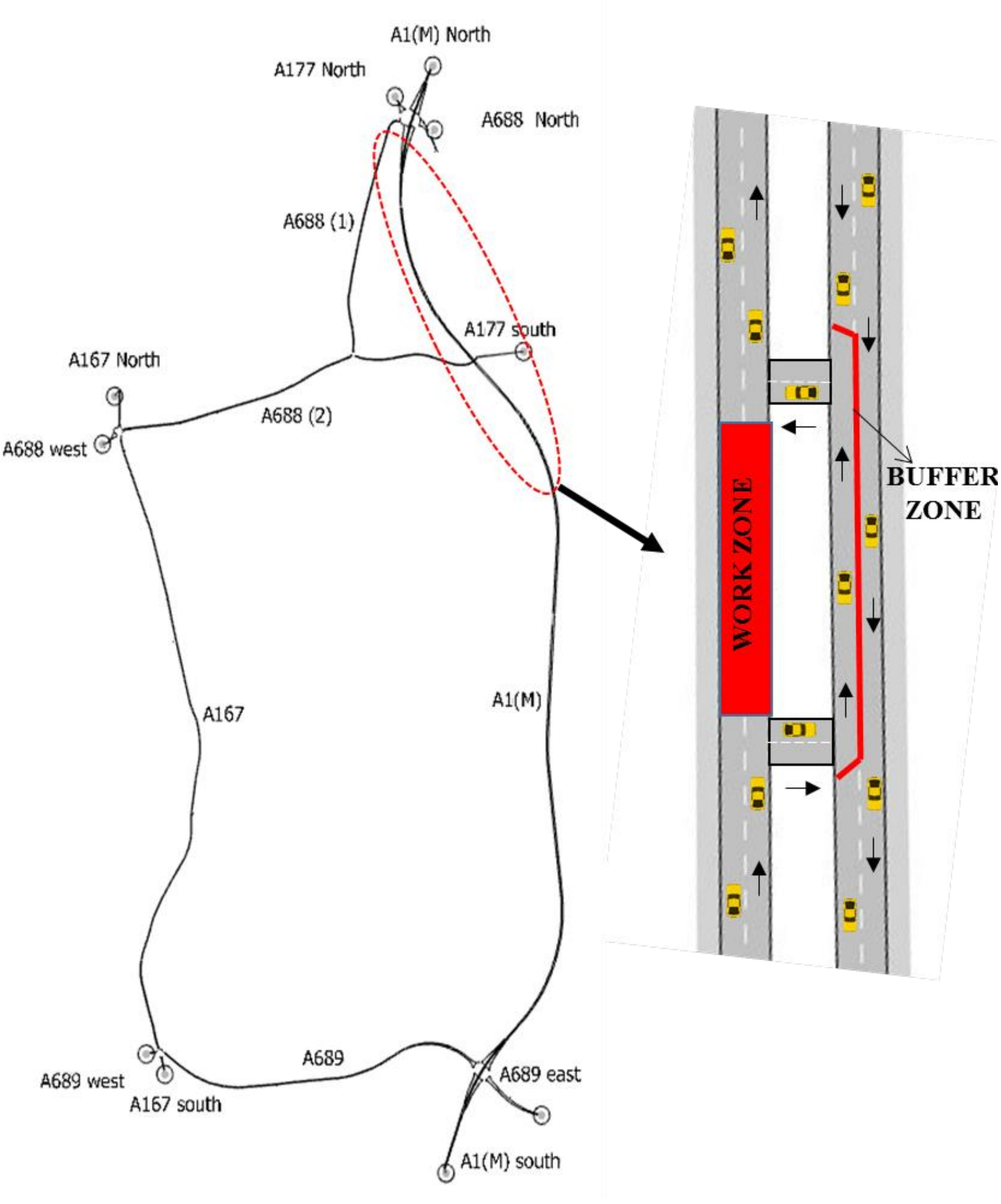


Figure 5.7: Base case scenario TM layout for the A1(M)

5.4.1 Comparison of the CO_2 emissions calculated with the HCM and Aimsun model

The additional CO_2 emissions due to the work zone were estimated with two different approaches:

- A sophisticated approach based on the microsimulation model Aimsun, able to define the average queue speed, length and the instantaneous speed. This program includes a vehicle emission model able to convert the fuel consumption into CO_2 emissions.
- A simplified approach, based on a two-step method, including a traffic model and an emission model. The traffic model selected is the macroscopic analytical/deterministic method described in the HCM. This is based on the D-C model and the queuing theory and analyses the work zone average queue and speed. The output data obtained from this model were then converted into CO_2 emissions, with the EFT vehicle emission model.

Further details related the two approaches are describe in Chapter 3.

The HCM describes theories, guidelines and computational procedures for estimating the capacity and level of service of several types of highway facilities (i.e. freeways, highways, arterial roads, roundabouts, signalized and unsignalized intersections, rural highways) during "freeway" driving conditions of the network (no congestion). However, the computational methodologies provided by the HCM are not suitable to describe and model construction activities or queues increasing over time (congested network), unless specific modifications are performed by the analyst. For this reason, an adaption of the methodology of the HCM was necessary for the two case studies, in order to assess the congested network during maintenance events. However, since the TM of the base case scenario of the two case studies are different (the A17 section involves the use of traffic lights, while the A1(M) is based on a carriageway closure and contraflow on the other carriageway), it was not possible to implement the same exact approach. Therefore, the HCM method was adapted to the TM of each specific case study.

For the A1(M), the computational approach developed by the FHWA, to estimate the user cost of the work zone traffic delay in Life Cycle Cost Analysis (LCCA) (Walls III and Smith 1998), was implemented. This methodology represents an adaption of the HCM to calculate the user cost due to work zone traffic delay during maintenance activities. It is based on the D-C model and the queue theory and it is suitable when the TM involves closure of one or more lanes and, consequently, the overall reduction of the capacity of the carriageway at the work zone. In this method, the roadway capacity is compared with the hourly traffic demand and the work zone components and the number of vehicles affected are identified.

For the A17, where the TM involves the use of traffic lights, an approach integrating the D-C model and queuing theory with the analysis of traffic at signalized intersections, as described in the HCM (Transportation Research Board 2010), was implemented. For each approach regulated by a traffic light, the number of vehicles traversing the work zone at reduced speed, the number of vehicles in the queue and the idling time during the red time (or during congestion) was calculated. From now on, we will refer to them as HCM_LCCA for the A1(M) and HCM_TL for the A17.

The output data obtained from the two methodologies for the A1(M) and the A17 are then converted in CO_2 emissions, by using the EFT model (UK Department for Environment Food & Rural Affairs 2014). Therefore, the EF, used for the HCM and Aimsun are different; for the first one the EFT model is used, while Aimsun incorporates the environmental model Panis et al. (2006). This needs to be taken into account when the results - obtained by running the two models - are compared: both the traffic model and the environmental model can impact the output results and this impact cannot easily be allocated to the individual component.

5.4.1.1 Aimsun

Aimsun is a traffic modelling software that allows to perform traffic operation assessment of any scale and complexity. It includes traffic modelling, static and dynamic traffic assignment with mesoscopic, microscopic and hybrid simulation within a single software application (Transport Simulation System (TSS) 2017).

In this research the microsimulation approach was selected for the assessment of the environmental carbon footprint of the road works. This will allow a comparison of a detailed, resource intensive approach to the simpler HCM approach, so conclusions can be drawn about the level of complexity needed in traffic modelling in pavement LCA. The main components and advantages of the microscopic simulation have already been described in the Chapter 3.

For the A17, the results obtained with the microsimulation model Aimsun were calculated in previous research (Galatioto et al. 2015). Therefore, from now on, the description of the computational procedure with Aimsun used to assess the emissions due to the work zone traffic delay will be related only to the A1(M) case study.

The procedure used in this study for running Aimsun to simulate the traffic on a road involved the following steps:

- Import the map of the road section from internet as a network and check and fix the geometry configuration.
- Insert the hourly traffic demand in terms of Origin-Destination (O-D) matrices, describing the number of trips between centroids for each type of vehicle in a time period. This step requires the identification of the centroids of the network analysed, their flows and their connection. As will be discussed below, in section 5.4.2, in this study, several network boundary extension scenarios were be taken into account (mini, small and big), in order to assess the potential impact of this component (see figure 5.15). The small network (base case scenario) includes only two centroids, producing a 2 x 2 O-D matrix. The small and the big network, with, respectively, seven and ten centroids, are characterized by 7 x 7 and 10 x 10 O-D matrices. Figures 5.8 and 5.9 show, respectively, the 24 hours total OD matrix during weekly days for the big network extension scenario and its associated centroid configuration. The daily flow distribution for each type of network extension is included in Appendix A.
- Define operating control plans (traffic light). This step was not necessary for the A1 (M) case study.
- Define appropriate TM strategies to modify the traffic network and simulate specific events. A TM strategy includes one or more policies that are applied to the network to solve a problem (i.e. reduce traffic congestion). Each policy consists of one or more complementary actions (such as lane closure, speed reduction, forced turn) that are activated together at the same time, in certain conditions, time or trigger. The administration and implementation of these strategies are a useful tool to simulate work zone TM conditions.
- Run the simulations for normal and work zone conditions. The microsimulation process uses a stochastic model to predict the behaviour and the arrival of the vehicles. To overcome the randomness of the process and the variation of the results, multiple replications (15) of each simulation were run and the average value was considered (Wennström 2010).

Main | Summary | Profile

User Class: All | Grouping: None | Units: Vehs

	23253: A1(M) North	23256: A177 North	23259: A688 North	23263: A167 North	23264: A688 West	23269: A177 South	23272: A689 West	23275: A167 South	3278: A1(M) South	23281: A689 East	Total
23253: A1(M) North	0	2535.59	2148.45	3394.94	4668.95	1862.32	2262.51	3122.58	10350	5809.78	36155.1
23256: A177 North	1498.85	0	219.46	337.67	475.55	180.61	223.58	314.5	964.27	578.84	4793.33
23259: A688 North	1422.45	246.7	0	319.16	450.48	174.02	215.57	295.32	912.09	555.8	4591.59
23263: A167 North	2937.15	421.28	359.17	0	770.56	301.57	370.67	508.28	1369.29	715	7752.97
23264: A688 West	3856.99	565.34	478.2	732.99	0	401.91	495.31	678.02	1801.56	962.93	9973.25
23269: A177 South	1333.43	221.39	188.92	295.12	411.76	0	200.91	274	864.75	506.75	4297.03
23272: A689 West	1634.23	279.65	240.08	368.23	519.23	197.54	0	343.32	1054.37	632.02	5268.67
23275: A167 South	2075.05	354.68	300.07	461.37	649.49	255.71	314.11	0	1342.84	796.95	6550.27
23278: A1(M) South	12563.1	607.34	504.6	1040.3	1639.8	298.17	488.49	900.49	0	2201.7	20244
23281: A689 East	6767.11	350.35	257.32	554.77	923.18	135.13	251.02	485.63	2701.4	0	12425.9
Total	34088.4	5582.32	4696.27	7504.55	10509	3806.98	4822.17	6922.14	21360.5	12759.8	112052

Figure 5.8: 24 hours total OD matrix during weekly days for the A1(M) case study (see centroid configuration of Figure 5.9)

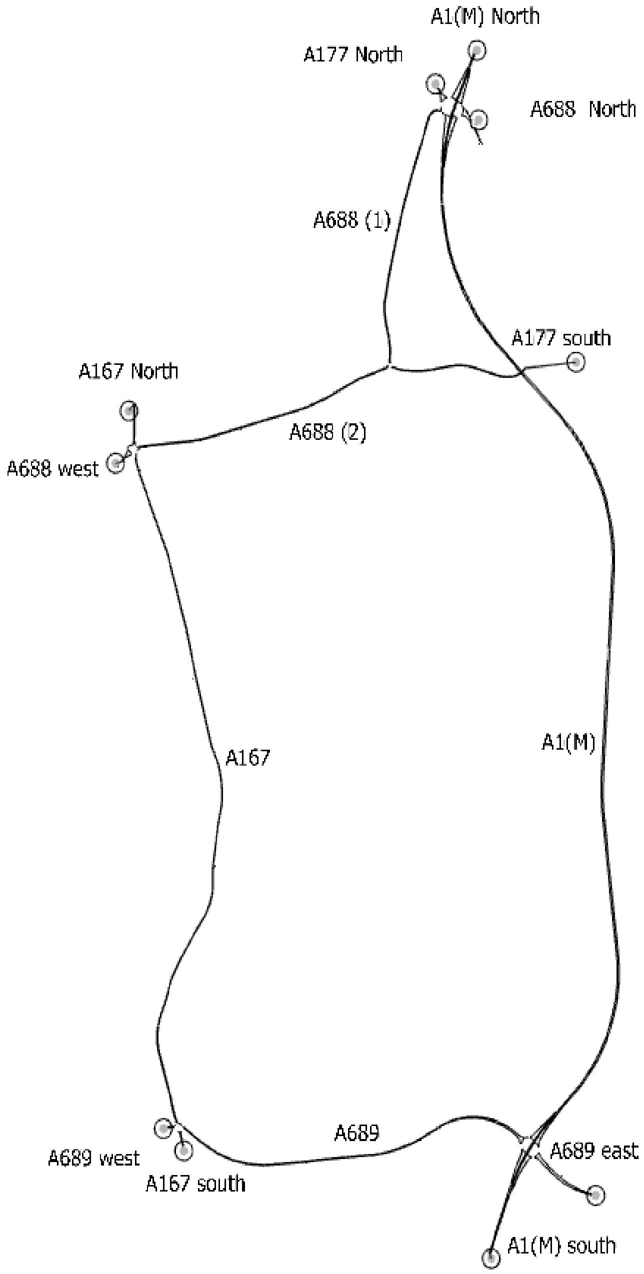


Figure 5.9: Example of centroid configuration for the A1(M) case study

Regarding the EF, the Aimsun software includes three different environmental models to obtain the fuel consumption and the emissions due to the work zone: 1) the fuel consumption model, 2) QUARTET Pollution emission model and 3) Panis et al (2006) emission model (Transport simulation system (TSS) 2015). However, only the last one provides the additional fuel consumption directly in terms of CO_2 emissions. In the Panis et al (2006) emission model, in each step of simulation, the same formula is used to calculate instantaneous traffic emissions, but with different factors, based on the vehicle type, fuel type and instantaneous acceleration and deceleration. Therefore, the Aimsun provides second by second speed, acceleration and deceleration of each single vehicle, based on the driving style, vehicle mechanisms and their interaction with other vehicles and the road network elements. The traffic emissions generated by this process are then modelled with the instantaneous emissions model, Panis et al, that is based mainly on empirical data in urban traffic. This represents a limitation of this environmental model, since the traffic in highways (higher speeds) is not sufficiently represented, and the EF for highway traffic could be different. Another interesting element related to the emission model developed by Panis et al. (2006) is that, to validate this model, the authors compared the results obtained with three other validated emission models: COPERT III, Methodologies for estimating air pollutant emissions from transport (MEET) (Samaras et al. 1998) and Handbook Emission Factors for Road Transport (HBEFA) (Keller, 2010). The results obtained are strongly different and they cannot be explained by the operator choices or parameter setting used.

Appendix B includes a summary of the calculations performed with Aimsun for the A1(M) case study and for the different scenarios assessed.

5.4.1.2 HCM_TL (A17 case study)

For the A17, where the TM for the Base Case scenario involves the use of traffic lights, a procedure integrating the D-C model and the traffic at a signalized intersection was implemented (Mannering and Washburn 2012).

In this case, the CO_2 emissions components associated with the work zone are:

- CO_2 emission variation due to vehicles' speed reduction in the area before and after the work zone and in the work zone.
- CO_2 emission variation due to the vehicles idling at the signalized intersection. For each hour of the work zone, it was necessary to calculate the number of vehicles stopping at the traffic light during the red time or during congestion and the average time of idling of the vehicles.

These calculation were performed for all the TM phases and for each flow of traffic (approach) (see figure 5.10). The same hourly traffic demand adopted in Galatioto (2015) was applied in this case study for each approach (see table 2.7).

Table 5.7: Hourly traffic demand of the A17 case study

Time of the day	From 1	From 2	From 3	From 4
0-1*	27	32	5	4
1-2*	21	28	3	3
2-3*	17	19	2	2
3-4*	24	24	5	4
4-5*	49	56	10	9
5-6*	115	104	21	19
6-7	192	193	40	37
7-8	308	290	61	57
8-9	606	449	112	99
9-10	792	603	149	132
10-11	804	643	144	137
11-12	784	591	139	130
12-13	676	577	130	120
13-14	569	606	124	113
14-15	606	665	133	123
15-16	582	759	140	132
16-17	561	708	135	124
17-18	513	453	124	91
18-19	353	280	66	59
19-20*	258	217	49	45
20-21*	168	199	37	35
21-22*	117	326	40	45
22-23*	79	237	28	31
23-24*	50	98	14	14

*work zone timing

The queuing model assumed in this study is with deterministic arrivals and departures and with one departure channel (D/D/1). This means that for each hour, there are uniform arrivals through the traffic light cycle and uniform departures during the green time.

In order to explain the analytical concepts and the methodology used, it is important to introduce some key concepts and terminology commonly used in the analysis of signalized intersections.

Cycle length (C), total time (in seconds) to complete one sequence (for all approaches) of signal indications (green, amber, red). In this study we have not considered the amber indication.

Green (G) and Red (R) Time, time (in seconds) within a cycle for which a movement or a combination of movement receives a green (G) or red (R) indication.

All-red time (AR), the time (in sec) within a cycle in which all approaches have a red indication.

Table 5.8 shows the traffic light cycles considered for the A17 case study for each approach, during the four work zone phases.

Table 5.8: Traffic light cycles for the A17 case study

Approaches/ Centroids			Green time (sec)				Cycle (sec)	All red (sec)
			East (1)*	**West (2)***	**North (3)***	**South (4)***		
Phase 1 & 2	19.30	21:00	52	52	-	-	180	76
	21:00	00:00	22	22	-	-	120	76
	00:00	06:00	22	22	-	-	120	76
Phase 3 & 4	19.30	21:00	40	40	10	7	180	100
	21:00	22.30	43	45	5	5	180	92
	22.30	00:00	23	25	5	5	140	92
	00:00	06:00	23	25	5	5	120	72

*See figure 5.10

Figure 5.10: Approaches/Centroids layout

The Green and the Red time need to be converted in **the effective Green (g)** and **Red (r) times**, to take into account the **Lost Time (t_L)** for a movement during a cycle parameter (in seconds), given by the sum of the **start-up lost time (t_{sl})** and the **clearance lost time (t_{cl})**.

$$g = G + Y + AR - t_L \quad (9)$$

$$r = R + t_L \quad (10)$$

Saturation flow rate (s), represent the maximum hourly volume that can pass through an intersection, if the lane was allocated constant green during the considered hour. According to the HCM, this value currently is equal to 1900 passenger cars per hour per lane (pc/h/ln).

Defining **v** the **arrival rate** during an hour (veh/sec) and **s** the **departure rate** or saturation flow (veh/sec), v*t and s*t represent, respectively the "Arrivals" and the "Departures" at the time t, and v*C and s*g the arrivals and the departure/Capacity during one cycle.

Taking into account one traffic cycle and one approach, two different conditions can apply:

- if v*C < s*g (arrivals smaller than Capacity), under saturated conditions;
- if v*C > s*g (arrivals smaller than Capacity), over saturated conditions;

Under saturated conditions

Under these conditions (see Figure 5.11), for each cycle the maximum number of vehicles in the queue, during the red time is Q_{max}:

$$Q_{max} = v * r$$

(11)

The delay time (corresponding to the idling time) can span between 0 and the red time r. The average delay d_{avg} per vehicle is:

$$d_{avg} = \frac{r^2}{2 * C * (1 - v / s)}$$

(12)

Based on these equations, it is possible to calculate for each cycle and therefore for each hour to characterize for under saturated conditions, the number of vehicles idling during the red time and the average time delay per vehicle.

Over saturated conditions (v*C > s*g)

In this case, once the queue starts to accumulate cycle by cycle (v*t and s*g are constant and the first one is bigger than the second one), the average delay time (idling time) will increase.

Table 5.12 shows the behaviour of signalized intersection under oversaturated conditions for several hours for one approach. During the first three hour the arrivals exceed the capacity and the queue develops. During the fourth hour the arrivals are smaller than the capacity and the accumulated queue start to reduce and when the two curves meet, the queue dissipates. The average delay time is given by the difference between the area under the arrival line and the area under the capacity line.

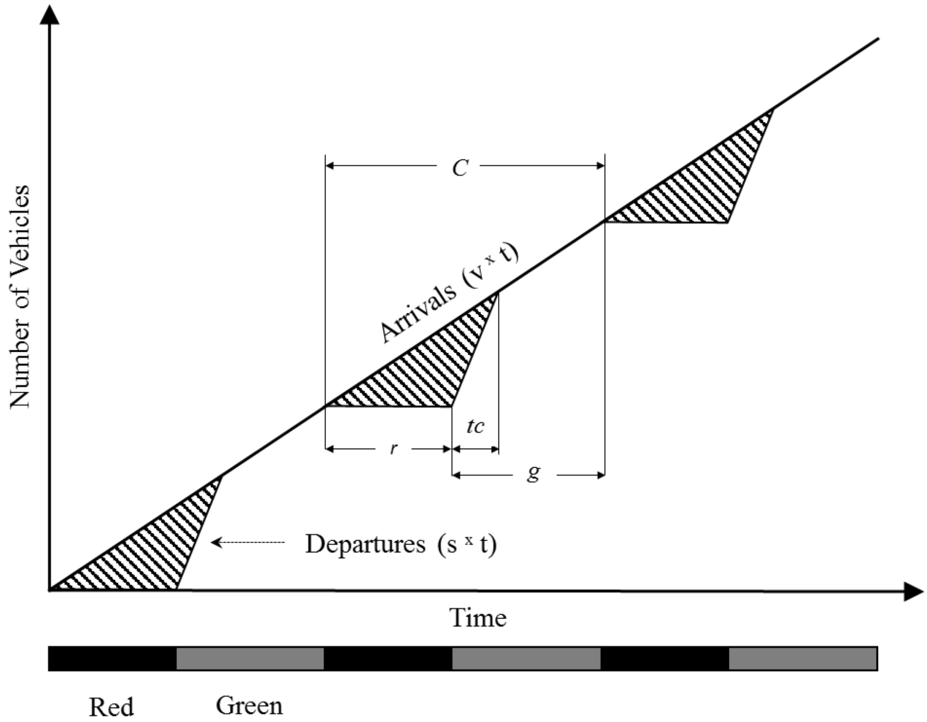


Figure 5.11: Signalized intersection with approach Capacity exceeding arrivals for all cycles, adapted from Mannering and Washburn (2012)

The average delay time d_{avg1} in seconds during the first hour would be

$$d_{avg1} = \frac{C_1 * n_{1*} \Delta q_1}{2} - \frac{(s*g)*g}{2} * n_1 - (s*g)*\frac{(n_1*(n_1-1))}{2} \quad (13)$$

Where

Δq_1= number of vehicles arriving per cycle during the first hour (veh/sec) =$v_1 * C_1$

v_1=arrivals rate during the first hour (veh/sec)

C_1= cycle length during the first hour (sec)

n= number of cycles during one hour.

Analysing the first hour of the graph in figure 5.12 the first term of the equation represents the area of the big triangle, the second term the sum of the areas of the small triangles and the third one the sum of the areas of the small rectangles.

After some algebraic steps and defining $C_1=C$ and $n_1=n$, Equation (6) becomes:

$$d_{avg2} = \frac{n_1}{2} * \left\{ n_1 * \Delta q_1 * C_1 - s * g^2 * \left[1 + \frac{C_1 * (n_1 - 1)}{g} \right] \right\} \quad (14)$$

Using the same approach, it is possible to obtain the average delay time d_{avg2} and d_{avg3}.

$$d_{avg2} = \frac{n_2}{2} * \left\{ (2*n_1*\Delta q_1 + n_2*\Delta q_2)*C_2 - s*g^2*\left[1 + \frac{C_2*(2*n_1+n_2-1)}{g}\right]\right\} \quad (15)$$

$$d_{avg3} = \frac{n_3}{2} * \left\{ (2*n_1*\Delta q_1 + 2*n_2*\Delta q_2 + n_3*\Delta q_3)*C_3 - s*g^2*\left[1 + 2*\frac{C_3}{g}*(n_1+n_2) + C_3*(n_3-1)\right]\right\} \quad (16)$$

If $n=n_1=n_2=n_3$ and $C=C_1=C_2=C_3$, equations (8) and (9), can be written:

$$d_{avg2} = \frac{n_2}{2} * \left\{ n*(2*\Delta q_1 + \Delta q_2)*C - s*g_2**(1+\frac{C}{g}(3*n-1) \right\} \quad (17)$$

During the fourth hour, where the queue dissipates (intersection point), the average delay time d_{avg4} is calculated using the oversaturated approach before the intersection and the under saturated approach after it. Appendix C includes an example of calculation procedure for the Base case scenario, approach 1 during phase 1 of works.

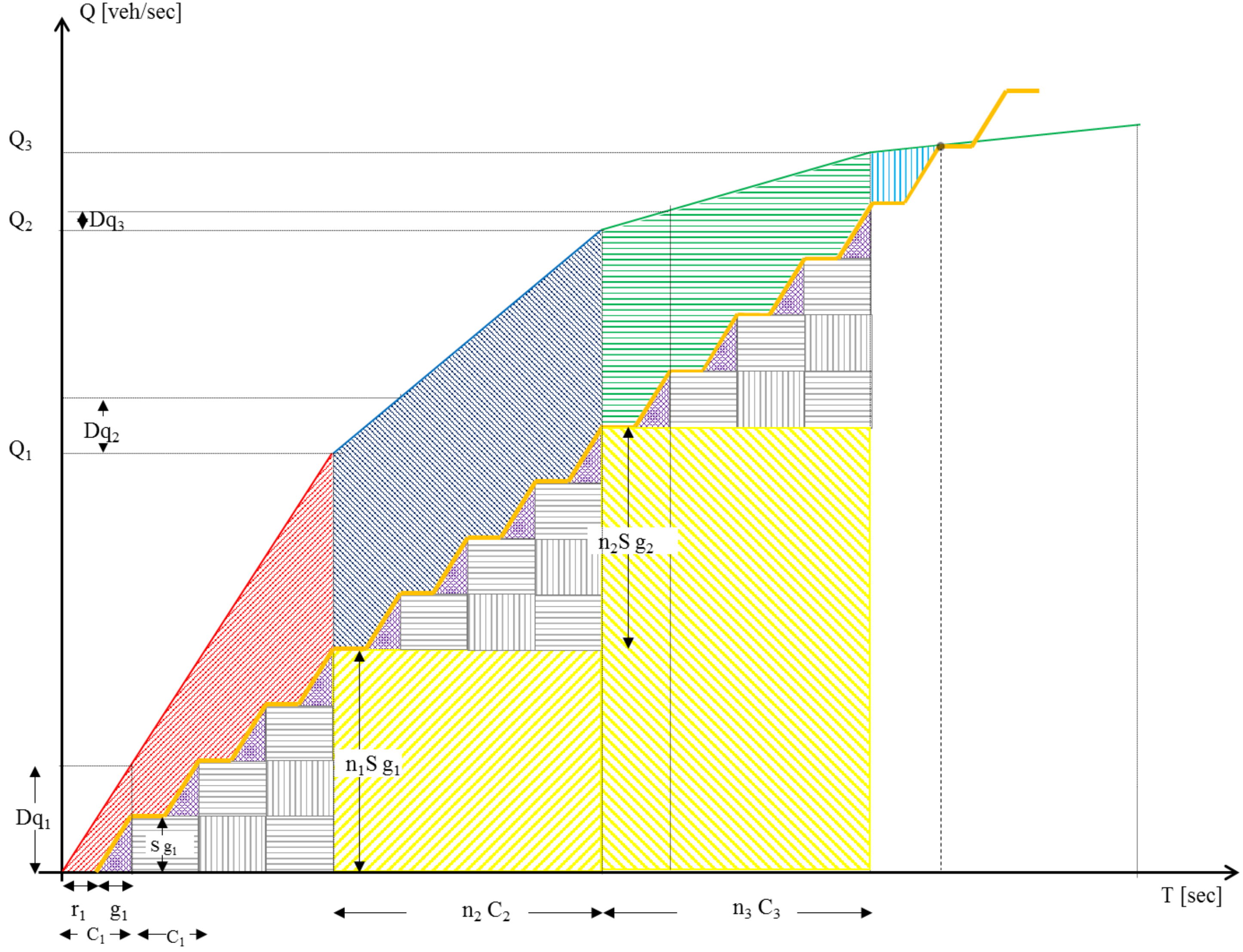


Figure 5.12: Signalized intersection with approach Capacity not exceeding arrivals for all cycles

5.4.1.3 HCM_LCCA (A1(M) case study)

As mentioned above, the LCCA work zone user method was selected to estimate the traffic delay for the A1(M) road segment, where the TM Base Case scenario consists in the carriageway closure and contraflow in the other direction and one lane closure for each carriageway during the installation and the removal of the work zone. This method involves several steps of calculation, described below.

- Project future year traffic demand, for each vehicle class for the year the work -zone will be in place. This value is based on the current AADT, the vehicle class percentage and the growth rate (see formula (9)).

$$Future\ Year\ AADT = Base\ Year\ AADT\ x\ Vehicle\ class\ \%\ x\ (1 + growth\ rate)^{(Future\ Yr. - Base\ Yr.)} \quad (18)$$

The maintenance year analysed in this study took place in 2009. Therefore, the AADT is known (see table 5.1) and there was no need to calculate this value. In order to identify the traffic demand during weekdays (average values) and weekend days (Saturday and Sunday), specific daily distribution factors for the UK motorways were applied to the AADT (see Table 5.9) (UK Department for Transport 2017).

Table 5.9: Average daily distribution factors from UK Department for Transport (2017)

	Cars & taxis	Goods vehicles
Monday	100	117
Tuesday	97	128
Wednesday	100	129
Thursday	103	130
Friday	112	116
Saturday	92	46
Sunday	95	35

- Calculate the work zone directional hourly demand. Table 5.10 shows the car traffic distribution on all roads by time of the day in Great Britain, in 2009. It was used to generate the work zone hourly traffic demand for the case study for the weekdays, Saturday and Sunday (see tables 5.11, 5.12 and 5.13).

Table 5.10: Car traffic distribution on all roads by time of day in Great Britain, 2009

							Index: Average hour in week =100
Time of day	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
00:00-01:00	16	12	12	13	15	23	27
01:00-02:00	9	7	7	8	8	13	16
02:00-03:00	6	5	5	6	6	9	10
03:00-04:00	7	5	5	6	6	8	8
04:00-05:00	14	10	9	10	10	10	8
05:00-06:00	37	29	28	28	27	18	12
06:00-07:00	94	87	85	82	76	34	21
07:00-08:00	177	179	177	172	159	60	34
08:00-09:00	187	197	197	190	175	98	55
09:00-10:00	143	148	149	145	139	138	96
10:00-11:00	139	129	132	131	144	176	143
11:00-12:00	144	128	132	134	157	194	172
12:00-13:00	145	131	136	139	169	191	178
13:00-14:00	145	135	141	144	179	182	172
14:00-15:00	148	143	149	153	189	168	170
15:00-16:00	161	162	169	172	204	161	175
16:00-17:00	192	202	207	208	219	159	183
17:00-18:00	207	218	222	221	222	157	172
18:00-19:00	156	165	171	174	183	134	149
19:00-20:00	99	104	112	118	140	101	125
20:00-21:00	69	69	74	83	101	72	98
21:00-22:00	51	53	56	61	70	53	72
22:00-23:00	37	41	43	44	51	45	47
23:00-00:00	22	24	26	27	35	38	29

Table 5.11: Hourly directional traffic demand of the A1 case study during weekdays

WEEKDAYS			
AADT	**Time (hour)**	**Demand (vehicles/h)**	
51502		**S**	**N**
	12-1	193	190
	1-2	145	142
	2-3	132	129
	3-4	144	141
	4-5	220	217
	5-6	463	456
	6-7	1027	1010
	7-8	1768	1740
	8-9	1877	1847
	9-10	1557	1532
	10-11	1494	1471
	11-12	1534	1510
	12-13	1566	1541
	13-14	1604	1578
	14-15	1670	1644
	15-16	1787	1759
	16-17	1985	1954
	17-18	1945	1914
	18-19	1574	1549
	19-20	1101	1083
	20-21	793	780
	21-22	603	594
	22-23	461	454
	23-24	314	309
		25957	25545

Table 5.12: Hourly directional traffic demand of the A1 case study during Saturday

SATURDAY			
AADT	**Time (hour)**	**Demand (vehicles/h)**	
41593		**S**	**N**
	12-1	352	346
	1-2	271	267
	2-3	238	234
	3-4	236	232
	4-5	270	265
	5-6	379	373
	6-7	560	551
	7-8	793	780
	8-9	1061	1044
	9-10	1334	1313
	10-11	1593	1567
	11-12	1696	1669
	12-13	1636	1610
	13-14	1543	1518
	14-15	1410	1388
	15-16	1336	1315
	16-17	1298	1277
	17-18	1264	1244
	18-19	1087	1070
	19-20	830	817
	20-21	606	596
	21-22	452	445
	22-23	386	380
	23-24	332	326
		20963	20630

Table 5.13: Hourly directional traffic demand of the A1 case study during Sunday

SUNDAY			
AADT	**Time (hour)**	**Demand (vehicles/h)**	
41376		**S**	**N**
	12-1	278	274
	1-2	191	188
	2-3	147	145
	3-4	133	131
	4-5	140	138
	5-6	199	196
	6-7	302	297
	7-8	434	427
	8-9	609	599
	9-10	928	914
	10-11	1292	1271
	11-12	1517	1493
	12-13	1568	1543
	13-14	1532	1508
	14-15	1533	1508
	15-16	1576	1551
	16-17	1642	1616
	17-18	1562	1537
	18-19	1388	1366
	19-20	1206	1187
	20-21	988	972
	21-22	762	750
	22-23	543	534
	23-24	382	376
		20853	20522

- Estimate the Road Capacity of the road. This value changes during maintenance and, therefore, it is possible to identify three different values of Capacity:
  - Free Flow Capacity under normal condition = 1944 (vphpl)
  - Work zone Capacity = 1500 (vphpl)

  These values of Capacity were calculated based on the procedures and the recommendations provided in the Life-Cycle Cost Analysis Technical Bulletin (Walls III and Smith 1998). In order to understand the applicability of these values to a UK case study, they were compared with traffic capacities of urban roads, according to UK standards (UK Government 1999a). This comparison confirmed the applicability, since the values are just slightly different.
- Compare the Roadway Capacity during the work zone with the traffic demand and identify the work zone component (i.e. upstream traffic, queuing zone, slowing down zone) and the number of vehicles affected in each component. The D-C model used in this procedure involves uniform hourly arrivals (demand) and departures (capacity). When the demand does not exceed the capacity, the vehicles flow freely and there is no development of a queue. Once the demand overtakes the capacity, a queue develops and the arriving vehicles need to slow down before approaching the work zone and stop at the upstream end of the queue and creep the length of the queue under forced flow conditions.
- Calculation of the queue and the speed length (during queue conditions). The average hourly queue is determined by dividing the average number of vehicles in the queue during each hour by the change in traffic density between the upstream free-flow section and the queue section during the hour. The calculation of the average speed on which the fuel consumption and the CO_2 emissions depend - is based on the use of a graph (Forced-Flow Average Speed versus Volume to Capacity V/C ratio) for level of Service F (congested condition) contained in the earlier versions of the HCM (see Figure 5.13). According to the HCM, the curve in the graph is unstable and the values represent estimations. This fact generates a high level of uncertainty in the results, since the change in fuel consumption related to the variation of speed is much more significant at low speeds (0-25 mph) found in work zone queues (see figure 5.14).

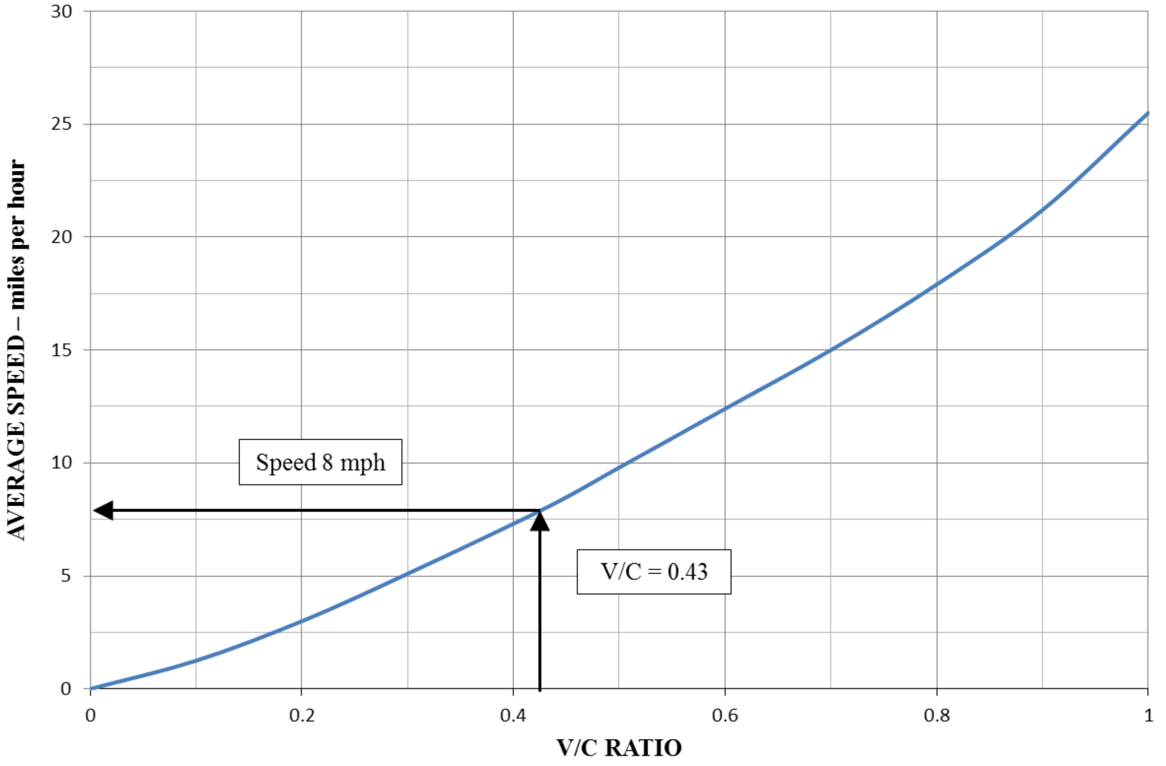


Figure 5.13: Average speed versus V/C ratio (for level of Service F), adapted from Walls III and Smith (1998)

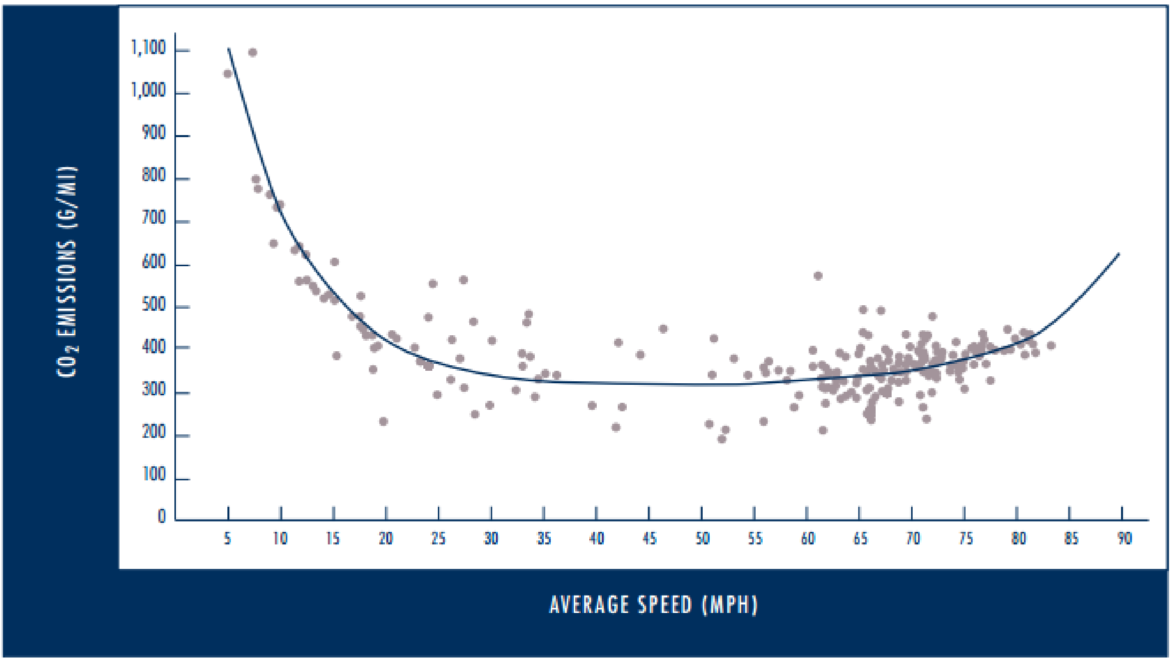


Figure 5.14: CO_2 emission and average speed correlation, from Barth and Boriboonsomsin (2009)

- Use the output from the traffic models in EFT to calculate the CO_2 emissions. The EF for the CO_2 are those published by the UK Department for Transport (Boulter et al. 2009).

Table 5.14: Coe emission rates from EFT (Boulter et al. 2009)

CO_2 emission rates with EFT model				
Work zone Status	**Speed (mph)**	**CO2 emissions (g/Km)**		
		CAR	**LGV**	**HGV**
Work zone + queue	8	279	367	1528
Work zone, no queue	60	157	231	808
Normal condition - No work zone	74.4	177	307	835

Appendix C includes an example of calculation procedure for the Base case scenario.

5.4.2 Sensitivity test and scenario modelling

In order to identify the parameters that affect the results in the work zone impact analysis, a sensitivity test was performed on some specific variables. For each of them, several scenarios involving a variation of the analysed parameter were considered and compared with the base case scenario. As mentioned before, for the A17, the traffic volume parameter and TM layout have been investigated in another study (Galatioto et al. 2015) and the results are presented in the next chapter.

Traffic volume

As above mentioned, the sensitivity analysis on this parameter is necessary to evaluate the level of uncertainty related to the available data and the hourly, daily and monthly fluctuations and to evaluate future scenarios of maintenance treatments for the same road segment. Three different scenarios were assessed, taking into account a volume of traffic increase of 10%, 20% and 30% for both case studies and models.

Traffic management

Several TM solutions and scenarios have been considered to test the impact of this variable. Table 5.15 shows the details of the TM options considered for the two case studies. For both case studies, the first scenario is represented by the Base case scenario described above. For the A1(M) case study, Scenario 2 is the same as the Base case scenario, but the hard shoulders are used as a supplementary running lane. Scenario 3 involves eight overnight carriageway closures of nine hours each (starting from 20:00), with diversion onto adjacent roads (about 9.5 miles instead of 6.5 miles).

For the A17 case study, the other two options are an earlier start of TM with traffic lights from 18.00 instead of 19.30 (Scenario 2) and a two shift closure of 12 hours each - starting from 19:00 on Saturday evening - and a one shift closure of the A17 for 24 hours - from 13:00 on Saturday afternoon - with diversion onto adjacent roads (about 20 miles instead of 10 miles) (Scenario 3).

The sensitivity analysis was mainly performed with the Aimsun software, suitable to model every scenario assessed in this study. It was not possible to apply the HCM approach to some specific scenarios. In particular, TM options involving a detour cannot be analysed with this approach. In addition, the HCM methodology was not deemed appropriate to assess the second scenario, involving the use of the hard shoulder as running lane, for the A1(M) case study.

Table 5.15: TM options details for the A1(M) and the A17 road segments

TM Options	A1(M)	Timing	A17	Timing
Base case scenario	Lane Closure and contraflow	17 days	Traffic light from 19.30	3 overnight shifts
Scenario 2	Lane Closure and contraflow, including hard shoulders	17 days	Traffic light from 18.30	3 overnight shifts
Scenario 3	Road closure and detour	8 overnight shifts (9 hours)	Road closure and detour	2 overnight shifts (12 hours) 1 shift (24 hours)

The HCM methodology is based on the comparison between the traffic flow and the reduced capacity in the work - zone. The estimation of this capacity is based on empirical data collected in USA studies for maintenance events and work zone involving the reduction of the number of running lanes. The use of the hard shoulder as running lane considered in the second scenario for the A1(M) case study does not involve a reduction in the number of available lanes, but a decrease of the total widths of the carriageway and in turn of the total capacity. This new capacity could be calculated considering two lanes in normal condition (no work zone), but with a smaller width. However, in the HCM the reduction of this capacity is not so significant to generate the development of a queue. Therefore, overall a reduction of the CO_2 emissions compared to normal condition would happen, due the reduction of the speed in the work – zone. Instead, in a microscopic model the narrowing of the carriageway affects other parameters (such as the car following and lane-changing model) that produces an overall increase in the emissions, because it generates congestion

Emission factors

The sensitivity analysis on the emission factors was performed with the HCM approach, comparing the EF from the MOVES software and from EFT. This was not undertaken for Aimsun which is already provided with an instantaneous emission model. In both models, all calculations are based on the average fleet composition for a given year and for a given road type.

Table 5.16 shows the EF from MOVES and EFT at different speed for different type of vehicles used for the A1(M) case study.

Table 5.16: CO_2 emission rates with MOVES and EFT

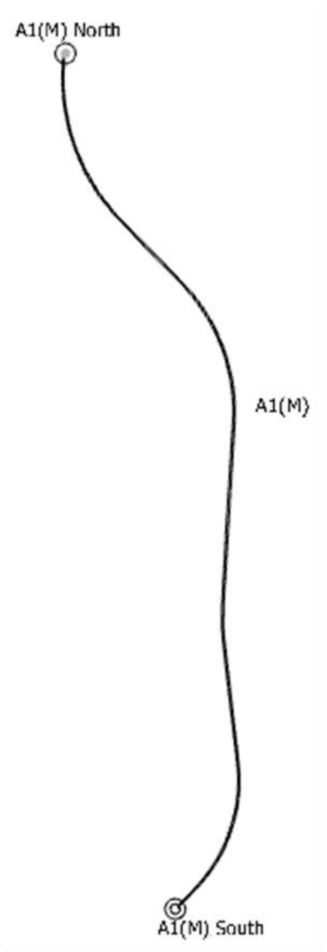
Speed (mph)	CO_2 emission rates (g/Km) with MOVES			CO_2 emission rates (g/Km) with EFT		
	CAR	LGV	HGV	CAR	LGV	HGV
8	629	786	2289	279	367	1528
60	300	438	1145	157	231	808
74.4	319	471	1200	177	307	835

Clearly, the EF rate from MOVES are much larger than the ones from EFT (between 1.4 and 2.2) and this will clearly impact the results. This significant difference is probably due to the different average size of the vehicle fleet and to the different legislation targets on GHG in Europe and in the USA. A recent study (Nisbet et al 2016), commissioned by the European Parliament's Committee on emission measurements in the automotive sector, has estimated past and projected future standards in the EU and US and their impact on fuel economy, showing that European standard are, overall more demanding than those in the USA.

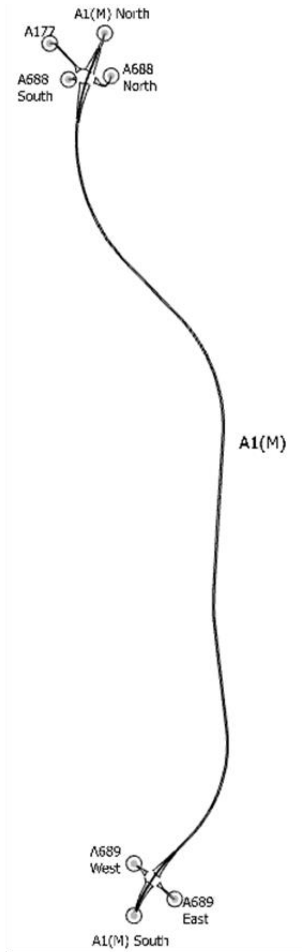
Network Boundary

The traffic modelling requires the identification of the extent of the road network impacted by the work zone. For a comprehensive understanding, the modelling should cover the whole network affected. During a maintenance event, the behaviour of the vehicles is affected by the congestion occurring in the work zone and they could take alternative routes, thus affecting other roads. Or, in the worst case scenario, the congestion could extend to an area not included in the modelling boundary. The microsimulation approach is more flexible, allowing the area of analysis to be extended, taking into account the interaction of elements, such as traffic lights, roundabouts, other junctions, etc.

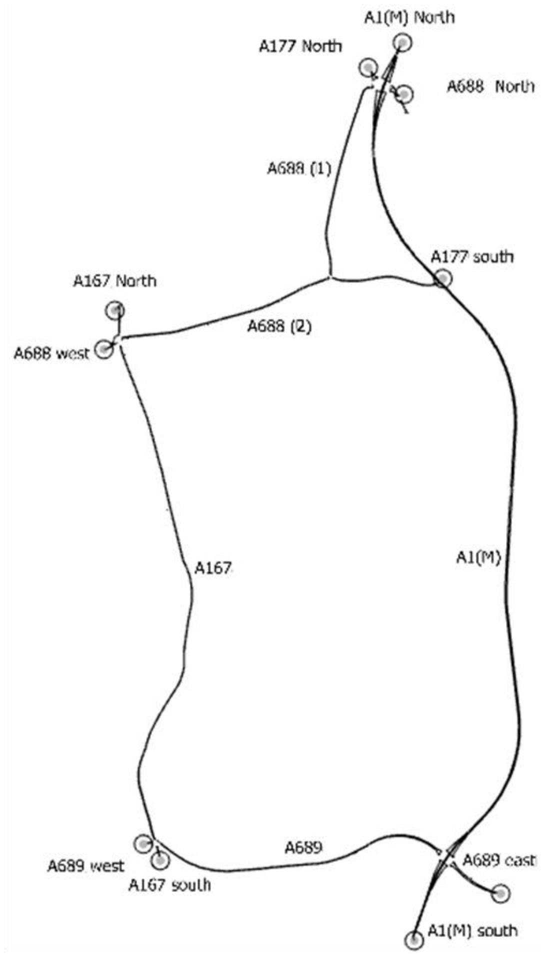
In order to assess the impact of the network boundary, three different scenarios were considered for the A1(M) road section: the ‘mini network’ that represents the base case scenario (2 centroids), the ‘small network’ including two roundabouts at the A1(M) junctions and joining traffic streams (7 centroids) and the ‘big network’ that includes possible diversions that vehicles could take in case of congestion (10 centroids) (see figure 5.15).



BASE CASE SCENARIO:
MINI NETWORK



SMALL NETWORK



BIG NETWORK

Figure 5.15: Network extension scenario

5.5 Rolling resistance

Figure 5.16 shows the outline of the methodology adopted to estimate the effect of the pavement surface conditions on vehicle fuel consumption. The methodology involves the calculation of the CO_2 emissions due to the PVI rolling resistance, using two models from the literature and a sensitivity analysis performed on several variables.

5.5.1 Comparison of the CO_2 emissions calculated with the UCPRC and VTI model

The CO_2 emissions due to the effect of the pavement surface properties on vehicle fuel consumption for two different UK case studies were estimated using: the model developed at the University of California Pavement Research Center (UCPRC, Davis) and implemented in several studies (Wang et al. 2014a; Wang et al. 2012a) and the model developed by the Swedish National Road and Transport Research Institute (VTI), within the European Commission project Miriam (Models for rolling resistance In Road Infrastructure Asset Management systems) (Hammarström et al. 2012). Details related to the models are provided in Chapter 4, but the key elements are summarised here. This comparison was made to test the sensitivity of the results to the models used to assess the rolling resistance impact during the use of a road.

In the UCPRC model, as implemented in (Wang et al. 2014a), the vehicle CO_2 EF are a continuous function of MPD and IRI, but the coefficients in the function are different for each combination of the categorical variables (pavement, road and road-access type, vehicle type). The CO_2 emissions for a specific vehicle type can be calculated directly, based on the analysed pavement segment's MPD and IRI values by using equation (19) and multiplying it by the vehicle mileage travelled.

$$T_{CO_2} = a_1 \times MPD + a_2 \times IRI + Intercept \qquad (19)$$

Where T_{CO2} is the tailpipe CO_2 emission factor, the terms a_1, a_2 and *Intercept* are the coefficients derived from the linear regression, depending on surface type and access type, year and vehicle type, *IRI* is the road roughness (m/km) and *MPD* is the macrotexture (mm). The Intercept term identifies the total CO_2 emissions related to the total driving resistance, excluding the impact of the pavement condition, which is estimated from the other two terms.

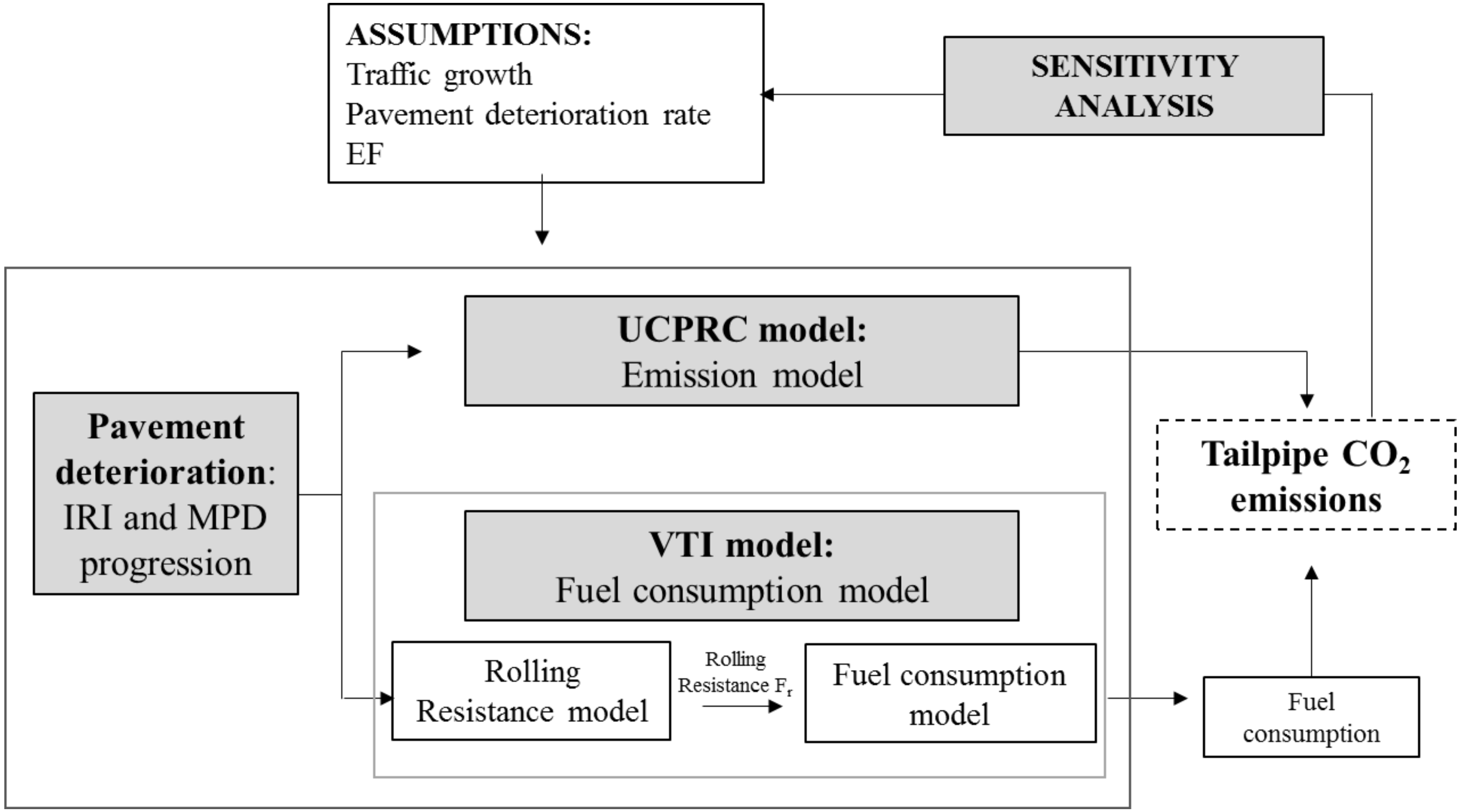


Figure 5.16: Outline of the adopted process for the rolling resistance impact (adapted from Trupia et al. (2016))

This study provides all these coefficients for each combination of categorical variable (see Appendix D). Therefore, based on the surface type (asphalt for both cases), the road type and access type (urban restricted-access road for the A1(M) and urban unrestricted-access road for the A17), the year and the vehicle type, the tailpipe CO_2 EF can be calculated.

The VTI model includes a general rolling resistance model (equation (20)) to estimate the contribution of the rolling resistance to the total driving resistance and a fuel consumption model (equation (21)) to calculate the vehicle fuel consumption (Hammarström et al. 2012). Once the fuel consumption related to a specific type of vehicle was estimated using this model, it was converted to CO_2 emissions, assuming the conversion process proposed by International Carbon Bank & Exchange (ICBE) (2010).

$$F_r = m_1 \times g \times \left(0.00912 + 0.0000210 \times IRI \times V + 0.00172 \times MPD\right) \quad (20)$$

$$F_{CS} = 0.286 \times \left(\begin{pmatrix} 1.209 + 0.000481 \times IRI \times V + 0.394 \times MPD + 0.000667 \times V^2 + 0.0000807 \times \\ ADC \times V^2 - 0.00611 \times RF + 0.000297 \times RF^2 \end{pmatrix}^{1.163} \right) \times V^{0.056} \quad (21)$$

The rolling resistance model developed by VTI is mainly based on empirical data from coastdown measurements in Sweden; the fuel consumption model has been calibrated based on results obtained from a software VETO, based on a theoretical model developed at VTI to calculate fuel consumption and exhaust emissions from traffic due to various characteristics of vehicles, roads and driving behaviour (Hammarström and Karlsson 1987; Karlsson et al. 2012).

For both models, only the CO_2 emissions directly related to the pavement surface properties (IRI, MPD) are calculated; the other terms of the equations are considered equal to zero, since their estimation is not the aim of the study.

Applying the equations previously defined, it is possible to estimate the total CO_2 emissions related to the pavement condition in terms of IRI and MPD (see figure 5.17), namely the total component (total area, representing the total CO_2 emissions related to the IRI and MPD). This total component can be considered as the sum of the basic component (green area, representing the value of emissions if the IRI and MPD remain constant over time – no deterioration) and the deterioration component (red area, equal to the difference between the first two and representing the emissions due to the deterioration of the pavement properties during the study analysis period, in terms of IRI and MPD).

Pavement engineering studies tend to focus on the deterioration component because of the opportunity to reduce these PVI emissions, taking direct action on the road surface condition, through appropriate maintenance. Obtaining pavement condition improvements is in general more rapid and easy than other approaches to reduce rolling resistance emissions that involve technology improvements or traffic reduction.

In this thesis, all the components were estimated, since they can provide a better understanding of the behaviour of the two rolling resistance models.

The calculations performed for the A1(M) case study with the two rolling resistance models are included in the Supplementary material 1. and 2., attached to this thesis.

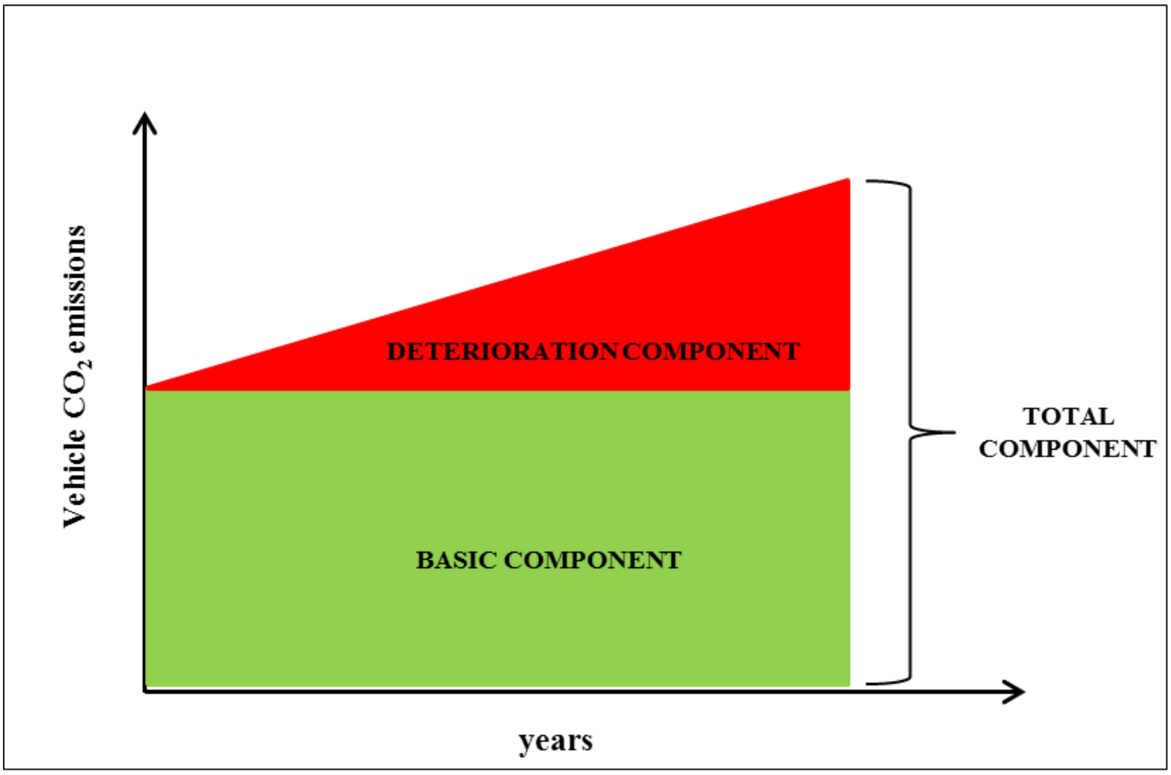


Figure 5.17: Total CO_2 emissions, divided into basic (green area) and deterioration components (red area), for a case without traffic growth and emission factor change, adapted from Trupia et al. (2016)

5.5.2 Sensitivity test and scenario modelling

In order to identify the parameters that affect the results in the work zone impact analysis, a sensitivity test was performed on the pavement deterioration rate, the traffic growth and the EF. For each of them, several scenarios involving a variation of the analysed parameter were considered and compared with the base case scenario. The traffic growth and the pavement deterioration during the analysis period tend to increase the CO_2 emissions, while the emission factor reduction affects the results in the opposite way, as vehicles become more fuel efficient.

Pavement deterioration rate

The use of these models, correlating pavement surface properties to vehicle fuel consumption and emissions, requires as an input parameter, the estimation of pavement condition deterioration rate with time (in terms of IRI and MPD).

As mentioned in the introduction, in the UK there are no models able to predict the deterioration rate of these parameters over the years. For this reason, the time progression of IRI and MPD on the assessed road segments over the analysis period (20 years) is generated according to literature data for specific maintenance strategies (Aavik et al. 2013; Jacobs 1982; UK Goverment 1999a; Wang et al. 2014a). In order to take into account the uncertainty related to these parameters and the range of potential impact during the use phase, different scenarios of deterioration of IRI and MPD are considered for the two case studies (see table 5.17) and compared in a sensitivity analysis.

The average deterioration values include an initial and final condition value and a linear change with time is assumed. This is also the case for the IRI values in the worst deterioration scenario. The MPD in the worst deterioration scenario and the MPD and IRI for the no deterioration scenario are held constant. Note that in the average deterioration scenario, the MPD falls with time from a high initial value; this is common in the UK were high MPD values are specified for new surfacing to assist in provision of high-speed wet skidding resistance.

Table 5.17: Pavement deterioration rate, in terms of IRI and MPD, during the analysis period

	Scenario	**MPD**	**IRI**
		mm	**m/km**
A17	Average deterioration	1.8-0.8	1.0-2.3
	Worst deterioration	1.5	1.0-5.0
	No deterioration	1.8	1
A1(M)	Average deterioration	1.6-0.6	1.0-2.3
	Worst deterioration	1.3	1.0-5.0
	No deterioration	1.5	1

Traffic growth

The AADF data for this study is extracted from the traffic dataset provided by the UK Department for Transport (UK Department for Transport 2014), where the vehicle data is classified based on the area, the year and the vehicle type. In order to quantify the impact of pavement surface properties in the use phase, it is necessary to estimate the future AADF, using a growth factor. This was estimated using TEMPRO (Trip End Model Presentation Program) (UK Department for Transport 2013b), a tool developed by the UK Department for Transport that analyses local data and, used in conjunction with national or regional traffic growth forecasts, provides local traffic projection factors. Since traffic growth is an uncertain factor, the sensitivity test performed for this variable took into account three different scenarios; the first one includes the estimated traffic growth projections (Average), the second assumes no traffic growth during the analysis period (No), and the third one a further increase of the traffic growth projections of 10% (Average + 10%). The traffic growth factor was assumed to evolve linearly over the lifetime of the pavement.

EF/Fuel efficiency improvement

In order to test the sensitivity of the main inputs to the two models, different scenarios of variation of the EF in the UCPRC model and fuel efficiency in the VTI model will be considered. In the UCPRC model, changing the EF based on the MOVES software (that result in the coefficients a1, a2 and intercept of the linear regression, developed in (Wang et al. 2014)) will be assessed. These factors change year by year based on predictions of future fuel economy and new vehicle technologies (e.g. electric vehicles). In the VTI model, changing the fuel efficiency will be tested, by using road emission projections resulting from the Department for Transport's National Transport Model (NTM) (UK Department for Transport 2013a). Again, in order to assess the sensitivity of the results to the EF forecast, three different scenarios are considered over the analysis period; EF and fuel efficiency constant (No); EF reduction and fuel efficiency increase, based on MOVES and NTM projections (Average) and; further variation of 10% in EF reduction and fuel efficiency increase based on MOVES and NTM projections (Average +10%).

To assess the results, two baseline case scenarios have been defined (Table 5.18): the base case scenario to compare the results from the two rolling resistance models and the average case scenario to compare the results of the sensitivity test (based on the different assumptions made for the traffic growth, pavement deterioration and EF/fuel efficiency).

Table 5.18: Base and average case scenario parameters

Case scenario	**Pavement deterioration**	**Traffic Growth**	**Fuel efficiency /EF**	**Comments**
Base case scenario	Average	No	No	Comparison of rolling resistance models
Average case scenario	Average	Average	Average	Comparison of sensitivity test

6 Results

This chapter summarizes the results obtained for the two case studies and following the procedures described in Chapter 5. The first three sections present the results obtained for the two case studies for the phases of: i) Construction/M&R, ii) the work zone impact and iii) the impact of the rolling resistance, in terms of pavement surface properties, on the fuel consumption and CO_2 emission of vehicles.

The sections related to the impact of the work zone and the rolling resistance are divided into three parts. The first one includes a comparison of the results obtained using two different models, the second one the results related to sensitivity tests performed on several variables and the third one a discussion of the results obtained.

As mentioned above, the results related to the construction phase and the traffic delay impact for the A17 were calculated in other previous studies. Since CO_2 is over 99.8% of the total tailpipe CO_2e emissions, other tailpipe emissions are not taken into account for the work zone and the rolling resistance impact. This chapter only reports the results obtained in this research. The discussion of these results and the conclusions are included in the next chapter.

6.1 Material production, Construction/M&R phase

Table 6.1 shows the CO_2e emissions for the two case studies, related to the original construction and a maintenance event in 2009 (excluding the work zone impact component), as described in section 5.1.

The results related to the A17 case study were determined in another research involving the same case study, where the impact of raw materials, construction and maintenance (but not the work zone impact) phases have been investigated (Spray 2014). To obtain the results of the A1(M) case study the same methodological approach and assumptions were used in this research.

The emissions related to these phases of a pavement LCA for the two cases studied were estimated and reported in this thesis only to allow a comparison with the work zone and the rolling resistance components and to evaluate their overall impact.

Table 6.1: CO_2 emissions due to the construction phase, for the two case studies

Event / Case study	Original construction		Maintenance	
	Description	**$CO_2e(t)$**	**Description**	**$CO_2e(t)$**
A17*	HRA_1989	702	Reconstruction (HRA)_2009	370
A1(M)	HRA_1980	4031	Thin surfacing_2009	223

* from Spray (2014)

6.2 Work zone traffic delay

This section summarizes the results obtained for the two case studies, comparing the HCM and the Aimsun models and analysing the effects of the traffic volume, the work zone TM, the EF and the road network boundary on the results. As mentioned in section 5.4, the results for the microsimulation with Aimsun for the A17 case study were calculated in previous research related to the same case study (Galatioto et al. 2015).

6.2.1 Comparison of the CO_2 emissions calculated with the HCM and Aimsun model

Table 6.2 shows the additional CO_2 emissions due to the work zone for both case studies, comparing the two models used, the HCM and the microsimulation models for the Base case scenario. The two case studies are characterized by different types of road design, traffic volume, length of work zone, TM layout and timing. Further, the HCM approach used for the two case studies is different, since they are characterized by different TM work zone and require a different macroscopic analytical/ deterministic method. This does not allow for a direct comparison of the two case studies.

However, it can be seen that in both case studies, the simplified approach with the HCM produces greater values of CO_2, even though the microsimulation model is able to take into account the emissions due to acceleration and deceleration. This difference is marginal in the case study with a low volume of traffic (A17) and gets significantly bigger for the A1(M), characterized by a higher volume of traffic. The impact of the chosen model on the A1, compared to the A17, cannot immediately be referred to the larger volume of traffic of the former because the two case studies, are also characterized by different maintenance strategies and TM that significantly affect the results.

Table 6.2: Additional tCO_2 from traffic during road works

	Simplified approach (HCM)	Sophisticated approach (Aimsun)
A17	2.4	1.9 (-20%)*
A1(M)	329.27	48.58 (-85%)

* from Galatioto et al. (2015)

The impact of the chosen traffic model on the results of the A1(M) case study is due to the fact that the HCM model predicts queuing during much of the day (the traffic flow being bigger than the capacity of the road) at an average speed of 8 mph, while the microsimulation model predicts steady flow with no queue. In the A17 case study, the slightly larger value of the emissions with the HCM approach may be due to an underestimation of the saturation flow, which is a fixed value. Based on the calculation from the HCM, in the minor road sections, flowing into the A17, (see figure 5.6) the effective green time is so low that only one vehicle would pass per traffic light cycle and this is probably an underestimation of the actual scenario.

6.2.2 Sensitivity test and scenario modelling

Tables 6.3, 6.4, 6.5 and 6.6 show a comparison of the tons of CO_2 emissions, due to the work zone, obtained for the Base case scenario (as defined in Chapter 5) and other scenarios involving a variation of the analysed sensitive parameters (traffic volume, TM, EF and network boundary). Each table is divided into three sections; the first one shows the case study and the model assessed, the second one the tons of CO_2 emissions related to every scenario and the third one the change – in percentage terms – of these emissions, compared to the base case scenario.

Table 6.3 is related to the impact of the traffic volume on the results. As expected, the increase of traffic volume generates a rise in the CO_2 emissions due to the work zone. This increase, based on the scenarios considered, spans between 66.7% and 410.3% for the A17 case study and 33.2% and 3201.9% for the A1(M) case study, depending on the model used to calculate the impact of the work zone.

The results obtained do not allow a general conclusion to be drawn related the impact of the increase traffic volume on the results based on the original AADT (low-medium-high level of traffic) or the model used. This is because, if in the A17 the impact of the increase of traffic volume is bigger with Aimsun microsimulation model, the opposite is true for the A1(M), where the impact of this variable, for an increase of the 30% of the original value, generates results over 30 times bigger by using the HCM. In addition, in this last case, once the traffic volume increases (from 10% to 30 %), the increase of CO_2 emissions is very significant.

In the base case scenario of the A1 (M), the HCM model predicts queuing during much of the day, at an average speed of 8 mph, while the microsimulation model does not. This different behaviour of the two models impacts the results of the base case scenario, but has also an impact on the sensitivity test. With the HCM, the congestion and increase of the traffic approaching the work – zone, will generate not only a rise in the number of vehicles that produce CO_2 emissions at reduced speed, but also an increase of the length of the queue. This means that a greater number of vehicles will drive for a longer distance (queue length) at an average speed of 8 mph. Therefore, during congestion, the increase of tailpipe emissions is not directly proportional to the increase in the number of vehicles.

It can be concluded that the sensitivity of the result to the traffic used grows with increasing traffic and that the results are very sensitive to the assumed rate of traffic growth.

Table 6.3: Traffic volume impact on the traffic CO_2 emission results

Case study	**Model**	**Traffic volume CO_2 (ton)**				**Change in traffic volume (%)**		
		0% Base case scenario	**10%**	**20%**	**30%**	**10%**	**20%**	**30%**
A17	HCM	2.4	4.0	4.9	7.9	66.7%	104.2%	229.2%
	Aimsun	1.9	3.4	4.6	9.9	75.3%	137.1%	410.3%
A1(M)	HCM	329.7	1913.1	5193.6	10885.5	480.3%	1475.4%	3201.9%
	Aimsun	48.6	64.7	96.6	143.1	33.2%	98.8%	194.6%

Table 6.4 shows the impact of the selected TM strategies on the results. In the table, there are some missing data because it was not possible to evaluate the CO_2 emissions related to some specific scenarios with the HCM approach, as explained above. In the A17 case study, the scenario 2 involving bringing the timing of lane closure forward to 18.00 produced an increase in the CO_2 emissions between about 6-7 times bigger than the base case scenario (the increment is comparable for the two models). The diversion onto adjacent roads in this case study would generate a significant increase of the CO_2 emissions up to about 20 times more, in case of 24 hour TM proposals.

For the A1(M) case study, both the scenarios 2 (hard shoulder as running lane) and 3 (detour) involve a reduction of the CO_2 emissions. Overall, for the A1(M) case study, the different TM solutions produce smaller changes in the CO_2 emissions compared to the A17.

Concluding, for the A17, the Base case scenario represents the TM option with lowest emissions. Scenario 2, involving an earlier closure of the road, shows how a change in the starting time of the road works can significantly impact the results. Scenario 3 with the road closure and extensive traffic diversion has the highest emissions of CO_2. In the A1(M) case study, Scenario 2, requiring the use of the hard shoulders as a running lane and providing larger road capacity, has the lowest impact, although it lasts longer than Scenario 3, in terms of number of days. However, the use of hard shoulders is subject to a condition survey (assessment of the existing surface course, any ironwork, sufficient width etc.) and is not always an option. Generally, road closures are the safest and most economical way of resurfacing high speed roads, since they do not involve interaction between opposing traffic flows and with road workers. It represents an easy and quick solution to install once the diversion route has been established. However, this option is not always a viable alternative (in the A17 the diversion distance is too long), or associated with the lowest emissions.

The sensitivity analysis on the EF was performed with the HCM approach, comparing the values from the MOVES software and from EFT. The results in table 6.5 show that by using the MOVES EF the CO_2 emissions are about three times that using the EFT EF for both case studies.

Table 6.4: TM impact on the results

Case study	Model	TM impact CO_2 (ton)			TM impact (%)	
		Base case scenario	Start 18.00	Detour	Start 18.00	Detour
A17	HCM	2.4	17.9	-	647.1%	-
	Aimsun	1.9	16.5	46.3	748.5%	2285.1%
		Base case scenario	Hard shoulder	Detour	Hard Shoulder	Detour
A1(M)	HCM	329.7	-	-	-	-
	Aimsun	48.6	29.1	47.31	-40.1%	-2.6%

Table 6.5: EF impact on the results

Case study	EF impact (ton)		EF impact (%)
	EFT Base case scenario	Moves	Moves
A17 (HCM)	2.4	6.3	162.5%
A1(M) (HCM)	329.7	837	153.9%

Table 6.6 shows the results obtained performing a sensitivity test on the network boundary for the A1(M) case study, using the microsimulation approach, in order to investigate if and how the area of impact of the work zone can affect the results and how microsimulation software can be helpful in this process.

The results obtained are sensitive to the definition of the area of impact of the work zone. The Mini network is composed of a linear segment in the A1 (M) that includes the work zone area but does not consider any potential diversions for the vehicles. The Small network takes into account the traffic generated at the two roundabout junctions to the North and the South of A1(M) and the associated traffic streams, but it does not allow any change in route choices. This network, compared to the Mini network, estimates larger emissions, because it considers also the emissions produced at the roundabouts due the extension of the congestion from the work zone. By contrast, in the Big network, the extra emissions estimated are smaller than in the Mini network, because the vehicles have the possibility to change their route during congestion to reach the same destination point.

Table 6.6: Network boundary impact on the results

Case study/Model	Network boundary impact CO_2 (ton)			Network boundary impact (%)	
	Mini Network Base case scenario	Small Network	Extended Network	Small Network	Extended Network
A1(M) (Aimsun)	48.58	53.85	41.88	+10.8%	-13.8%

6.3 Rolling resistance

This section summarizes the results obtained for the two case studies, comparing the UCPRC and the VTI models and analysing the effects of the traffic growth, the EF/energy efficiency and the pavement deterioration rate on the results. As shown in Table 5.18, two baseline case scenarios have been defined to assess the results, the base case scenario to compare the results from the two rolling resistance models and the average case scenario for the sensitivity test.

6.3.1 Comparison of the CO_2 emissions calculated with the UCPRC and VTI models

Table 6.7 summaries the results obtained for the two case studies with the UCPRC and the VTI models, in terms of basic, deterioration and total component, as defined in Chapter 5 (see Figure 5.17). In both case studies, the use of these models provides considerably different results for all the components. It amounts to one order of magnitude for the basic and the total component, while the deterioration component is positive in the UCPRC model and negative in the VTI model. This means that in the VTI model, the total component is smaller than the basic component, due to the reduction of the deterioration component over the years. The opposite is true for the UCPRC model. The behaviour is the same for both case studies.

Table 6.7: CO_2 emissions due to pavement surface condition obtained with the two models – base case scenario

Case study	Model	CO_2 emissions (ton)		
		Total emissions	Basic component	Deterioration component
A17	UCPRC	1387	1170	217
	VTI	9672	10272	-600
A1(M)	UCPRC	22645	18058	4586
	VTI	105139	109344	-4205

Analysing each component in detail, it is possible to identify some "key" elements for each of the two models.

The difference in results obtained for the basic component shows an interesting aspect related to the comparison of the two models; regardless of the deterioration in the IRI and MPD over the analysis period, the two models return considerably different results (10272 ton against 1170 ton for the A17 and 109344 ton against 18058 ton for the A1(M)). This difference reflects the substantially different estimated total components.

The deterioration term for the VTI model is negative for both case studies and this means that overall the deterioration in pavement surface properties produces a reduction of the vehicle tailpipe CO_2 emissions over the years, rather than an increase as was expected. The negative term related to the deterioration component is due to the different impact given to the IRI and MPD terms by the two models (see figures 6.1and 6.2).

The VTI model assigns to the MPD term a greater impact on the rolling resistance and on the emission estimate than for IRI (even at high speed, which increases the impact of the IRI); the opposite consideration is true for the UCPRC model, where the IRI term has a larger impact.

The significance of this different behaviour becomes particularly relevant for pavement surfaces where the IRI tends to increase and the MPD tends to decrease, as in these case studies. The VTI model gives a negative value for the deterioration component, because the MPD term decreases faster than the IRI term increases. Therefore, the pavement surface' deterioration and the models used to describe them have a significant impact on the emissions results. This consideration is confirmed by the sensitivity test performed on this input variable that shows how the IRI and MPD deterioration rate can change the rolling resistance results in a pavement LCA.

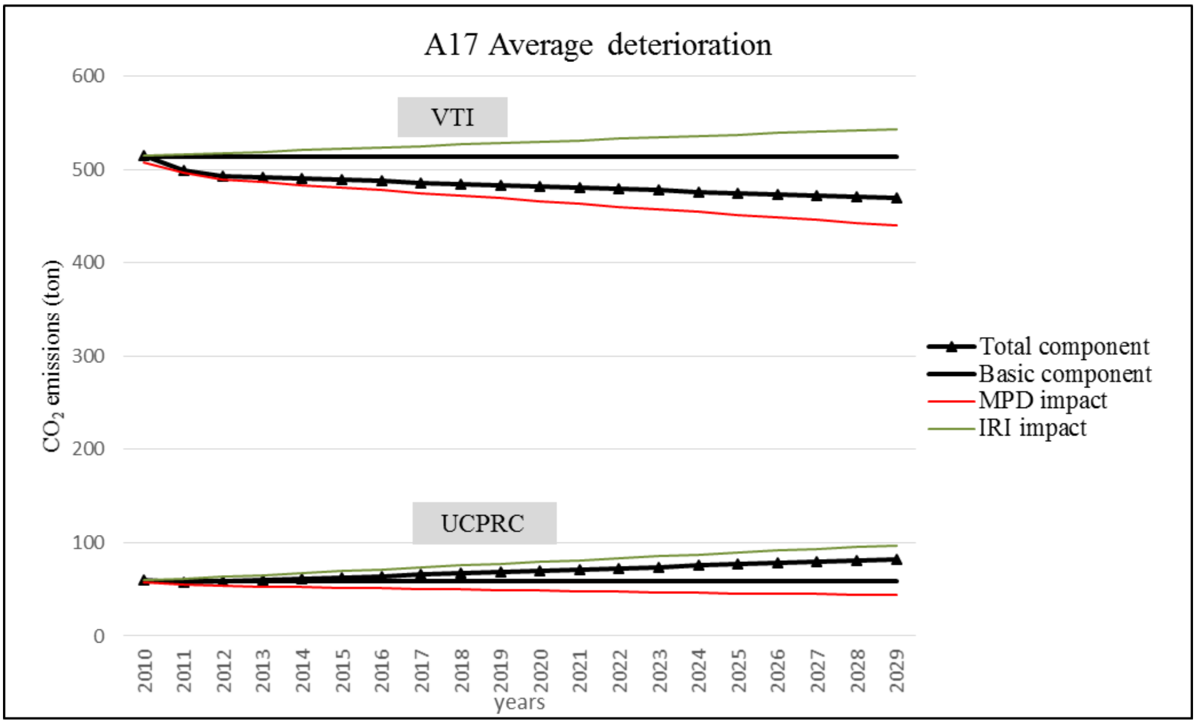


Figure 6.1: Impact of IRI and MPD in the VTI and the UCPRC models for the A17 case study

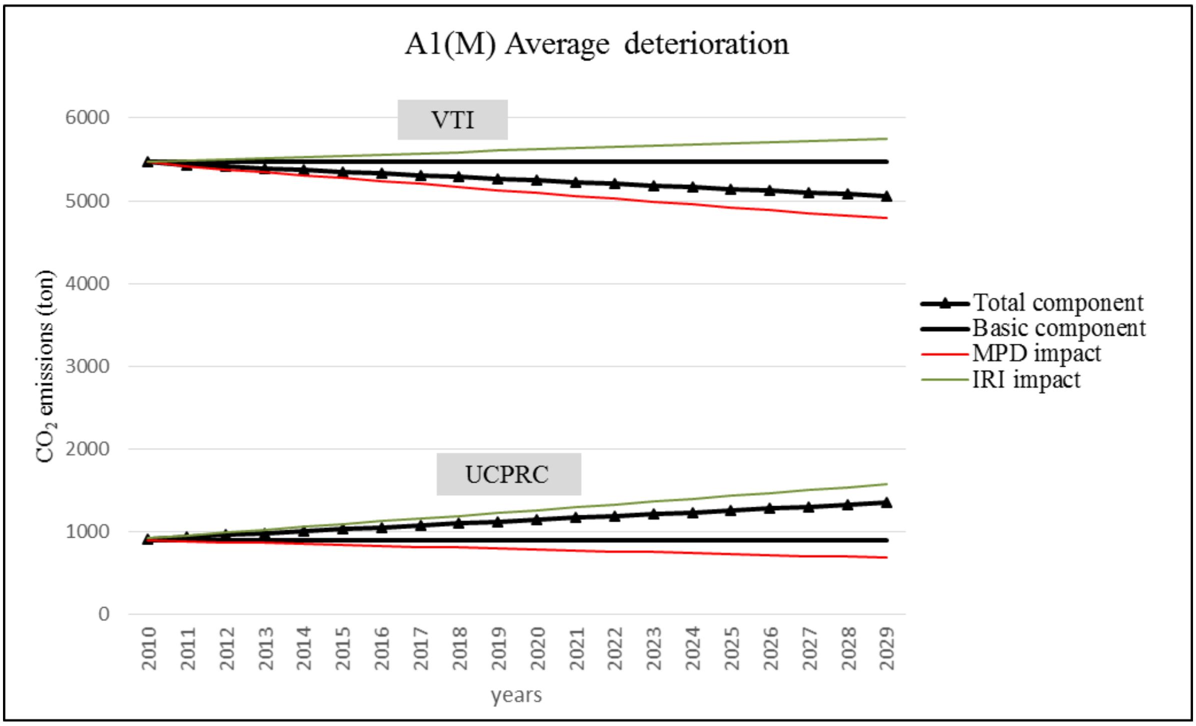


Figure 6.2: Impact of IRI and MPD in the VTI and the UCPRC models for the A1M) case study

6.3.2 Sensitivity test and scenario modelling

This section summaries the overall results of the sensitivity test related to both case studies with the VTI and the UCPRC models, performed on some specific variables, traffic growth, EF and pavement deterioration rate. As explained in Chapter 5, several scenarios have been defined for each single parameter and compared to the average scenario, characterized by average data of deterioration rate, traffic growth and EF, as previously defined.

Figures 6.3, 6.4, 6.5 and 6.6 show for each component (basic, deterioration and total), the variation, in percentage terms, of CO_2 emissions in each scenario compared to the average case scenario. The red and the grey areas represent respectively the basic and the deterioration components. When the deterioration component is negative, in order to obtain the total component, it is necessary to subtract from the basic component the deterioration component. The figures show a certain uniformity in the results for both case studies and models. The basic component (red area) is affected by the traffic growth and the EF changes and, compared to the average case scenario, its range spans between -12.5% and 12.8% for the A17 and -12.55 and 17.7% for the A1(M) depending on the model and the scenario considered. Clearly, the deterioration rate does not affect the basic component (ΔIRI=ΔMPD=0). The deterioration component (grey area) – positive or negative, based on the model used and on the deterioration rate - is affected by all parameters, though to different degrees. If the effect of the EF change and the traffic growth is confined between -17.2 and +16% for the A17 and -12.5 and 14.4 for the A1(M), the impact of the deterioration rate is much more significant. Moreover, the traffic growth during the analysis period tends to increase the CO_2 emissions, the emission factor reduction affects the results in the opposite way, as vehicles become more fuel efficient. Therefore, even if the traffic growth and the emission factor parameters affect the results, this combined impact is not significant overall. By contrast, the CO_2 emissions due to the pavement roughness are very sensitive to the pavement surface deterioration over time. Actually, the traffic growth impact on the results is not only due to greater number of vehicles producing CO_2 emissions. Indeed, the traffic volume and the traffic fleet affect the road pavement deterioration (IRI and MPD time progression) and, consequently, the CO_2 emissions due to the PVI Rolling resistance. Therefore, the traffic growth has further impact on the vehicle tailpipe emissions, since it not only produces a greater number of vehicles generating CO_2 emissions, but it also has a direct impact on the deterioration component of the rolling resistance. However, as already mentioned, the lack of deterioration models for UK roads does not allow for this effect to be taken into account.

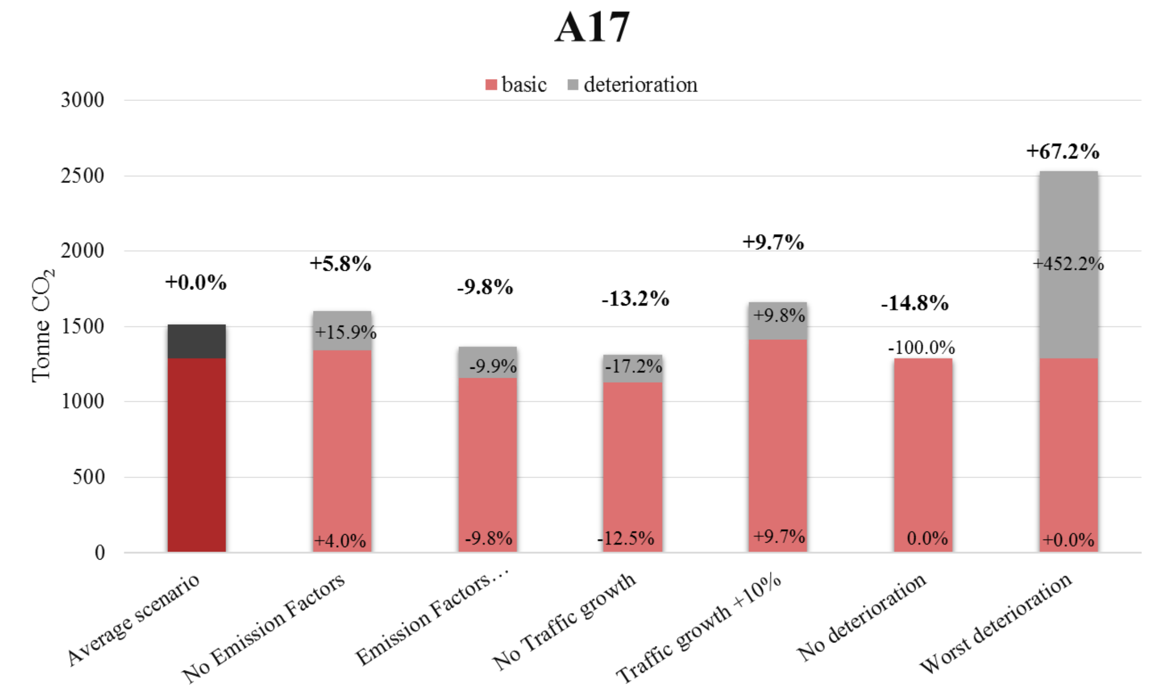


Figure 6.3: A17 Sensitivity analysis-impact of each variable on emissions due to pavement rolling resistance_UCPRC

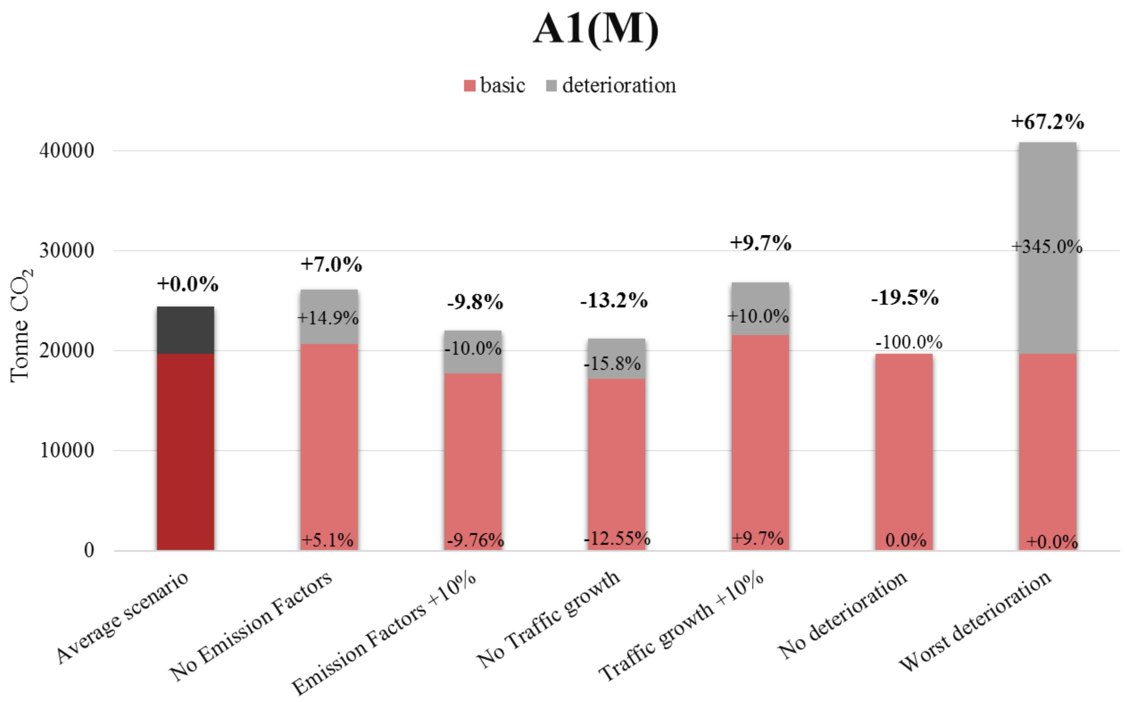


Figure 6.4: A1 (M) Sensitivity analysis-impact of each variable on emissions due to pavement rolling resistance_UCPRC

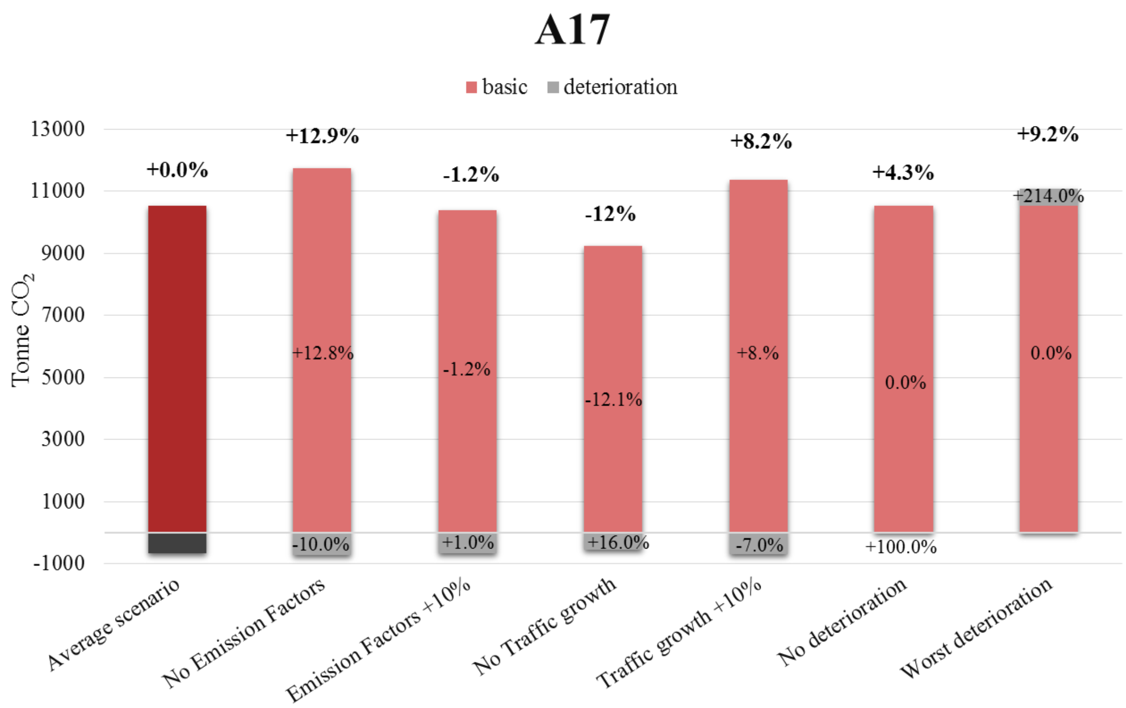


Figure 6.5: A17 Sensitivity analysis-impact of each variable on emissions due to pavement rolling resistance_VTI

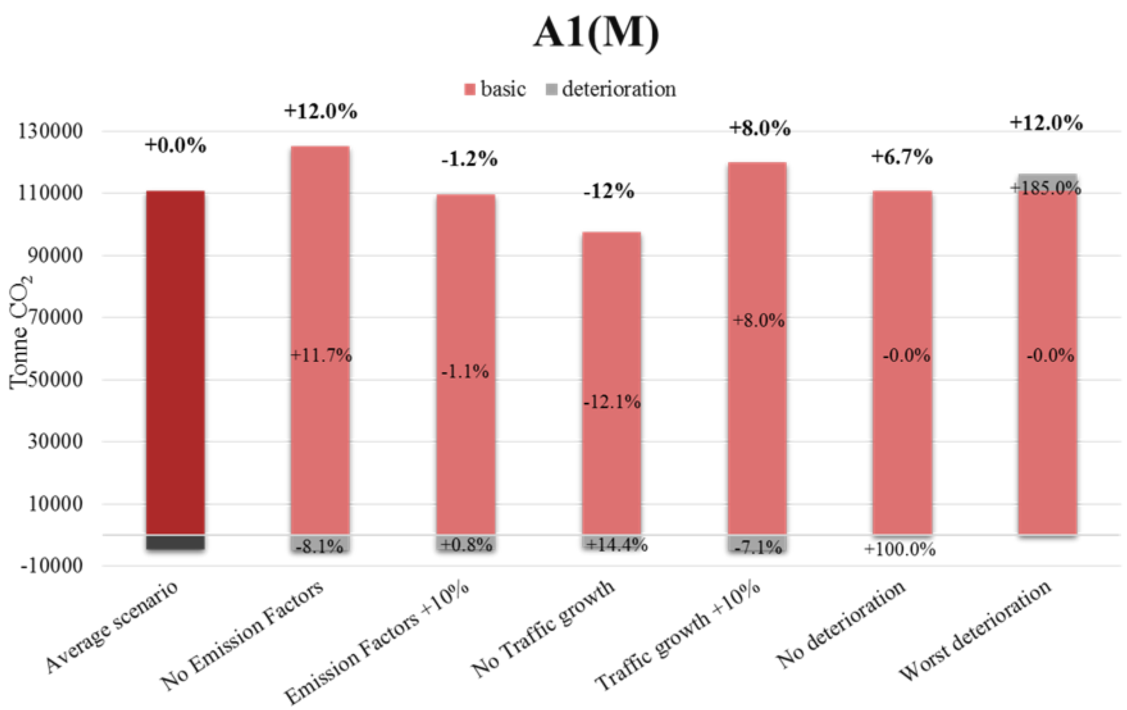


Figure 6.6: A1(M) Sensitivity analysis-impact of each variable on emissions due to pavement rolling resistance_VTI

Tables 6.8 and 6.9 show in detail the results of the sensitivity test performed on the deterioration parameter for the A17 and the A1(M) case studies.

Table 6.8: Sensitivity analysis-on pavement deterioration for the A17 case study

A17						
Deterioration Rate Scenario	**Emissions of CO_2 (ton)**					
	VTI			**UCPRC**		
	Basic	Deterioration	Total	Basic	Deterioration	Total
Average	10272	-634	9638	1170	217	1387
Worst	10272	500	10772	1170	1134	2304
No	10272	0	10272	1170	0	1170
	% compared to the Average deterioration scenario					
Average	100	100	100	100	100	100
Worst	100	-79	112	100	522	166
No	100	0	107	100	0	84

Table 6.9: Sensitivity analysis on pavement deterioration for the A1(M) case study

A1(M)						
Deterioration Rate Scenario	**Emissions of CO_2 (ton)**					
	VTI			**UCPRC**		
	Basic	Deterioration	Total	Basic	Deterioration	Total
Average	109344	-4205	105139	18058	4586	22645
Worst	109344	4716	114059	18058	19634	37693
No	109344	0	109344	18058	0	18058
	% compared to the Average deterioration scenario					
Average	100	100	100	100	100	100
Worst	100	-112	108	100	428	166
No	100	0	104	100	0	80

The results obtained performing the sensitivity test for the two case studies show:

- For both models, the range of potential impact due to the PVI rolling resistance is wide;
- The lowest emissions in the two models occur under different pavement deterioration rate scenarios (no deterioration in the UCPRC model and average deterioration in the VTI model). In the UCPRC model the deterioration component increases over time, so the absence of deterioration minimizes the total emissions.
- In the VTI model, the deterioration component, under the average condition of pavement deterioration, tends to decrease, producing an overall reduction in the calculated emissions. This effect levels off under the "worst deterioration" pavement condition, when the IRI effect is larger than the MPD effect.
- This means that in both models, the CO_2 emissions are significantly higher in the case of the worst pavement deterioration scenario.
- The results shows the CO_2 emissions due to the pavement roughness are very sensitive to the pavement surface deterioration over time.

Tables 6.10 and 6.11 show under which conditions there are the average, the lowest and the highest CO_2 emissions with the two models, considering all the possible combinations of the variables.

Table 6.10: Sensitivity analysis results for the UCPRC model

UCPRC MODEL							
Case scenario	Sensitivity Parameter			Case study	Emission of CO_2 (tonne)		
	Pavement deterioration	Traffic growth	EF		Basic	Deterioration	Total
Average	Average deterioration	Average	Average	A17	1288	225	1513
				A1(M)	19696	4767	24462
Best	No pavement deterioration	No	Average+10%	A17	1020	0	1020
				A1(M)	15588	0	15588
Worst	Worst deterioration	Average+10%	No	A17	1755	1210	2965
				A1(M)	22682	25904	48586

Table 6.11: Sensitivity analysis results for the VTI model

VTI MODEL							
Case scenario	**Sensitivity Parameter**			**Case study**	**Emission of CO_2 (tonne)**		
	Pavement deterioration	**Traffic growth**	**EF**		**Basic**	**Deterioration**	**Total**
Average	Average deterioration	Average	Average	A17	10372	-514	9858
				A1	110887	-4575	106311
Best	Average deterioration	No	Average+10%	A17	9141	-557	8584
				A1	96358	-3804	92555
Worst	Worst deterioration	Average+10%	No	A17	10272	3281	13553
				A1	137015	6418	143432

By evaluating the best and the worst case scenarios for the two different models and considering the impact on the basic, deterioration and total components of vehicle CO_2 emissions, the sensitivity analysis shows the following:

– for both models, the potential emissions due to PVI rolling resistance have a large range of values;

– this is particularly so in the deterioration component, especially in the VTI model, here the CO2 emissions can vary between 0.80 and 7.38 times the average value;

– the best case scenario (lowest emissions) occurs under different assumptions for the two models (no deterioration in the UCPRC model and average deterioration in theVTI model).

6.4 Summary

Table 6.12 includes a summary of the results obtained and/or analysed in this research. As confirmed in previous studies (Santero et al. 2011a; Santero and Horvath 2009), the traffic delay and the PVI Rolling Resitance components can have a relevant impact in the life cycle of a pavement, compared to other phases. If, in this study, this is always true for the PVI Rolling resistance phase, for the work zone impact, the methods and the methodological assumptions make the results span a big range.

Traffic delay

In both case studies, the simplified approach with the HCM provides larger values of CO_2, than the microsimulation model. This difference is marginal in the case study with a low volume of traffic (A17) and gets significantly bigger for the A1(M), characterized by a higher volume of traffic.

The results are sensitive to all the analysed parameters: traffic volume, TM strategy, EF and road network boundary extension.

The increase in traffic volume generates a rise in the CO_2 emissions. This increase, based on the assumptions made, spans between 66.7% and 410.3% for the A17 case study and 33.2% and 3201.9% for the A1(M) case study, depending on the model used to calculate the impact of the work zone.

If in the A17 the impact of the increase in traffic volume is bigger with the Aimsun microsimulation model, the opposite is true for the A1(M), where the impact of this variable, for an increase of 30% over the original value, generates results over 30 times bigger. In addition, in this last case, once the traffic impact increases (from 10% to 30 %), the increase of CO_2 emissions is very large.

The TM strategy selected can strongly impact the results, both in terms of timing and layout. For the A17, the Base case scenario represents the TM option with lowest emissions. Scenario 2, involving an earlier closure of the road, produces an increase of the CO_2 emissions between about 6-7 times bigger than the base case scenario (the increment is comparable for the two models). Scenario 3 with the road closure and extensive traffic diversion has the highest emissions of CO_2. In the A1(M) case study, Scenario 2, requiring the use of the hard shoulders as a running lane and providing larger road capacity, has the lowest impact, although it lasts longer than Scenario 3 (detour).

The EF selected to estimate the CO_2 vehicle emissions significantly affect the results; by using the MOVES EF the CO_2 emissions are about three times that using the EFT EF for both case studies.

The definition of the area of impact of the work zone is relevant in the traffic modelling process. The small network, compared to the Mini network, estimates larger emissions. By contrast, in the Big network, the extra emissions estimated are smaller than in the Mini network.

PVI Rolling resistance

In both case studies, the use of these models provides considerably different results for all the components. It amounts to one order of magnitude for the basic and the total component, while the deterioration component is positive in the UCPRC model and negative in the VTI model. This means that in the VTI model, the total component is smaller than the basic component, due to the reduction of the deterioration component over the years. The opposite is true for the UCPRC model.

Regardless of the deterioration in the IRI and MPD over the analysis period, the two models return considerably different results (10272 ton against 1170 ton in the A17 and 109344 ton against 18058 ton in the A1(M).

In the sensitivity tests, the results are affected by all parameters, though to different degrees. While the traffic growth and the emission factor parameters affect the results, the combined impact is not significant overall. However, in this study the impact of the traffic volume and fleet on the pavement deterioration (IRI and MPD) was not taken into account, due to the lack of available models. This may affect the actual influence of the traffic growth on the vehicle emissions.

The CO_2 emissions due to the pavement roughness are very sensitive to the pavement surface deterioration over time. In fact, for both models, not only is the range of potential impact due to the PVI wide, the lowest emissions in the two models occur under different pavement deterioration rate scenarios (no deterioration in the UCPRC model and average deterioration in the VTI model).

Table 6.12: Summary of the results

TOTAL RESULTS											
Phase	**Activities**	**Year/Event**	**Variables**		**Model**	**A17** CO_2**(e)(ton)**			**A1(M)** CO_2**(e)(ton)**		
Construction	Raw materials/ transport/ onsite equipment	Original Construction	Base case scenario		Simapro	*702			4,031		
		Maintenance 2009	Base case scenario		Simapro	*370			223		
	Traffic delay	Maintenance 2009	Base case scenario		Aimsun	**1.94			48.58		
					HCM	2.40			329.84		
			Sensitivity testTraffic Volume	10	Aimsun	**3.43			67.74		
					HCM	4.00			1,913		
				20	Aimsun	**4.67			96.58		
					HCM	4.90			5,194		
				30	Aimsun	**9.99			143.08		
					HCM	7.95			10.45		
			Sensitivity testTraffic Management	Scenario 2	Aimsun	16.46			29.09		
					HCM	17.93			52.76		
				Scenario 3 (Detour)	Aimsun	63.29			47.31		
			EF	Moves	HCM	6.30			837.00		
					***	B	D	T	B	D	T
Use phase	Rolling resistance	2009-2029	Base case scenario		UCPRC	1170	217	1387	18058	4586	22645
					VTI	10272	-600	9,672	109344	-4205	105,139
			Average case scenario		UCPRC	1,288	225	1,513	19,696	4,767	24,462
					VTI	10,515	-657	9,858	110,887	- 4,575	106,311
			Sensitivity test Emission Factors	No	UCPRC	1,340	261	1,601	20,702	5,480	26,182
					VTI	11,748	-709	11,039	125,056	- 5,032	120,023
				10%	UCPRC	1,162	203	1,365	17,773	4,290	22,064
					VTI	10,395	-651	9,744	109,517	- 4,530	104,987
			Sensitivity test Traffic growth	No	UCPRC	1,127	186	1,313	17,225	4,012	21,237
					VTI	9,241	-562	8,679	97,503	- 3,841	93,662
				10%	UCPRC	1,413	247	1,660	21,597	5,242	26,840
					VTI	11,358	-703	10,654	119,971	- 4,894	115,077
			Sensitivity test Pavement Deteriorration	No	UCPRC	1,288	-	1,288	19,696	-	19,696
					VTI	10,515	-	10,515	110,887	-	110,887
				Worst	UCPRC	1,288	1,242	2,530	19,696	21,214	40,910
					VTI	10,515	558	11,073	110,887	5,216	116,102

* from (Spray 2014)

** from (Galatioto et al. 2015)

*** B: Basic; D: Deteriorration; T=Total

7 Discussion and Conclusion

In this chapter the implications and impact of the results obtained in this study and described in Chapter 1 are discussed in the context of the literature review in Chapters 2, 3 and 4 and the methodology described in Chapter 5. The main aim of this chapter is to describe how the study has met the research aims and objectives stated in section 1.2.1 and how it has answered some outstanding questions and filled some significant research gaps, as highlighted in section 4.6.

While the first section describes the overall conclusions of the study, the other two sections discusses in details specific 'key' considerations of the work zone traffic delay impact and rolling resistance components.

7.1 Pavement LCA

As discussed in section 2.3, the implementation of LCA principles in the pavement domain is complex, due to some methodological issues that reduce the accuracy and reliability of the results obtained. For long time, the traffic delay and the rolling resistance components, whose impact can be significant under specific conditions, have been omitted from previous pavement LCA studies. In the last years, the research has made progress, either assessing the impact of these components and developing or using models able to explain their behaviour.

The results obtained in this research have, first of all, confirmed the relevance of these two components in the life cycle of a road pavement compared to other phases. Therefore, as already stated in previous studies, performing pavement LCA assessment, withouth taking into account the work zone traffic delay and the PVI rolling resistance components, may lead to incorrect, or at least incomplete, conclusions.

An important outcome from this thesis is the significant influence of the models applied to analyse both the traffic delay and the rolling resistance. To assess the impact of the traffic delay during construction and maintenance events, existing traffic and emission models have been used with different level of sophistication, which has a significant impact on the LCA results. Therefore, the choice of the traffic and emission models needs to be based on the study objectives and on the available resources. The estimation of the impact of the

Rolling resistance on the vehicle emissions requires the development of models to estimate the deterioration of the pavement surface properties (both in terms of IRI and MPD) over time and to correlate them with the and with the vehicle fuel consumptions. Currently, there are few models available in the literature, which are calibrated for site-specific conditions. The results are sensitive both to the model used to estimate the PVI rolling resistance CO_2 emissions, and to the surface deterioration rate chosen. Site specific elements and methodological choice affect the development of the rolling resistance and fuel consumption models, meaning they are not suitable for all geographical locations.

The selected model is not the only source of uncertainty in the assessment of these components, requiring specific methodological assumptions. These, as shown in this study, can have a relevant impact on the results, generating a high level of uncertainty. The traffic delay results are sensitive to all the input variables considered in this study: the traffic growth, the TM strategy adopted, the EF model and the extent of the road network modelled around the work zone.

For the rolling resistance, if the deterioration rate is a significantly sensitive parameter, the traffic growth and the EF/fuel efficiency predictions, combined to predict future vehicle emissions, have a relatively small effect because they cancel out to a large extent. Changes in predicted future traffic levels or EF could change this result and should be kept under review.

These research outcomes highlight the importance of incorporating uncertainty into pavement LCA. The reliability and accuracy of an LCA is affected by the reliability of the assumptions, methodologies and models adopted. LCA results should not be presented as 'single figure' absolute values, but rather as a range of values to estimate the uncertainties and variability that lie behind them.

7.2 Work zone traffic delay

Chapter 3 has shown that the analysis of traffic delay during maintenance activities in pavement LCAs is generally based on macroscopic analytical models or microsimulation models, whose main features have been described in the same chapter.

The level of sophistication of the model used to assess the impact of the work zone during maintenance events has a significant impact on the LCA results, as described in section 6.2.1. For both case studies and approaches used, the HCM provides higher values of CO_2 emissions (over 50%), despite the fact that it does not estimate the impact due to acceleration and deceleration of the vehicles in the work zone. This significant dissimilarity of the results may be due to specific features of the HCM models that determine an overestimation of the additional fuel consumption caused by the traffic delay.

For the A1(M), the macroscopic approach with the HCM involves queuing during much of the day (average speed of 8 mph), while the microsimulation model does not. As explained in section 5.4.1.3, the calculation of the emissions with the HCM_LCCA model is strongly affected by the speed of the queuing traffic, since a small change in this value in congested conditions (between 0 and 25 mph) can generate significantly different results, in terms of fuel consumption and CO_2 emissions. However, the curve used in the LCCA procedure to calculate this value does not allow a precise and accurate evaluation of the queue speed, reducing the reliability of the outcome of the model. In order to use this model in a confident way, this procedure should be updated by using more accurate methods of evaluating queue speed and associated emissions.

Instead, in the A17 case study, the bigger value of the emissions with the HCM approach may be due to an underestimation of the real value of the saturation flow, which affect the number of vehicles passing at green during the traffic light cycle and, therefore, the length of the queue and the idling time.

Other factors explaining the results obtained are the different emissions factors used in the two models, the different approaches used to estimate the queue speed (in Aimsun, it is based on other factors, such as the car-following models) and the fact that in the HCM, several parameters (such as Capacity and average speed) are based on empirical data on USA roads.

When traffic models are used, therefore, these model input parameters need to be accurately monitored and controlled, in order to provide a better understanding of the outcome of the study.

As stated in section 3.3, other potentially significant variables to take into account in the analysis of the traffic delay impact are the traffic volume considered for the study, TM strategy adopted, the EF model to convert the vehicle power in the fuel consumption and CO_2 emissions and last, but not least, the extent of the road network modelled around the work zone. The results of this study have shown that, in different ways and with different level of impact, the final results are sensitive to all the chosen parameters. In particular:

- A greater value of AADT results in an increase in CO_2 emissions due to the work zone. However, based on the results obtained, it is not possible to draw a general conclusion related to the impact of the increased traffic volume on the results based on the original AADT (low-medium-high level of traffic) or the model used. In fact, while in the A17 the impact of the increase of traffic volume is bigger with Aimsun microsimulation model, the opposite is true for the A1 (M). Instead, it is possible to state that, during congestion, the increase of tailpipe emissions is not directly proportional to the increase in the number of vehicles (AADT), since the congestion and increase of the traffic approaching the work – zone, will generate not only a rise in the number of vehicles that produce CO_2 emissions at reduced speed, but also an increase of the length of the queue.

- The sensitivity analysis has also shown that the TM of the road works, in terms of type, duration and timing, significantly affect the results, but not always in the same ways. For instance, road closure and diversion onto adjacent roads, which is usually the safest and most economical option (no interaction between opposite traffic flow or road workers), is not always an alternative with a lower carbon footprint.
- The EF model selected to convert the output of the traffic model into CO_2 emissions can vary the output results substantially. This is due, as seen in the section 3.2, to the different approach used to calculate the FC and emissions (average or instantaneous model) and to the fact that they have been developed in different countries and validated under different conditions.
- The extent of the road network modelled is a relevant factor in the analysis of the traffic delay component. During a maintenance event, the behaviour of the vehicles is influenced by the traffic in the work zone and they could select alternative route directions to reach the same destination point. In the worst scenario, the congestion generated in the work zone could extend beyond the modelling area. An incorrect evaluation of the area of impact may lead to an underestimation or overestimation of the actual value of the CO_2 emissions.

7.3 PVI Rolling resistance

As mentioned in Chapter 4, currently there are few rolling resistance models in the literature that have explored the combined effect of IRI and MPD, but not in the UK. The results obtained in this research have shown that existing models linking pavement condition to rolling resistance and hence vehicle emissions are not broadly applicable to the use phase of road pavement LCA and further research is necessary before a widely-used methodology can be defined. In particular, under specific conditions, these models significantly affect the results - both in terms of the general contribution of the pavement surface properties to the rolling resistance (basic component) and in terms of the impact of the different components (IRI and MPD) - and can lead to conflicting conclusions.

These considerable differences are due to the fact that the development of rolling resistance and fuel consumption models is strongly affected by methodological components (such as different rolling resistance measuring methods, road surface measures, approach used to develop the models) and by site-specific components (weather, vehicle types and technology, type of roads, pavement design models and deterioration). The UCPRC model was developed in California, using the HDM-4 model calibrated for US conditions and MOVES, the US EPA highway vehicle emission model based on national data. The VTI model developed in Sweden includes a rolling resistance model based on empirical data and a fuel consumption model calibrated using calculated values from VETO, a theoretical model. California and Sweden are geographical locations characterized by different climates, types of roads, pavement deterioration processes and models, traffic distribution and technology, that seriously affect the models developed and the results produced.

The difference in results obtained for the basic component means that, regardless of the deterioration rate of the IRI and MPD over time, the two models estimate the impact of the rolling resistance on the fuel consumption in dissimilar way. The different validation of the two models, together with the different approaches used, can be considered the main reason for this significant difference in the results: indeed, the models were calibrated for different countries with different input data, in terms of weather, vehicles, and roads.

The results for the deterioration component obtained with the two models are conflicting (negative for the VTI and positive for the UCPRC) and this is due to the fact that the two models consider the impact of the pavement surface properties, IRI and MPD, in different ways (in the UCPRC model, the IRI has a larger impact on the rolling resistance than the MPD and the opposite consideration is true for the VTI model). This difference is particularly significant in these case studies, where the MPD falls over time, producing opposite results when the two models are used; in the UCPRC model, the deterioration component is positive, since the impact of the increase in IRI is larger than that due to the reduction in MPD, while for the VTI model, the deterioration component is negative. Therefore, the pavement condition deterioration over time has a strong impact on the rolling resistance, significantly affecting the results. This is confirmed by the sensitivity test performed on the IRI and MPD deterioration rate that showed that the CO_2 emissions due to PVI rolling resistance are very sensitive to this factor.

By contrast, traffic growth and the EF changes do not have a large impact on the results, because they tend to offset each other. However, as mentioned in section 6.3.2, in this study, due to the lack of pavement deterioration models for UK roads, it was not possible to consider the impact of the traffic growth on the deterioration for IRI and MPD, which may produce a relevant impact. In addition, the prediction of traffic growth and EF is characterized by uncertainty; as stated in section 4.5, the first one is consistently overestimated by the UK Department for Transport, while the second one may be underestimated, since the boost given in the last years to the electric vehicles sector.

8 Recommendations and future research

The potential impact of the factors explored in this study on the results of pavement LCA including the maintenance and the use phases is significant. For this reason, LCA practitioners should be careful to report the models and assumptions they use in a detailed and transparent way (Huang and Parry 2014). Development of widely accepted approaches and agreement to use and declare them is a prerequisite for the development of LCA practice in this domain.

Table 8.1 includes a summary of recommendations and future research needs identified in this research.

The results show that the model used can significantly influence the traffic delay work zone emission estimates and their relationship could be unpredictable. For this reason, road pavement LCA studies should take into account different levels of sophistication in traffic modelling or, at least, the selection of the traffic analysis tool should be considered based on the specific context of the project.

Some precautions need to be adopted when a macroscopic approach, based on the HCM (both HCM_LCCA and HCM_TL), is used to assess the impact of the traffic delay during maintenance events:

- For the calculation of the queue speed, the approach currently adopted needs to be updated, by using a more accurate method of evaluating this parameter.
- Monitor the impact of the saturation flow, when the TM in site involves the use of traffic lights.

In addition, in order to increase their reliability, these models may be optimized, introducing a further level of sophistication. As mentioned in section 3.2, several studies related to the impact of the traffic delay during maintenance events have implemented adjustments and improvements to reduce the impact of the limitations of macroscopic models. These methodologies and procedure may be implemented also in pavement LCA studies including the analysis of traffic delay to reduce the uncertainty of the macroscopic approach.

The sensitivity test has shown that all the parameters or elements assessed, namely traffic volume, TM, EF model and network boundary, affect the results, but they do not always have the same impact on different case studies.

Road LCA studies, including analysis of future maintenance works, should monitor the impact of the traffic volume and possible fluctuations and explore different TM options and justify their selection. The choice of the EF model needs to be based on the traffic model adopted for the analysis and should be representative of the vehicles and area assessed in the study. Finally, as already mentioned in the literature review, the traffic modelling requires the identification of the extent of the network impacted by the work zone. For a comprehensive understanding, the modelling should cover the whole network affected. As a result of this investigation, the author believes that further research is necessary to analyse the basic requirements in terms of modelling and input variables, required to introduce the work zone traffic delay into the system boundary of a pavement LCA.

In terms of PVI rolling resistance, taking into account the results obtained in the selected case study, the use of the UCPRC and VTI models in the UK should be treated with caution because they produce significantly different results. The different weight that the models give to the different pavement condition variables means the relative results from the two models are very sensitive to both level of pavement condition and its deterioration rate.

For UK roads, there is currently insufficient modelling available to predict the deterioration of roughness and texture depth over time depending on maintenance treatments, traffic volume, surface properties and materials. This must be corrected before pavement LCA studies can be extended to the use phase.

Traffic growth and the EF/fuel efficiency predictions, combined to predict future vehicle emissions, have a relatively small effect because they cancel out to a large extent. Changes in predicted future traffic levels or EF could change this result and should be kept under review.

As a result of this investigation, the author believes that overall, further research is necessary to develop standardized procedures for PVI rolling resistance emission estimates, so to obtain comparable and reliable pavement LCA results beneficial in the decision making process. Furthermore, it is recommended to any national or regional road authority that wants to introduce the use phase into the pavement LCA framework, to at least carry out an exhaustive calibration and validation of the existing models presented in this work, if not developing their own models to accurately predict evolution of pavement surface properties of their road networks over time. In particular, for UK roads, research is needed to develop reliable pavement deterioration models and PVI rolling resistance models, before introducing this component.

Finally, sensitivity and uncertainty analyses need to be implemented in pavement LCA studies through standardized procedures to enhance the understanding of the model's structure and ensure reliability and consistency of the LCA results. This study has identified some potential sensitive parameters in pavement LCA studies that assess the impact of the work zone and the rolling resistance. Pavement LCA studies should perform sensitivity analysis to verify possible variations which may affect the main conclusions. In this case, it might be necessary to apply uncertainty test to understand the effects of different sources of uncertainties. This procedure would quantify the uncertainty and variability that affect this methodology, especially with the work zone impact and rolling resistance components.

LCA and carbon footprint studies need to be reported in a way that makes the methods of modelling and the assumptions used transparent, before they can be interpreted by decision makers. Standard models and procedures should be developed in the pavement LCA field to make this possible and are needed before product category rules in this domain can be extended to include the use phase.

Table 8.1: Recommendations and future research

LCA phase	Parameter	Level of sensitivity*	Recommendations and Future Research
WORK ZONE IMPACT	**Traffic model**	Medium	- Consideration of different levels of sophistication and selection of the traffic analysis tool based on the specific context of the project. - If a macroscopic approach is used, update the approach used to calculate the queue speed during congestion and monitoring the traffic flow speed parameter. - Optimise the macroscopic methodologies currently used with adjustment and improvements implemented in other studies in literature.
	Traffic Volume	High	- Monitoring the impact of the AADT for future maintenance events.
	TM	Low to High	- Exploring different TM options and justify their selection.
	EF model	High	Selection of the EF model based on the traffic model used and representative of the vehicles and climate conditions of the area analysed.
	Network Boundary	Low	The analyst needs to take into account both the delay in the work zone and in the all network that may be affected by the TM layout. From this point of view, the simulation approach is more flexible, allowing the area of analysis to be extended and taking into account other traffic elements (traffic lights, junctions, roundabouts).
ROLLING RESISTANCE	**Rolling resistance Model**	High	Development of Rolling resistance models by national or regional road authorities or at least carry out an exhaustive calibration and validation of the existing models.
	Deterioration Model	High	Development of national/ regional deterioration models that take into account climate conditions, surface treatment, volume of traffic and traffic fleet.

LCA phase	Parameter	Level of sensitivity*	Recommendations and Future Research
	Traffic growth	Low	- Evaluation of the impact of traffic growth on the pavement deterioration rate. -Changes in the forecasts for this factor need to be monitored and studies updated to reflect them.
	EF	Low	Changes in the forecasts for this factor need to be monitored and studies updated to reflect them.

- Low sensitivity: 0-20% variation;
- Medium sensitivity: 20-100% variation;
- High sensitivity: 0ver 100% variation.

9 References

Aavik A, Kaal T, Jentson M (2013) Use Of Pavement Surface Texture Characteristics Measurement Results In Estonia. Paper presented at the XXVIII International Baltic Road Conference, Vilnius, Lithuania 26-28 August.

Agency USEP (1989) Exposure Factors Handbook vol 1. Exposure Assessment Group, Office of Health and Environmental Assessment, US Environmental Protection Agency.

Alexiadis V, Jeannotte K, Chandra A (2004) Traffic analysis toolbox volume I: Traffic analysis tools primer FHWA-HRT-04-038.

Amos D (2006) Pavement smoothness and fuel efficiency: an analysis of the economic dimensions of the Missouri Smooth Road Initiative.

Araújo JPC, Oliveira JRM, Silva HMRD (2014) The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transportation Research Part D: Transport and Environment 32:97-110 doi:http://dx.doi.org/10.1016/j.trd.2014.07.006.

AzariJafari H, Yahia A, Amor MB (2016) Life cycle assessment of pavements: reviewing research challenges and opportunities Journal of Cleaner Production 112:2187-2197.

Barth M, Boriboonsomsin K (2009) Traffic congestion and greenhouse gases ACCESS Magazine 1.

Beauving J, De Jonghe T, Goos D, Lindahl T, Stawiarski A (2004) Environmental Impacts and Fuel Efficiency of Road Pavements. *European Roads Review*, (2).

Bedford T, Cooke R (2001) Probabilistic risk analysis: foundations and methods. Cambridge University Press.

Bendtsen H (2004a) Rolling resistance, fuel consumption-a literature review. Road Directorate, Danish Road Institute, Denmark.

Bendtsen H (2004b) Rolling resistance, fuel consumption and emissions: A literature review SILVIA project report.

Berthiaume R, Bouchard C (1999) Exergy analysis of the environmental impact of paving material manufacture Transactions of the Canadian Society for Mechanical Engineering 23:187-196.

Bevington PR, Robinson DK (2003) Data reduction and error analysis McGraw-Hill.

Bjorklund, A. (2002). Survey of approaches to improve reliability in LCA. The International Journal of Life Cycle Assessment 7(2), 64–72. doi: 10.1007/BF02978849.

Bojacá CR, Schrevens E (2010) Parameter uncertainty in LCA: stochastic sampling under correlation The International Journal of Life Cycle Assessment 15:238-246.

Borge R, De Miguel I, de la Paz D, Lumbreras J, Pérez J, Rodríguez E (2012) Comparison of road traffic emission models in Madrid (Spain) Atmospheric Environment 62:461-471.

Boulter PG, Barlow TJ, McCrae IS, Latham S (2009) Emission factors 2009: Final summary report N. PPR361. Transport Research Laboratory.

Boxill SA, Yu L (2000) An Evaluation of Traffic Simulation Models for Supporting ITS. Houston, TX: Development Centre for Transportation Training and Research, Texas Southern University.

Brander M, Tipper R, Hutchison C, Davis G (2009) Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels Technical paper TP-090403-A, Ecometrica Press, London, UK.

Bryce JM (2014) Applying Pavement Life Cycle Assessment Results to Enhance Sustainable Pavement Management Decision Making. Virginia Polytechnic Institute and State University.

Bryce JM, Santos J, Flintsch G, Katicha S, McGhee K, Ferreira (2014) Analysis of rolling resistance models to analyse vehicle fuel consumption as a function of pavement properties. In: International Conference on Asphalt Pavements Raleigh, North Carolina, USA, 1-5 June, 2014. CRC Press/Balkema, pp 263-276.

BSI (2008) PAS 2050 - How to assess the carbon footprint of goods and services.

BSI (2011) PAS 2050:2011 - specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

Butt AA, Toller S, Birgisson B (2015) Life cycle assessment for the green procurement of roads: a way forward Journal of Cleaner Production 90:163-170.

Carlson A (2011) Life cycle assessment of roads and pavements: Studies made in Europe. Statens väg-och transportforskningsinstitut.

Carlson R, Häggström S, Pålsson A-C (2003) LCA training package for users of LCA data and results. Industrial Environmental Informatics.

Cass D, Mukherjee A (2011) Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: case study for pavement operations Journal of Construction Engineering and Management 137:1015-1025.

Chan AW-C (2007) Economic and environmental evaluations of life cycle cost analysis practice: a case study of Michigan DOT pavement projects (PhD thesis) . University of Michigan.

Chatti K, Zaabar I (2012) Estimating the effects of pavement condition on vehicle operating costs (Vol. 720). Transportation Research Board.

Chen F, Zhu H, Yu B, Wang H (2015) Environmental burdens of regular and long-term pavement designs: a life cycle view. International Journal of Pavement Engineering 17:300-313.

Chester MV, Horvath A (2009) Environmental assessment of passenger transportation should include infrastructure and supply chains. Environmental Research Letters 4:024008.

Chien S, Schonfeld P (2001) Optimal work-zone lengths for four-lane highways. Journal of Transportation Engineering 127:124-131.

Consoli F, Toxicology SoE, Chemistry (1993) Guidelines for life-cycle assessment: a" code of practice"; from the SETAC Workshop held at Sesimbra, Portugal, 31 March-3 April 1993.

Curran, M. A. (2006). LIFE CYCLE ASSESSMENT: PRINCIPLES AND PRACTICE.

Curtis D, Funderburg KA (2003) States estimate work zone traffic delay using QuickZone. Institute of Transportation Engineers ITE Journal 73:40.

Davis G, Yang S (2001) Accounting for uncertainty in estimates of total traffic volume: an empirical Bayes approach. Journal of Transportation and Statistics:27.

De Koning, A., D. Schowanek, J. Dewaele, A. Weisbrod, and J. Guinee (2009). Uncertainties in a carbon footprint model for detergents; quantifying the confidence in a comparative result. The International Journal of Life Cycle Assessment 15(1), 79–89. doi: 10.1007/s11367-009-0123-3.

Demir E, Bektaş T, Laporte G (2011) A comparative analysis of several vehicle emission models for road freight transportation .Transportation Research Part D: Transport and Environment 16:347-357.

Department for Transport/Highways Agency (2009) Traffic Signs Manual, Chapter 8, TSO: London, UK.

ECRPD (2010) Energy conservation in road pavement design, maintenance and utilisation.

Ekvall T (1999) System expansion and allocation in life cycle assessment with implications for wastepaper management. Chalmers University of Technology.

Ekvall T, Azapagic A, Finnveden G, Rydberg T, Weidema BP, Zamagni A (2016) Attributional and consequential LCA in the ILCD handbook.The International Journal of Life Cycle Assessment 21:293-296.

Ekvall T, Finnveden G (2001) Allocation in ISO 14041—a critical review. Journal of cleaner production 9:197-208.

EPA's Office of Transportation and Air Quality (OTAQ) (2014) User Guide for MOVES 2014.

EPA US (2010) Highway Vehicle Population and Activity Data. U.S. Environmental Protection Agency, Washington, D.C.

Eurobitume (2011) Life cycle inventory: Bitumen. Technical report, European Bitumen Association,www.bitumenuk.com/images/library/files/LifeCycleInventoryBitumen14Mar2011.pdf .

Fava JA (1994) Life-cycle assessment data quality: a conceptual framework. Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education.

Federal Highway Administration F (2017a) QuickZone. U.S. Department of Transportation. https://ops.fhwa.dot.gov/WZ/traffic_analysis/quickzone/index.htm.

Federal Highway Administration F (2017b) Work Zone and Traffic Analysis. U.S. Department of Transportation. https://ops.fhwa.dot.gov/wz/traffic_analysis/index.htm.

Fellendorf M (1994) VISSIM: Ein Instrument zur Beurteilung verkehrsabhängiger Steuerungen (VISSIM: a tool to analyse vehicle actuated signal control), In: Verkehrsabhängige Steuerungenam Knotenpunkt edited by the German Research Foundation for transport and roads (FGSV), Kassel, p 31–38.

Finnveden G et al. (2009) Recent developments in life cycle assessment. Journal of environmental management 91:1-21.

Franco V, Kousoulidou M, Muntean M, Ntziachristos L, Hausberger S, Dilara P (2013). Road vehicle emission factors development: A review Atmospheric Environment 70:84-97.

Funtowicz SO, Ravetz JR (1990) Uncertainty and quality in science for policy vol 15. Springer Science & Business Media.

Gadda S, Magoon A, Kockelman KM Estimates of AADT: Quantifying the uncertainty. In: Proceedings of the 86th Annual Meeting of the Transportation Research Board, 2007. Citeseer.

Galatioto F, Huang Y, Parry T, Bird R, Bell M (2015) Traffic modelling in system boundary expansion of road pavement life cycle assessment. Transportation Research Part D: Transport and Environment 36:65-75

Garcia R, Freire F (2014) Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. Journal of Cleaner Production 66:199-209.

Gaudreault, C. (2012). Methods for open-loop recycling allocation in life cycle assessment and carbon footprint studies of paper products. NCASI, National Council for Air and Stream Improvement.

Gkatzoflias, D., Kouridis, C., Ntziachristos, L., & Samaras, Z (2007) "COPERT 4: Computer programme to calculate emissions from road transport." *ETC-ACC (European Topic Centre on Air and Climate Change)*.

Groen EA, Heijungs R, Bokkers EA, de Boer IJ Sensitivity analysis in life cycle assessment. In: Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, 2014. pp 8-10.

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., ... & Rydberg, T. (2010). Life cycle assessment: past, present, and future.

Haider M, Conter M (2012) MIRAVEC Deliverable D1.1. - Report on the road infrastructure effects contributing to road vehicle energy consumption and their governing parameters.

Haider M, Conter M, Glaeser K-P (2011) MIRIAM Deliverable D 5.2.1 Discussion paper – “What are rolling resistance and other influencing parameters on energy consumption in road transport” SP2 vol SP2.

Häkkinen T, Mäkelä K (1996) Environmental Impact of Concrete and Asphalt Pavements. Concrete and Asphalt Pavements (VTT, Finland: Technical Research Center of Finland).

Hammarström U, Eriksson J, Karlsson R, Yahya M-R (2012) Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions VTI Rapport 748A.

Hammarström U, Karlsson B (1987) VETO: Ett datorprogram för beräkning av transportkostnader som funktion av vägstandard VTI meddelande, ISSN 0347-6049.

Hammarström U, Karlsson R, Sörensen H (2008) Road surface effects on rolling resistance – coastdown measurements with uncertainty analysis in focus. ECRPD Deliverable D5.

Handbook, I. L. C. D. "General guide for life cycle assessment-detailed guidance." Luxembourg. doi 10.38479 (2010): 0.

Harvey J, Kendall A, Lee I-S, Santero N, Van Dam T, Wang T Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines. In: Pavement Life Cycle-Assessment Workshop, Davis, California, 2010.

Harvey JT, Mejijer J, Ozer H, Al-Qadi IL, Saboori A, Kendall A (2016) Pavement Life-Cycle Assessment Framework FHWA-HIF-16-014. FHWA.

Heijungs R (2010) Sensitivity coefficients for matrix-based LCA The International Journal of Life Cycle Assessment 15:511-520.

Heijungs R, Huijbregts MA (2004) A review of approaches to treat uncertainty in LCA. In: Proceedings of the IEMSS conference, Osnabruck.

Hellweg S, i Canals LM (2014) Emerging approaches, challenges and opportunities in life cycle assessment Science 344:1109-1113.

Horvath A, Hendrickson C (1998) Comparison of environmental implications of asphalt and steel-reinforced concrete pavements Transportation Research Record: Journal of the Transportation Research Board:105-113.

Huang Y (2007) Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements. PhD Thesis. Newcastle University.

Huang Y, Bird R, Bell M (2009) A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation Transportation Research Part D: Transport and Environment 14:197-204 doi:http://dx.doi.org/10.1016/j.trd.2008.12.003.

Huang Y, Galatioto F, Parry T (2014) Road pavement maintenance life cycle assessment- a UK case study. Paper presented at the International Symposium on Pavement Life Cycle Assessment, Davis, California, USA.

Huang Y, Spray A, Parry T (2013) Sensitivity analysis of methodological choices in road pavement LCA. The International Journal of Life Cycle Assessment 18:93-101.

Huijbregts M (2002) Uncertainty and variability in environmental life-cycle assessment The International Journal of Life Cycle Assessment 7:173-17.3

Huijbregts MA (1998) Application of uncertainty and variability in LCA The International Journal of Life Cycle Assessment 3:273.

International Organitazation for Standardization (ISO) (1994) Acoustics -Specification of test tracks for the purpose of measuring noise emitted by road vehicles.

International Organization for Standardization (ISO) (1992) ISO 8767:1992 Tyres and wheels. Tyres. Car tyres. Method of measuring rolling resistance.

International Organization for Standardization (ISO) (2004) Characterization of pavement texture by use of surface profiles - Part 1: Determination of Mean Profile Depth (ISO 13473-1:2004).

International Organization for Standardization (ISO) (2006a) BS EN ISO 14040:2006 Environmental managment - Life cycle assessment - Principles and framework. British Standard Institution.

International Organization for Standardization (ISO) (2006b) BS EN ISO 14044:2006 Environmental managment - Life cycle assessment - Requirements and guudelines. British Standard Institution.

International Organization for Standardization (ISO) (2009) ISO 28580:2009 Passenger car, truck and bus tyres — Methods of measuring rolling resitance — Single point test and correlation of measurement results. International.

International Organization for Standardization (ISO) (2011) BS EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. British Standard Institution.

Inti S, Martin SA, Tandon V (2016) Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements Elsevier 145:972-979.

Jacobs F (1982) M40 High Wycombe By-pass: Results of a Bituminous Surface-texture Experiment. Transport and Road Research Laboratory, UK.

Jensen AA, Hoffman L, Møller B, Schmidt A, Christiansen K, Elkington J, Van Dijk F (1998) Life cycle assessment (LCA): A guide to approaches, experiences and information sources. European Environment Agency.

Jiang X, Adeli H (2003) Freeway work zone traffic delay and cost optimization model Journal of transportation engineering 129:230-241.

Jiang Y (1999) Traffic capacity, speed, and queue-discharge rate of Indiana's four-lane freeway work zones Transportation Research Record: Journal of the Transportation Research Board:10-17.

Jiang Y (2001) Estimation of traffic delays and vehicle queues at freeway work zones. In: 80th Annual Meeting of the Transportation Research Board, Washington, DC.

Karlsson R, Carlson A, Dolk E (2012) VTI - Energy Use Generated by Traffic and Pavement Maintenance: Decision Support for Optimization of Low Rolling resistance Maintenance Treatments. Statens väg-och transportforskningsinstitut.

Keller, Mario. Handbook of emission factors for road transport (HBEFA) 3.1. quick reference. Technical report, INFRAS, 2010.

Kerali HG, Odoki J, Stannard E (2000) Overview of HDM-4. The World Road Association (PIARC).

Kioutsioukis, I., Kouridis, C., Gkatzoflias, D., Dilara, P., & Ntziachristos, L. (2010). Uncertainty and sensitivity analysis of national road transport inventories compiled with COPERT 4. *Procedia-Social and Behavioral Sciences*, *2*(6), 7690-7691.

Klüppel H-J (1997) Goal and scope definition and life cycle inventory analysis The International Journal of Life Cycle Assessment 2:5-8.

Kloepffer, Walter. "Life cycle sustainability assessment of products." *The International Journal of Life Cycle Assessment* 13.2 (2008): 89.

Lacirignola M, Blanc P, Girard R, Pérez-López P, Blanc I (2017) LCA of emerging technologies: addressing high uncertainty on inputs' variability when performing global sensitivity analysis Science of The Total Environment 578:268-280 doi:http://dx.doi.org/10.1016/j.scitotenv.2016.10.066.

Lloyd SM, Ries R (2007) Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches Journal of Industrial Ecology 11:161-179.

London TSO (2009) Chapter, Traffic Signs Manual "8–Part 1: Design." Traffic Safety Measures and Signs for Road Works and Temporary Situations. Department for Transport/Highways Agency.

Lu Q, Kohler ER, Harvey JT, Ongel A (2009) Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results UCPRC-RR-2009-01.

Mallela J, Sadasivam S (2011) Work Zone Road User Costs - Concepts and Applications. Federal Highway Administration (FHWA).

Mannering FL, Washburn SS (2012) Principles of Highway Engineering and Traffic Analysis Fifth edition.

Masters J (2015) Efforts redoubled to get right traffic growth predictions. Transportation Professional.

Mattinen MK, Nissinen A, Hyysalo S, Juntunen JK (2015) Energy Use and Greenhouse Gas Emissions of Air-Source Heat Pump and Innovative Ground-Source Air Heat Pump in a Cold Climate Journal of Industrial Ecology 19:61-70.

Matute JM, Chester M, Eisenstein W, Pincetl S Life-Cycle Assessment for Transportation Decision Making. In: Transportation Research Board 93rd Annual Meeting, 2014. vol 14-1287.

McCoy PT, Pang LM, Post ER (1980) Optimum length of two-lane two-way no-passing traffic operation in construction and maintenance zones on rural four-lane divided highways Transportation research record 773:20-24.

Meil J (2006) A life cycle perspective on concrete and asphalt roadways: embodied primary energy and global warming potential Athena Research Institute.

Meng Q, Weng J (2013) Optimal subwork zone operational strategy for short-term work zone projects in four-lane two-way freeways Journal of Advanced Transportation 47:151-169.

Michelin (2003) "The tyre - Rolling resistance and fuel savings". . Société de Technologie Michelin, 23 rue Breschet, FR-63000 Clermont-Ferrand, France (also available on CD).

Miller TD, Fugro Consultants I, Austin T (2012) Characterization of surface texture: technology update. Paper presented at the 7th symposium on pavemnt surface characteristics, Norfolk, Virginia/September 19-22, 2012.

Morgan MG, Henrion M, Small M (1992) Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge university press.

Mroueh, U. M., Eskola, P., Laine-Ylijoki, J., Wellman, K., Mäkelä, E., Juvankoski, M., & Ruotoistenmäki, A. (2000). Life cycle assessment of road construction. Tielaitoksen selvityksiä.

Muench ST, Lin YY, Katara S, Armstrong A (2014) Roadprint: Practical Pavement Life Cycle Assessment (Lca) Using Generally Available Data. Paper presented at the International Symposium on Pavement LCA 2014, Davis, California, USA, October 14-16 2014.

Muga HE, Mukherjee A, Mihelcic JR, Kueber MJ (2009) An integrated assessment of continuously reinforced and jointed plane concrete pavements Journal of Engineering, Design and Technology 7:81-98 doi:10.1108/17260530910947277.

NAPA (2016) Product Category Rules (PCR) for Asphalt Mixtures.

Nesbit M, Fergusson M, Colsa A, Ohlendorf J, Hayes C, Paquel K, Schweitzer JP (2016) Comparative study on the differences between the EU and US legislation on emissions in the automotive sector, IP/A/EMIS/2016-02.

Nicholson AL, Olivetti EA, Gregory JR, Field FR, Kirchain RE End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions. In: Sustainable Systems and Technology, 2009. ISSST'09. IEEE International Symposium on, 2009. IEEE, pp 1-6.

Nisbet M, Marceau M, VanGeem M, Gajda J (2001) Environmental life cycle inventory of Portland cement concrete and asphalt concrete pavements Portland Cement Association PCA R&D Serial.

Noshadravan A, Kirchain R, Gregory J (2012) Key Drivers of Uncertainty in Pavement LCA - Life Cycle Assessment Research Brief. Concrete Sustainability Hub@MIT.

Noshadravan A, Wildnauer M, Gregory J, Kirchain R (2013) Comparative pavement life cycle assessment with parameter uncertainty Transportation Research Part D: Transport and Environment 25:131-138.

Ntziachristos, L., Samaras, Z., Eggleston, S., Gorissen, N., Hassel, D., Hickman, A. J., ... & Zierock, L. (2000). Validation of road vehicle and traffic emission models, a review and meta-analysis: COPERT IV Computer Programme to Calculate Emissions From Road Transport, Methodology and Emissions Factors (Version 2.1). Technical Report No. 49. European Environment Agency.

Panis LI, Broekx S, Liu R (2006) Modelling instantaneous traffic emission and the influence of traffic speed limits Science of the total environment 371:270-285.

Park K, Hwang Y, Seo S, Seo H (2003) Quantitative assessment of environmental impacts on life cycle of highways Journal of construction engineering and management 129:25-31.

PTV and TORG (2004). EnvPro (Environmental Program) Version1.6: Introduction to the Use.

QUARTET (1992) Assessment of current tools for environment assessment in QUARTET, DRIVE II Project V2018.

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment - Part 2: impact assessment and interpretation The International Journal of Life Cycle Assessment 13:374-388.

Rebitzer G et al. (2004) Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications Environment international 30:701-720.

Resource Efficiency Knowledge Transfer Network Life Cycle Assessment Current practice and applications.

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

Rister B, Graves C (2002) The cost of construction delays and traffic control for life-cycle cost analysis of pavements

Ross SA, Cheah L (2016) Uncertainty Quantification in Life Cycle Assessments: Interindividual Variability and Sensitivity Analysis in LCA of Air-Conditioning Systems Journal of Industrial Ecology.

Rossi R, Gastaldi M, Gecchele G, Kikuchi S (2012) Estimation of annual average daily truck traffic volume. Uncertainty treatment and data collection requirements Procedia-Social and Behavioral Sciences 54:845-856.

Roudebush W (1999) Environmental value engineering assessment of concrete and asphalt pavement. Portland Cement Association PCA R&D Serial.

Russell A, Ekvall T, Baumann H (2005) Life cycle assessment–introduction and overview. Journal of Cleaner Production 13:1207-1210.

Samaras, Z., and L. Ntziachristos. "Methodologies for estimating air pollutant emissions from transport." Average Hot Emission Factors for Passenger Cars and Light Duty Trucks Deliverable 7 (1998).

Sandberg U, Ejsmont JA (2003) Book Review-//Tyre/Road Noise Reference Book. Noise Control Engineering Journal, 51(6), pp.348-348.

Sandberg U, Bergiers A, Ejsmont JA, Goubert L, Karlsson R, Zöller M (2011a) Road surface influence on tyre/road rolling resistance. Report MIRIAM SP1 04 deliverable.

Sandberg U. (2011b) Rolling resistance—Basic information and state-of-the-art on measurement methods. Linköping, Sweden: Swedish Road and Transport Research Institute.

Santero N (2010) Life cycle assessment of pavements: A critical review of existing literature and research. Lawrence Berkeley National Laboratory.

Santero N, Masanet E, Horvath A (2011a) Life-cycle assessment of pavements Part II: Filling the research gaps. Resources, Conservation and Recycling 55:810-818.

Santero N, Masanet E, Horvath A (2011b) Life-cycle assessment of pavements. Part I: Critical review. Elsevier Resources, Conservation and Recycling 55:801-809.

Santero NJ, Harvey J, Horvath A (2011c) Environmental policy for long-life pavements. Transportation Research Part D: Transport and Environment 16:129-136.

Santero NJ, Horvath A (2009) Global warming potential of pavements. Environmental Research Letters 4:034011.

Santos J, Ferreira A, Flintsch G (2014) A life cycle assessment model for pavement management: road pavement construction and management in Portugal International. Journal of Pavement Engineering 16:315-336.

Santos J, Ferreira A, Flintsch G (2015) A life cycle assessment model for pavement management: methodology and computational framework. International Journal of Pavement Engineering 16:268-286.

Smit R, Dia H, Morawska L (2009) Road traffic emission and fuel consumption modelling: trends, new developments and future challenges. Traffic-Related Air Pollution:29-68.

Spray A, Huang Y, Parry T Importance of some aspects of methodology in pavement life cycle assessment. In: Eurasphalt & Eurobitume Congress, 5th, 2012, Istanbul, Turkey, 2012. vol P5EE-493.

Spray AT (2014) Carbon Footprinting Methods and Their Application in Road Pavements PhD thesis. PhD thesis, University of Nottingham.

Stripple H (2001) Life cycle assessment of road. A pilot study for inventory analysis. Rapport IVL Swedish Environmental Research Institute, 96.

Tatari O, Nazzal M, Kucukvar M (2012) Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. Resources, Conservation and Recycling 58:18-24.

Taylor G, Farrel P, Woodside A (2002) Additional analysis of the effect of pavement structures on truck fuel consumption. National Research Council of Canada (NRC), Ottawa, Ontario.

Taylor G, Patten J (2006) Effects of pavement structure on vehicle fuel consumption-Phase III

Thomassen MA, Dalgaard R, Heijungs R, De Boer I (2008) Attributional and consequential LCA of milk production. The International Journal of Life Cycle Assessment 13:339-349.

Transport simulation system (TSS) (2015) Aimsun 8.1 User's Manual.

Transport simulation system (TSS) (2017) Aimsun: the integrated tool for transportation modelling applications. http://www.aimsun.com/. Accessed 30/01/2017 2017.

Transport for London (2010) Traffic Modelling Guidelines TfL Traffic Manager and Network Performance Best practice Version 3.0.

Transportation Research Board (2010) Highway Capacity Manual (HCM). National Research Council, Washington, DC.

Transport Reasearch Laboratory (TRL) (2017) Development of SCANNER and UKPMS, Project Report PPR816

TREE (2017) LCA (Life Cycle Assessment) and CARBON FOOTPRINT. http://tre-eng.com/en/environment/lca-life-cycle-assessment-and-carbon-footprint. Accessed 2017 .

Treloar GJ, Love PE, Crawford RH (2004) Hybrid life-cycle inventory for road construction and use. Journal of construction engineering and management 130:43-49.

Trupia L, Parry T, Neves L, Lo Presti D (2016) Rolling resistance Contribution To A Road Pavement Life Cycle Carbon Footprint Analysis. The International Journal of Life Cycle Assessment doi:10.1007/s11367-016-1203-9.

Tseng E (2012) The construction of pavement performance models for the California Department of Transportation new pavement management system. Department of Civil and Environmental Engineering - University of California Davis.

UK Department for Environment Food & Rural Affairs (2014) Emissions Factors Toolkit User Guide.

UK Department for Transport Traffic counts. https://www.dft.gov.uk/traffic-counts/about.php. 2017.

UK Department for Transport (2009) Publications. https://www.gov.uk/government/publications?keywords=&publication_filter_option=all&topics%5B%5D=all&departments%5B%5D=department-for-transport&official_document_status=all&world_locations%5B%5D=all.

UK Department for Transport (2016) Road Use Statistics Great Britain 2016.

UK Department for Transport (2017) Statistics at DFT. https://www.gov.uk/government/organisations/department-fortransport/about/statistics. Accessed 2016.

UK Department of Energy & Climate Change (2015) 2014 UK Greenhouse Gas Emissions, Provisional Figures.

UK Goverment (1999a) Design Manual for Roads and Bridges vol 7. sec. 5.2.

UK Goverment (1999b) Design Manual for Roads and Bridges vol 7. sec. 5.1.

UK Roads Liaison Group (UKRLG) (2013) The HMEP Highway Infrastructure Asset Management Guidance.

U.S. Environmental Protection Agency (US EPA) (1989) Exposure Factors Handbook vol 1. Exposure Assessment Group, Office of Health and Environmental Assessment, US Environmental Protection Agency.

Walls III J, Smith MR (1998) Life-Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin. Federal Highway Administration (FHWA),.

Wang T (2013) Reducing greenhouse gas emissions and energy consumption using pavement maintenance and rehabilitation: Refinement and application of a life cycle assessment approach. University Of California, Davis.

Wang T, Harvey J, Kendall A (2014a) Reducing greenhouse gas emissions through strategic management of highway pavement roughness. Environmental Research Letters 9:034007.

Wang T, Harvey J, Kendall A (2014b) Supplementary material for "Reducing greenhouse gas emissions through strategic managment of highway pavement roughness .

Wang T, Kim C, Harvey J (2014c) Energy consumption and Greenhouse Gas Emission from highway work zone traffic in pavement life cycle assessment. Paper presented at the International Symposium on Pavement Life Cycle Assessment, Davis, California, USA.

Wang T, Lee I-S, Harvey J, Kendall A, Lee EB, Kim C (2012a) UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling resistance.

Wang T, Lee I-S, Kendall A, Harvey J, Lee E-B, Kim C (2012b) Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. Journal of Cleaner Production 33:86-96.

Wayman M, Schiavi-Mellor I, Cordell B (2014) Further guidance on the calculation of whole life cycle greenhouse gas emissions generated by asphalt - Part of the asphalt Pavement Embodied Carbon Tool (asPECT). PROJECT REPORT PPR574 (version 4.0). Transport Research Laboratory.

Weber CL (2012) Uncertainty and variability in product carbon footprinting. Journal of Industrial Ecology 16:203-211.

Weidema BP (2003) Market information in life cycle assessment (Vol. 863, p. 365). Miljøstyrelsen, Weiland CD, Muench ST (2010) Life Cycle Assessment of Portland Cement Concrete Interstate Highway Rehabilitation and Replacement (No. WA-RD 744.4).

Weng J, Meng Q (2013) Estimating capacity and traffic delay in work zones: An overview. Transportation Research Part C: Emerging Technologies 35:34-45.

Wennström J (2010) Estimations of Delay Costs caused by Roadworks.

White P, Golden JS, Biligiri KP, Kaloush K (2010) Modeling climate change impacts of pavement production and construction. Resources, Conservation and Recycling 54:776-782.

Willis JR, Robbins MM, Thompson M (2015) Effects of pavement properties on vehicular rolling resistance: A literature review. National Center for Asphalt Technology Auburn University, Auburn, Alabama.

WRI (2011) Product life cycle accounting and reporting standard. available at: www.ghgprotocol.org/standards/product-standard.

Xu X, Gregory J, Kirchain R (2015) Role of the Use Phase and Pavement-Vehicle Interaction in Comparative Pavement Life Cycle Assessment. Paper presented at the Transportation Research Board 94th Annual Meeting, Washington DC, United States.

Yang RY (2014) Development of a pavement life cycle assessment tool utilizing regional data and introducing an asphalt binder model. University of Illinois at Urbana-Champaign.

Yu B, Liu Q, Gu X (2016) Data quality and uncertainty assessment methodology for pavement LCA International Journal of Pavement Engineering:1-7 doi:10.1080/10298436.2016.1176166.

Yu B, Lu Q (2012) Life cycle assessment of pavement: Methodology and case study Transportation Research Part D: Transport and Environment 17:380-388.

Yu B, Lu Q (2014) Empirical model of roughness effect on vehicle speed. International Journal of Pavement Engineering 15:345-351.

Zaabar I, Chatti K (2010) Calibration of HDM-4 models for estimating the effect of pavement roughness on fuel consumption for US conditions. Transportation Research Record: Journal of the Transportation Research Board:105-116.

Zachariadis T, Samaras Z (1997) Comparative assessment of European tools to estimate traffic emissions. International Journal of Vehicle Design 18:312-325.

Zaniewski JP (1989) Effect of pavement surface type on fuel consumption. Portland Cement Association: Skokie, IL.

Zapata P, Gambatese JA (2005) Energy consumption of asphalt and reinforced concrete pavement materials and construction. Journal of Infrastructure Systems 11:9-20.

Zhang H, Lepech MD, Keoleian GA, Qian S, Li VC (2010) Dynamic life-cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration. Journal of Infrastructure Systems 16:299-30

10 Appendices

- **Appendix A**

OD matrix flows for different network boundary extensions

- **Appendix B**

Aimsun calculation for the A1(M)

- **Appendix C**

HCM calculations

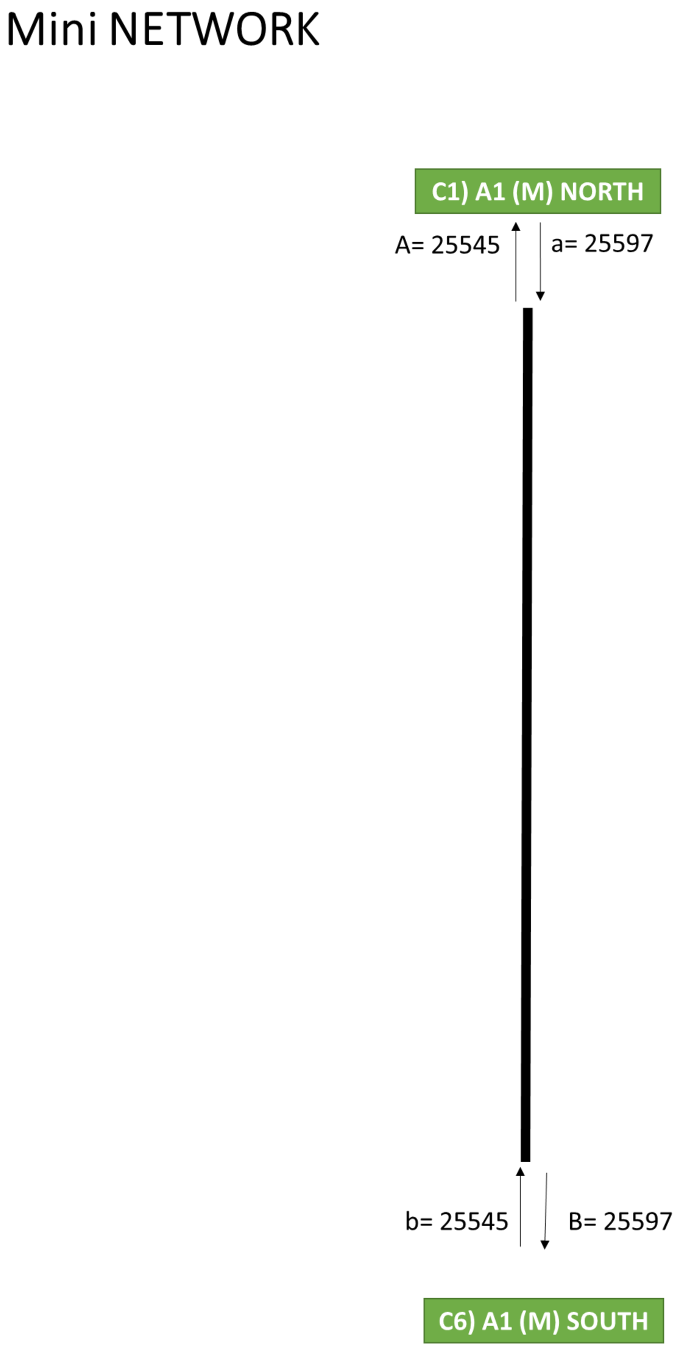
- A17: example of calculation procedure for the Base case scenario, approach 1 (see Figure 5.10) during phase 1 of works.
- A1(M): example of calculation procedure for the Base case scenario

- **Appendix D**

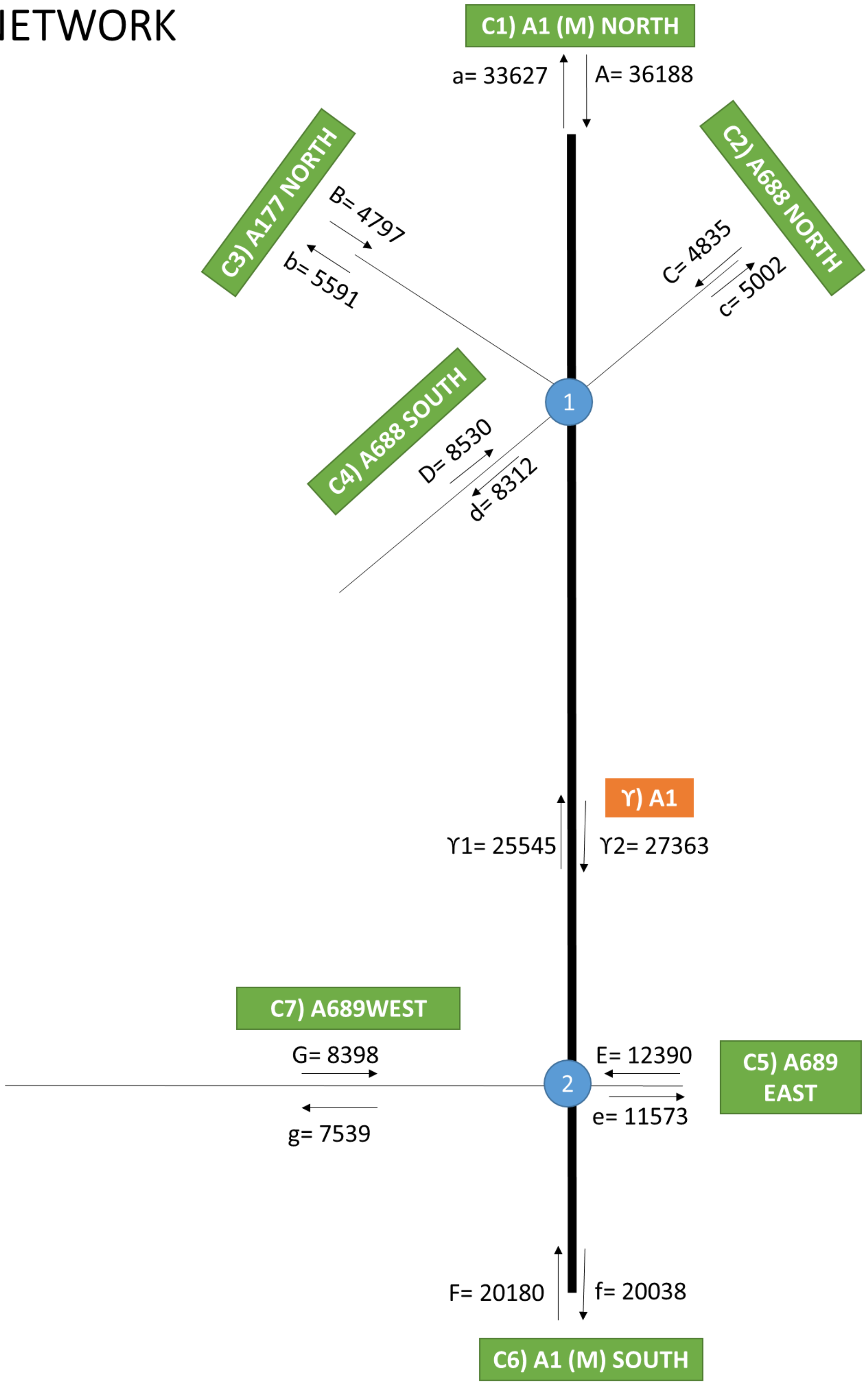
Coefficients of tailpipe CO_2 emission factors combination of factorial variables, adopted for the A17 and the A1 (M) case studies, from Wang et al. (2014a).

Appendix A

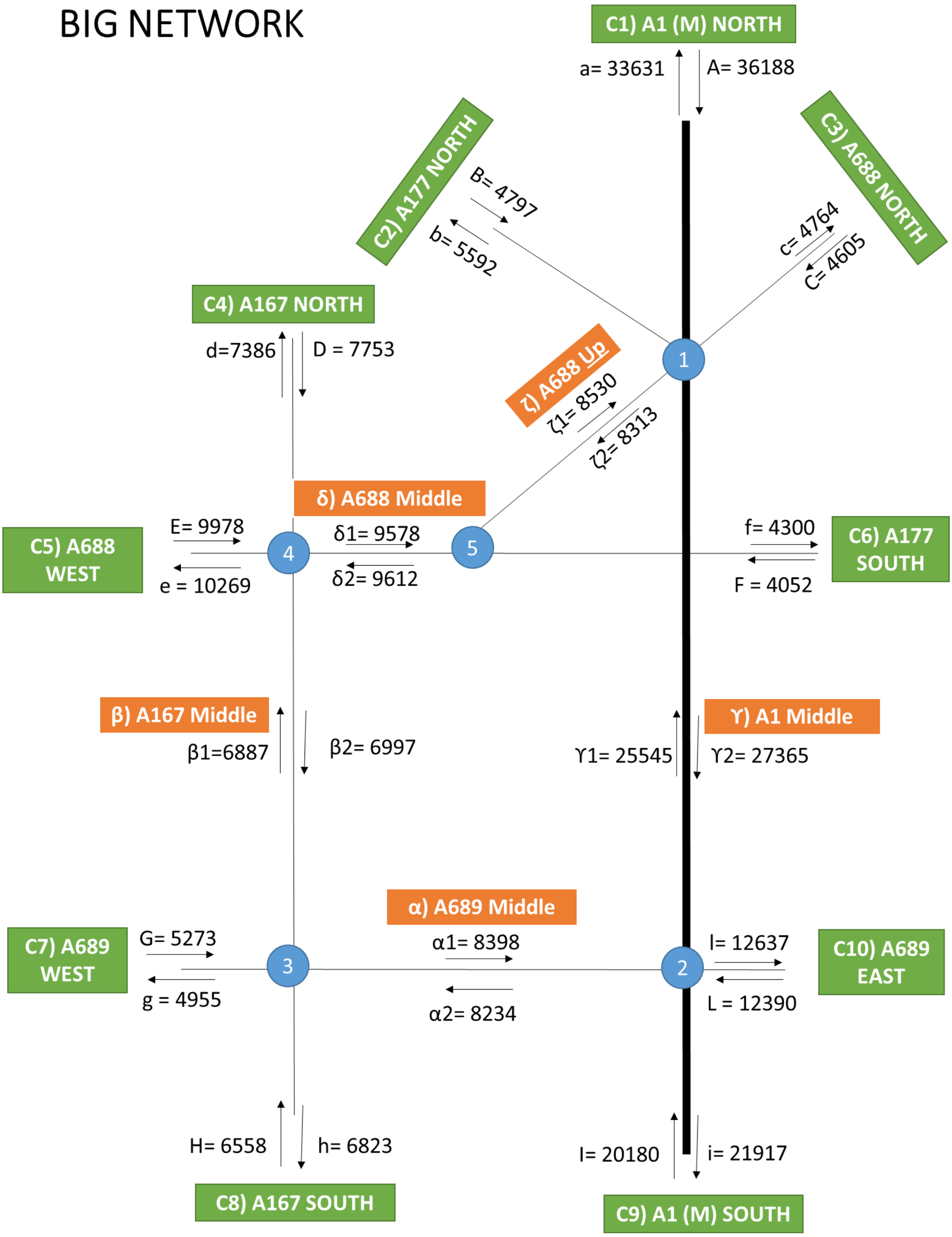
OD matrix flows for different network boundary extensions



SMALL NETWORK



BIG NETWORK


C1) A1 (M) NORTH
a= 33631
A= 36188
C2) A177 NORTH
B= 4797
b= 5592
C3) A688 NORTH
c= 4764
C= 4605
C4) A167 NORTH
d=7386
D = 7753
ζ) A688 Up
ζ1= 8530
ζ2= 8313
1
δ) A688 Middle
C5) A688 WEST
E= 9978
e = 10269
4
δ1= 9578
δ2= 9612
5
f= 4300
F = 4052
C6) A177 SOUTH
β) A167 Middle
β1=6887
β2= 6997
ϒ) A1 Middle
ϒ1= 25545
ϒ2= 27365
α) A689 Middle
C7) A689 WEST
G= 5273
g = 4955
3
α1= 8398
α2= 8234
2
l= 12637
L = 12390
C10) A689 EAST
H= 6558
h= 6823
C8) A167 SOUTH
I= 20180
i= 21917
C9) A1 (M) SOUTH

Appendix B

Aimsun calculation for the A1(M)

Base case scenario

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	0%	EFT	Mini network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	40.03	360.26
Saturday	31.89	95.68
Sunday	31.79	95.36
	Total	551.30

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	44.15	397.36
Saturday	33.88	101.65
Sunday	33.62	100.87
	Total	599.88

Results	**CO_2 emissions (ton)**
	48.58

+10% Traffic volume

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	10%	EFT	Mini network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	44.31	398.80
Saturday	35.19	105.57
Sunday	35.05	105.14
	Total	551.30

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	49.89	448.99
Saturday	37.70	113.10
Sunday	37.38	112.15
	Total	599.88

Results	CO_2 emissions (ton)
	64.74

+20% Traffic volume

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	20%	EFT	Mini network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	48.83	439.49
Saturday	38.73	116.19
Sunday	38.22	114.66
	Total	551.30

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	57.53	517.80
Saturday	41.70	125.11
Sunday	41.33	124.00
	Total	599.88

Results	**CO_2 emissions (ton)**
	96.58

+30% Traffic volume

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	30%	EFT	Mini network

Traffic management			
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	53.30	479.66
Saturday	42.08	126.25
Sunday	41.72	125.15
	Total	731.06

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	66.24	596.13
Saturday	46.61	139.84
Sunday	46.05	138.16
	Total	599.88

Results	CO_2 emissions (ton)
	143.08

TM_Scenario 2

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow, including hard shoulder	0%	EFT	Mini network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

The simulation is different during the preparation period and and work zone period

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	70.86	637.77
Saturday	56.35	169.04
Sunday	56.11	168.32
	Total	975.12

Preparation and depot		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	71.49	643.41
		643.41

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Saturday Northbound	60.44	181.32
Sunday Southbound	59.83	179.48
	Total	360.80

Results	**CO_2 emissions (ton)**
	29.09

TM_Scenario 3

TM	Traffic volume	Emission Factors	Network Boundary
Road closure and detour	0%	EFT	Mini network

Traffic management			
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	1 Hour *plus pre-start time	1 Shift for Northbound*4 km=4 shifts	1 Hour *plus removal
Southbound	1 Hour *plus pre-start time	1 Shift for Southbound*4 km= 4 shift	1 Hour *plus removal

Total workzone time	8 overnight shifts	from 20.00 to 5.00
Simulation time	from 18.00 to 8.00	

Normal time

Network	Day	CO_2 emissions (t) 1 day simulation	CO_2 emissions (t) total days simulation
All network	**Saturday**	39.09	156.35
	Sunday	41.67	166.68
		Total	323.03

Maintenance times

Network	Day	CO_2 emissions (t) 1 day simulation	CO_2 emissions (t) total days simulation
Northbound closure	**Saturday**	43.04	86.08
	Sunday	45.17	91.81
Southbound closure	**Saturday**	45.91	91.81
	Sunday	50.32	100.64
		Total	370.34

Results	CO_2 emissions (ton)
	47.31

Small Network

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	0%	EFT	Small network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	100.74	906.64
Saturday	77.93	233.80
Sunday	77.12	237.51
	Total	1377.95

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	105.94	953.45
Saturday	80.28	240.85
Sunday	79.17	237.51
	Total	1431.80

Results	**CO_2 emissions (ton)**
	53.85

Big network

TM	Traffic volume	Emission Factors	Network Boundary
Lane closure and contraflow	0%	EFT	Big network

	Traffic management		
Direction	**Time to deploy the workzone**	**Timeto Install 40mm Thin Surface Course for 1km – 2 Lanes**	**Time to remove the workzone**
Northbound	3 days	1 day (per 4 Km 4 days)	3 days
Southbound	3 days	1day (per 4 Km 4 days)	3 days

Total workzone time	17 days	3 week end +11week days
Simulation time	from 00.00 to 23.59	

Normal time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	168.51	1516.63
Saturday	132.93	398.80
Sunday	132.64	397.93
	Total	2313.35

Maintenance time		
Day	**CO_2 emissions (t) 1 day simulation**	**CO_2 emissions (t) total days simulation**
Week	172.02	1548.17
Saturday	134.60	403.81
Sunday	134.42	403.25
	Total	2355.23

Results	**CO_2 emissions (ton)**
	41.88

Appendix C

HCM calculations

- A17: example of calculation procedure for the Base case scenario, approach 1 (see Figure 5.10) during phase 1 of works.

1) Workzone data

	Length/speed				
	LENGTH		**SPEED**		
	Description	Meters	mph	Km/h	
L1	Speed reduction before traffic ligth/workzone	288.0	40	64.4	
L2	Speed reduction before traffic ligth/workzone	54.9	10	16.1	
L3	Speed reduction after traffic ligth in the workzone	500.0	10	16.1	
L4	Speed reduction after traffic ligth/workzone	54.9	10	16.1	
L5	Speed reduction after traffic ligth/workzone	288.0	40	64.4	
Ltot	**1185.8**	**55**	**88.5**		

Hourly traffic during the workzone shift		
hour	from 1	From 2-3-4
19-20	258	223
20-21	168	195
21-22	117	290
22-23	79	211
23-23	50	90
0-1	27	32

2) Traffic light data

Traffic light timing						
	Work time	**Light cycle (seconds)**	**Duration**	**Duration (seconds)**	**N. traffic light cycle**	**N. traffic light cycle in 1 hour**
t_1	19.30-21.00	180	1h30m	5,400	30	20
t_2	21.00-24.45	120	3h45m	13,500	113	30
TOTAL	19.30-24.45		5h15m	18,900	143	18,901

	Traffic light cycle					
			180 SEC		120 SEC	
			TIME	%	TIME	%
Timing	green G		52	0.3	22	0.2
	all red AR		38	0.2	38	0.3
	red R		52	0.3	22	0.2
	all red AR		38	0.2	38	0.3
	total C		180	1.0	120	1.0
Effective timing	g (G+AR-tl)		44		14.0	
	r (C-g=R+tl)		136		106	
	AR		76		76	
Lost time	start up	**tsl (sec)**	8		8	
	clearance	**tcl (sec)**	76		76	
	Lost time	**tl (sec)**	84		84	
Capacity	capacity	**c (veh/h)**	464		222	
	capacity	**c (veh/s)**	0.129		0.062	

3) Delay calculation		for 1 cycle						n. cycles		
	time	Arrivals rate v (veh/sec)	Arrival cycle v*C (veh/sec)	s*g Capacity (veh/sec)	Conditions -	Average delay (sec/veh)	Qmax -	n. cycles -	Qmax -	Delay total seconds
t_1	19.30-20	0.072	12.90	23.2	Under saturation	59.45	9.75	10	97.5	5794
	20-21	0.047	8.40	23.2	Under saturation	56.36	6.3	20	126.9	7154
t_2	21-22	0.033	3.90	7.4	Under saturation	49.89	3.4	30	103.4	5156
	22-23	0.059	7.03	7.4	Under saturation	52.67	6.2	30	186.4	9816
	23-24	0.014	1.67	7.4	Under saturation	48.08	1.5	30	44.2	2124
	24-24.45	0.008	0.90	7.4	Under saturation	47.49	0.8	22.5	17.9	850
									Total	30,894

4) Additional emission calculation	Δemission ton of CO_2						
		Length (Km)	speed (mph)	n. vehicles	KG of CO_2 per Km/vehicle	KG CO_2	Δemission ton of CO_2
Normal condition	Normal condition	1.2	55	563	0.19	128.36	**0.066**
Maintenance condition	Reduce speed	0.58	40	563	0.18	59.57	
	Reduce speed	0.61	10	563	0.31	107.14	
	Idling E	Delay total (sec)	speed (mph)		Emission rate at 0 mph		
		30,894	**0**		0.001	27.52	

A1(M): example of calculation procedure for the Base case scenario

Total CO_2 emission estimation	CO_2 emissions(g) Traverse WZ	Traverse queue	Total	CO_2 (t)	Number of days	ton for n of days
WEEK	- 5,833,760	44,745,128	38,911,368	38.91	9	350.20
SATURDAY	- 4,376,768	1,053,154	- 3,323,614	-3.32	3	-9.97
SUNDAY	- 4,138,522	673,440	- 3,465,082	-3.47	3	-10.40
					total	**329.84**

WEEKDAY

TRAVERSE WZ

		CAR				LGV				HGV			
	A	B	C	D	E	B'	C'	D'	E'	B"	C"	D"	E"
	WZ length (Km)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)
South	4	19,630	157	177	- 1,570,400	3,508	231	307	- 1,066,432	2,819	808	835	- 304,452
North	4	19,287	157	177	- 1,542,960	3,437	231	307	- 1,044,848	2,821	808	835	- 304,668
		Sum CO2 emissions (gr) F			- 3,113,360	Sum CO2 emissions (gr) F'			- 2,111,280	Sum CO2 emissions (gr) F"			- 609,120
	Tot (gr)	**- 5,833,760**											

TRAVERSE QUEUE

		CAR				LGV				HGV			
	A	B	C	D	E	B	C'	D'	E'	B	C"	D"	E"
	N. vehicle* average queue length (=i*j)	%	CO2 8mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)
South	163,060	0.76	279	177	12,578,075	0.14	367	307	1,322,223	0.11	1,528	835	12,272,189
North	114,919	0.76	279	177	8,850,174	0.13	367	307	927,722	0.11	1,528	835	8,794,745
		Sum CO2 emissions (gr) F			21,428,249	Sum CO2 emissions (gr) F'			2,249,944	Sum CO2 emissions (gr) F"			21,066,934
	Tot (gr)	**44,745,128**											

SATURDAY

TRAVERSE WZ

		CAR				LGV				HGV			
	A	B	C	D	E	B'	C'	D'	E'	B"	C"	D"	E"
	WZ length (Km)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)
South	4	15,853	157	177	- 1,268,247	2,833	231	307	- 861,245	2,277	808	835	- 245,874
North	4	13,345	157	177	- 1,067,627	2,378	231	307	- 722,966	1,952	808	835	- 210,810
		Sum CO2 emissions (gr) F			- 2,335,873	Sum CO2 emissions (gr) F'			- 1,584,211	Sum CO2 emissions (gr) F"			- 456,684

Tot (gr) - **4,376,768**

TRAVERSE QUEUE

		CAR				LGV				HGV			
	A	B	C	D	E	B	C'	D'	E'	B	C"	D"	E"
	N. vehicle* average queue length (=i*j)	%	CO2 8mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)
South	4,190	0.76	279	177	323,223	0.14	367	307	33,978	0.11	1,528	835	315,363
North	2,355	0.76	279	177	181,357	0.13	367	307	19,011	0.11	1,528	835	180,222
		Sum CO2 emissions (gr) F			504,581	Sum CO2 emissions (gr) F'			52,988	Sum CO2 emissions (gr) F"			495,584

Tot (gr) **1,053,154**

SUNDAY

TRAVERSE WZ

		CAR				LGV				HGV			
	A	B	C	D	E	B'	C'	D'	E'	B"	C"	D"	E"
	WZ length (Km)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	N. vehicles	CO2 60mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)
South	4	15,713	157	177	- 1,257,012	2,808	231	307	- 853,616	2,256	808	835	- 243,696
North	4	13,876	157	177	- 1,110,074	1,496	231	307	- 454,932	2,030	808	835	- 219,192
		Sum CO2 emissions (gr) F			- 2,367,086	Sum CO2 emissions (gr) F'			- 1,308,548	Sum CO2 emissions (gr) F"			- 462,888

Tot (gr) - **4,138,522**

TRAVERSE QUEUE

		CAR				LGV				HGV			
	A	B	C	D	E	B	C'	D'	E'	B	C"	D"	E"
	N. vehicle* average queue length (=i*j)	%	CO2 8mph (g/Km)	CO2 70mph (g/Km)	CO2 emissions (g) A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)	%	CO2 8mph (g/Km)	CO2 70mph	CO2 emissions A*B*(C-D)
South	3,210	0.76	279	177	247,579	0.14	367	307	26,026	0.11	1,528	835	241,558
North	979	0.76	279	177	75,421	0.13	367	307	7,906	0.11	1,528	835	74,949
		Sum CO2 emissions (gr) F			323,001	Sum CO2 emissions (gr) F'			33,932	Sum CO2 emissions (gr) F"			316,507

Tot (gr) **673,440**

Appendix D

Coefficients of tailpipe CO_2 emission factors combination of factorial variables, adopted for the A17 and the A1 (M) case studies, from Wang et al. (2014a)

Surface type	*Road type and access type* [1]	*Year*	*Vehicle type* [2]	*a1*	*a2*	*Intercept*
Asphalt	4	2012	1	0.001876219	0.010914562	0.369037412
Asphalt	4	2013	1	0.001854146	0.010782085	0.364698365
Asphalt	4	2014	1	0.001824042	0.010609294	0.359077828
Asphalt	4	2015	1	0.001800295	0.010466722	0.354198022
Asphalt	4	2016	1	0.001771294	0.010279044	0.348078859
Asphalt	4	2017	1	0.001747518	0.010125342	0.342929998
Asphalt	4	2018	1	0.001716612	0.009953112	0.337329717
Asphalt	4	2019	1	0.001693318	0.009800209	0.332192688
Asphalt	4	2020	1	0.001670324	0.009655745	0.327420275
Asphalt	4	2021	1	0.001649835	0.009526733	0.322610986
Asphalt	4	2012	2	0.012553133	0.011560899	1.137285825
Asphalt	4	2013	2	0.012556451	0.011564851	1.137245199
Asphalt	4	2014	2	0.012560835	0.011567753	1.137226028
Asphalt	4	2015	2	0.012567335	0.011569839	1.137252925
Asphalt	4	2016	2	0.012570129	0.011572265	1.137252867
Asphalt	4	2017	2	0.012569885	0.011573786	1.137283153
Asphalt	4	2018	2	0.012574128	0.011575101	1.137331343
Asphalt	4	2019	2	0.012573549	0.011577828	1.137399586
Asphalt	4	2020	2	0.012579934	0.011580319	1.137466708
Asphalt	4	2021	2	0.012579104	0.011581478	1.137514732
Asphalt	4	2012	3	0.020332832	0.020636288	1.852893111
Asphalt	4	2013	3	0.020332659	0.02063766	1.85272051
Asphalt	4	2014	3	0.020335155	0.02063908	1.852587615
Asphalt	4	2015	3	0.020338004	0.020640802	1.852572009
Asphalt	4	2016	3	0.020339445	0.020643045	1.852523842
Asphalt	4	2017	3	0.020341408	0.020644932	1.852523067
Asphalt	4	2018	3	0.020342432	0.020646317	1.852535215
Asphalt	4	2019	3	0.020346548	0.020648752	1.852595174
Asphalt	4	2020	3	0.02034914	0.020651165	1.852659489
Asphalt	4	2021	3	0.020349193	0.020652665	1.852683241
Asphalt	4	2012	4	0.03209003	0.032090273	2.758342792
Asphalt	4	2013	4	0.032087897	0.032088419	2.758360044
Asphalt	4	2014	4	0.032086321	0.032086797	2.758374811
Asphalt	4	2015	4	0.032085216	0.03208582	2.758379921
Asphalt	4	2016	4	0.032098152	0.032087006	2.758407759
Asphalt	4	2017	4	0.032096003	0.032084993	2.758432849
Asphalt	4	2018	4	0.032088854	0.032083877	2.758443049
Asphalt	4	2019	4	0.032104124	0.032087527	2.758437597
Asphalt	4	2020	4	0.032103623	0.032087142	2.758445973
Asphalt	4	2021	4	0.032095589	0.032086779	2.758467041
Asphalt	4	2012	5	0.037893891	0.037303795	3.09205854
Asphalt	4	2013	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2014	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2015	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2016	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2017	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2018	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2019	5	0.037893891	0.037303795	3.09205854
Asphalt	4	2020	5	0.037897752	0.037303877	3.092060208
Asphalt	4	2021	5	0.037897752	0.037303877	3.092060208

Surface type	*Road type and access type* [1]	*Year*	*Vehicle type* [2]	*a1*	*a2*	*Intercept*
Asphalt	5	2012	1	0.001123943	0.009291257	0.463408019
Asphalt	5	2013	1	0.001105561	0.00917158	0.45826631
Asphalt	5	2014	1	0.001086466	0.00902329	0.451962561
Asphalt	5	2015	1	0.001069826	0.00888975	0.445687936
Asphalt	5	2016	1	0.001051139	0.008724436	0.437872925
Asphalt	5	2017	1	0.001035232	0.008582857	0.4310739
Asphalt	5	2018	1	0.001016327	0.008432073	0.42414879
Asphalt	5	2019	1	0.00099884	0.008293196	0.417555686
Asphalt	5	2020	1	0.000984978	0.008168213	0.41151665
Asphalt	5	2021	1	0.000971819	0.008057446	0.405466128
Asphalt	5	2012	2	0.010565975	0.011187059	1.533392639
Asphalt	5	2013	2	0.010570156	0.01118635	1.533467647
Asphalt	5	2014	2	0.010569591	0.0111876	1.53353856
Asphalt	5	2015	2	0.010567568	0.011189425	1.533655235
Asphalt	5	2016	2	0.010569009	0.011189809	1.533725459
Asphalt	5	2017	2	0.010570257	0.011190702	1.533822385
Asphalt	5	2018	2	0.01056964	0.011191805	1.533922413
Asphalt	5	2019	2	0.010571479	0.011192644	1.534033246
Asphalt	5	2020	2	0.010572735	0.011193107	1.534137269
Asphalt	5	2021	2	0.010574575	0.011193935	1.53421794
Asphalt	5	2012	3	0.014478114	0.017753547	2.182781492
Asphalt	5	2013	3	0.014475923	0.01775157	2.182844673
Asphalt	5	2014	3	0.014472473	0.017750311	2.182872809
Asphalt	5	2015	3	0.014473591	0.017750403	2.183076824
Asphalt	5	2016	3	0.014474015	0.017748859	2.183176454
Asphalt	5	2017	3	0.014472595	0.017749489	2.18335814
Asphalt	5	2018	3	0.014475593	0.017750001	2.18351221
Asphalt	5	2019	3	0.014474959	0.01775033	2.183692309
Asphalt	5	2020	3	0.014475617	0.017751342	2.183844433
Asphalt	5	2021	3	0.014477351	0.017751741	2.183991181
Asphalt	5	2012	4	0.024470713	0.030419196	3.062864751
Asphalt	5	2013	4	0.024467095	0.030413316	3.062887019
Asphalt	5	2014	4	0.024452382	0.030419111	3.062899945
Asphalt	5	2015	4	0.024466097	0.030413958	3.062908129
Asphalt	5	2016	4	0.02446283	0.030409967	3.062928233
Asphalt	5	2017	4	0.024455963	0.030415519	3.062927375
Asphalt	5	2018	4	0.024477094	0.030412192	3.062930359
Asphalt	5	2019	4	0.024476245	0.030410849	3.062945263
Asphalt	5	2020	4	0.024455374	0.030417168	3.062952729
Asphalt	5	2021	4	0.024445859	0.030413152	3.062976786
Asphalt	5	2012	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2013	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2014	5	0.030727395	0.03203113	3.398543389
Asphalt	5	2015	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2016	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2017	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2018	5	0.030727395	0.03203113	3.398543389
Asphalt	5	2019	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2020	5	0.030714692	0.032026537	3.398572515
Asphalt	5	2021	5	0.030714692	0.032026537	3.398572515

Note:

[1] 4 represents urban restricted-access road; and 5 represents urban unrestricted-access road.

[2] 1 represents passenger car; 2 represents 2-axle truck; 3 represents 3-axle truck; 4 represents 4-axle truck; 5 represents 5 or more axle truc